Technology-Assisted Healthcare: Exploring the use of mobile 3D visualisation technology to augment home-based fall prevention assessments

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Abstract

Falls often cause devastating injuries which precipitate hospital and long-term care admission and result in an increased burden on health care services. Fall prevention interventions are used to overcome fall risk factors in an ageing population. There is an increasing need for technology-assisted interventions to reduce health care costs, whilst also lessening the burden that an ageing population increasingly has on health care services. Research efforts have been spent on reducing intrinsic fall risk factors (i.e. functional ability deficits and balance impairments) in the older adult population through the use of technology-assisted interventions, but relatively little effort has been expended on extrinsic risk factors (i.e. unsuitable environmental conditions and lack of assistive equipment use), considering the drive for healthcare outside of the clinical setting into the patients' home. In the field of occupational therapy, the extrinsic fall-risk assessment process (EFAP) is a prominent preventive intervention used to promote independent living and alleviate fall risk factors via the provision of assistive equipment prescribed for use by patients in their home environment. Currently, paper-based forms with measurement guidance presented in the form of 2D diagrams are used in the EFAP. These indicate the precise points and dimensions on a furniture item that must be measured as part of an assessment for equipment. However, this process involves challenges, such as inappropriate equipment prescribed due to inaccurate measurements being taken and recorded from the misinterpretation of the measurement guidance. This is largely due to the poor visual representation of guidance that is provided by existing paper-based forms, resulting in high levels of equipment abandonment by patients. Consequently, there is a need to overcome the challenges mentioned above by augmenting the limitations of the paper-based approach to visualise measurement guidance for equipment. To this end, this thesis proposes the use of 3D visualisation technology in the form of a novel mobile 3D application *(Guidetomeasure)* to visualise guidance in a well-perceived manner and support stakeholders with equipment prescriptions. To ensure that the artefact is a viable improvement over its 2D predecessor, it was designed, developed and empirically evaluated with patients and clinicians alike through conducting five user-centred design and experimental studies. A mixed-method analysis was undertaken to establish the design, effectiveness, efficiency and usability of the proposed artefact, compared with conventional approaches used for data collection and equipment prescription. The research findings show that both patients and clinicians suggest that 3D visualisation is a promising development of an alternative tool that contains functionality to overcome existing issues faced in the EFAP. Overall, this research makes a conceptual contribution *(secondary)* to the research domain and a software artefact *(primary)* that significantly improves practice, resulting in implications and recommendations for the wider healthcare provision *(primary)*.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this thesis is original and has not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other, University. This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

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Dedication

I would like to dedicate this thesis to my mother, Sophie, my wife, Camille, and my new born son, Luther.

List of Publications

The following list of research papers has been published or being submitted for publication as an output of the research reported in this thesis:

1. Hamm, J., Money, A.G., Atwal, A. and Paraskevopoulos, I., 2016. Fall prevention intervention technologies: A conceptual framework and survey of the state of the art. *Journal of Biomedical Informatics*, *59*, pp.319-345. **(Published)**

2. Hamm, J., Money, A.G., Atwal, A. and Ghinea, G., 2017. Mobile three-dimensional visualisation technologies for clinician-led fall prevention assessments. *Health Informatics Journal*, p.1460458217723170. **(Published)**

3. Hamm, J., Money, A. and Atwal, A., 2017. Fall Prevention Self-Assessments via Mobile 3D Visualization Technologies: Community Dwelling Older Adults' Perceptions of Opportunities and Challenges. *JMIR Human Factors*, *4*(2). **(Published)**

4. Hamm, J., Money, A. and Atwal, A., 2018. Enabling older adults to carry out paperless falls-risk self-assessments using guidetomeasure-3D: A mixed methods study. **(Submitted to a journal)**
5. Hamm, J., Money, A. and Atwal, A., 2018. guidetomeasure-OT: A mobile 3D application to improve the accuracy, consistency, and efficiency of clinician-led home-based falls-risk assessments. **(Submitted to a journal)**

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The first Brunel Computer Science Doctoral Consortium: 1st prize winner based on the research presented at the conference. Link to presentation slides presented at the conference.

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List of Acronyms and Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ADL	Activities of daily living
AE	Assistive Equipment
Async	Asynchronous
AU	Application use
Bal	Balance impairments
Bs	Bespoke sensor
C	Context
Co	Co-opted
Cog	Cognitive impairments
DB	Database
DC	Desktop Computer
DSR	Design Science Research
EFAP	Extrinsic fall-risk assessment process
Eh	Environmental hazards
Fun	Functional ability deficit(s)
G	Game
GC	Game Console
He	Home environment
Hs	Hospital
ICT	Information and communication technologies
ICTs	Information and communication technologies
ML	Machine Learning
NHS	National Health Service
Nii	Non-interactive interface
NUI	Natural User Interface
OT	Occupational therapist
OT	Occupational Therapy/Occupational Therapist
PEOU	Perceived ease of use
PU	Perceived usefulness
Rp	Repurposed sensors
S	Static
SA	Self-assessment
Sm	Smart-phone
SUS	System usability scale
Sync	Synchronous
TAM	Technology acceptance model
Ts	Touch screen
U	User-worn
UI	User interface
UK	United Kingdom
VR	Virtual Reality

Chapter 1
Introduction

1.1 Introduction

This chapter sets the scene for the research reported in this thesis. It is an exploration of the benefits of employing mobile three-dimensional (3D) visualisation technology to augment environmental assessment interventions aimed at overcoming extrinsic fall risk factors in the home environment. Following a discussion of the research problem and context of study, which introduces the fall prevention and technology-assisted fall prevention research domain areas, the need for augmenting environmental assessments for extrinsic risk factors as the problem statement is defined. The overall aim of the research and its objectives are then established, and the approach employed to achieve that aim is briefly described. After that, attention shifts to the research contributions: (1) conceptualisation of and conceptual framework based on a survey of the fall prevention technology research domain; (2) a novel mobile 3D visualisation artefact; and (3) implications and recommendations for the use of the artefact in practice, which are outlined in brief. Finally, a roadmap of the overall thesis is provided at the end of the chapter.

Specifically, the chapter is organised as follows: Section 1.2 provides the research problem, which is framed by issues that impact upon: (1) the independence of community-dwelling older adult patients in their home environment; (2) patient involvement; and (3) patient-clinician collaboration in shared decision-making. To address the research problem, exploitation of the benefits of 3D visualisation technology is proposed to overcome issues with conventional approaches/tools currently in use. Section 1.3 presents the overall research aim, and, thereafter, its objectives, based on the lack of effort expended on targeting environmental assessments to overcome extrinsic fall risks and the need for patient involvement and clinician-patient collaboration *(the research problem)*. The design science research approach employed to achieve the aim and objective of this research is briefly explained in Section 1.4. An overview of the three research contributions made by this thesis is presented in Section 1.5. The chapter finally concludes with a walkthrough of the thesis structure, along with a synopsis of each respective chapter, in Section 1.6.

1.2 Research problem and context of study

Falls are a major health concern and pose a significant challenge to the well-being of an ageing world population. The number of falls and related injuries has risen in recent years in the United Kingdom (UK), in part due to a growing population aged 80 years and over [1]. There have been many attempts in clinical literature to achieve a consensus as to how a ‘fall’ should be defined. According to the literature, the perception of what a fall is differs between clinicians and older adult patients, particularly if no injuries are sustained [2]. The different approaches in which they are investigated often creates considerable disparity between studies in the literature [3]. Consequently, it is important to set out a clear and standardised definition of what a fall actually is, and the different movements that may constitute such an event. The definition upon which this research work is based defines a fall as “an unexpected event in which the participant comes to rest on the ground, floor, or lower level” [4]. In terms of adverse effect, falls often cause debilitating injuries, which precipitate hospitalisation and long-term care admission and result in an increased burden on health care services [5]. The cost of falls to the National Health Service (NHS) in the UK is estimated at over £2.3 billion per year [6]. Recent UK Government initiatives highlight both the importance and need for innovative technology-based applications which utilise information and communication technologies (ICTs) within the falls prevention domain.

ICTs are seen as having the potential to reduce health care costs, whilst also lessening the burden that an ageing population increasingly places on health care services [7, 8]. Furthermore, it is acknowledged that ICTs have numerous additional benefits, such as the potential to deliver more effective patient-centred interventions, and improvements in levels of patient engagement and adherence; which is likely to enhance patient satisfaction and overall quality of life [7, 9]. There are numerous other benefits that can be realised as a consequence of extrinsic fall-risk assessment, including enablement of ageing-in-place and independent living, enhanced care facilitation, increased self-esteem, and overall improvement in quality of life [10]. Healthcare has evolved immensely by turning increasingly to the use of technology to assist with service delivery beyond the parameters of the clinical setting and into the home environment, where patients are expected to take responsibility for their own care. It is of interest to adapt the existing tools - that may have been developed in-mind for clinicians alone - to develop and/or complement this shift, thereby ensuring that patients are able to use it to take on such responsibility to self-care independently.

Approximately 50% to 66% of falls occur in or around the patient's home environment [11] from a complex interplay of multiple factors. Extrinsic fall risk factors focus on risks that are apparent within the environment in which patients carry out activities on a day-to-day basis, including poor lighting, slippery floor surfaces, raised door thresholds, stairs and steps, clutter, and trip hazards [12]. Extrinsic fall risk factors also include improper use of assistive equipment (AE), such as stair handrails, toilet raisers, bath boards, and bathroom grab rails; or its absence, where such equipment would normally be deemed necessary. Evidence from the literature indicates a lack of support provided for both occupational therapist (OT) and non-occupational therapist (non-OT) -led interventions that are conducted for adapting the home environment in accordance with the patient’s needs [13]. Against this background, ICT-assisted interventions appear to offer a promising alternative in reducing fall risk factors, thereby allowing patients with complex needs to live independently at home with a better quality of life [14, 15]. Fall prevention technology systems have been proposed in the literature that address multiple fall risk factors and which are positioned within the various sub-domains of the overall research domain. To understand this in its entirety, and identify the gaps that must be bridged, a survey of the literature is required.

Consequently, a comprehensive *literature survey* has been carried out *(in Chapter 2)*, which surveys and categorises technology-based fall prevention systems across the *fall prevention technology research* landscape. The survey concludes that, although the various fall prevention systems proposed in the literature are valuable in reducing the multiple fall risk factors, there is a paucity of systems which target environmental assessment interventions intended to overcome extrinsic risk factors. There is also a lack of systems that allow patients to self-assess their needs in the environment in which they usually function. Furthermore, systems in the literature also lack functionality that allows patients and clinicians to collaborate in assessments and provide additional contextual detail for the collection and interpretation of data that these systems generate.

Clinicians (mainly being OTs) work with the older adult population with the intention of reducing falls and alleviating their risk factors through various interventions (discussed in more detail in Chapter 2). OTs play a major role in assisting older adults who wish to remain in their home and perform daily living tasks safely. To achieve this, OTs conduct an assessment of the home environment as part of the discharge and rehabilitation process, irrespective of the point at which the patient enters the care pathway. Upon assessing the home environment, recommendations are made in the form of assistive equipment prescriptions and the removal of home hazards. Rehabilitation training to improve muscle strength and balance is also provided to the patient. However, there are challenges to these aims, particularly related to ineffective tools used to prescribe the equipment that assists patients in the home environment, and their lack of involvement in the intervention itself.

In an effort to overcome these challenges, the extrinsic fall-risk assessment process (EFAP) is used as a case example, as it is a widely-employed procedure for prescribing equipment within the home to reduce fall risks and involves clinicians and patients working collaboratively to carry out assessments. Augmenting the EFAP in a way that addresses the aforementioned challenges may ideally result in equipment prescriptions that are more compatible to patient needs and the home environment. This research explores the EFAP as a case example and investigates how suitable existing conventional approaches are to environmental assessment interventions, and the extent to which they involve and support patients. Furthermore, it will explore ways in which a technology-based solution could augment the EFAP. Figure 1-1 presents the link from the literature survey findings to the research topics in this thesis and the case example that will be used in this thesis.

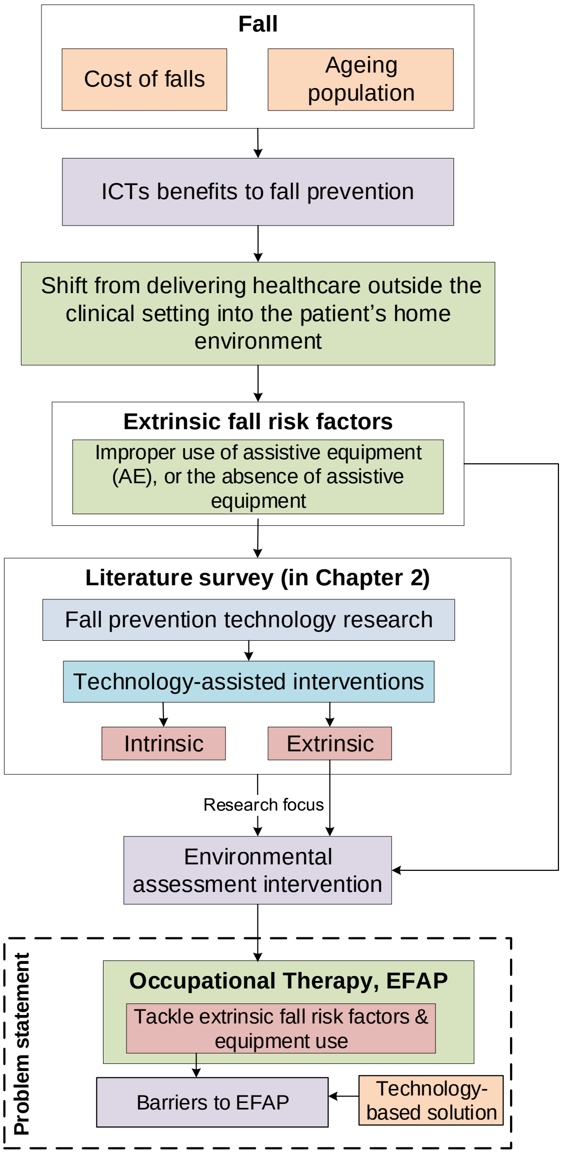


Figure 1-1: Link between the literature survey findings and EFAP topic of this research work.

1.2.1 Problem statement

It is recognised that in order to reduce the risk of falling, particularly to enable an older adult population to remain in their homes, targeting extrinsic risk factors is of equal importance to directing efforts to address intrinsic risk factors [16]. From the fall prevention technology systems reviewed (in Chapter 2), it is apparent that much of the research effort focuses on the development of technology-based solutions to augment evidence-based exercises and assessments.

Such solutions are designed to be deployed either in home or clinical settings that only target intrinsic risk factors or detect falls either obtrusively or unobtrusively via the use of sensor technologies. The findings of the survey raise important points regarding the considerable extent to which future fall prevention technology systems would benefit from addressing extrinsic risks. As mentioned previously, limited efforts have hitherto been spent on developing fall prevention technology for environmental assessments that address extrinsic risks, especially given the likelihood of fall occurrences caused by extrinsic risks as a result of the increasing push for patients to remain at home.

The EFAP, as an established intervention in the field of occupational therapy (OT), is typically conducted by clinicians. It involves working closely with patients to assess intrinsic and extrinsic fall risk factors, particularly in relation to how equipment can be successfully adopted by the clinicians conducting home assessments to help patients remain at home. Key tasks conducted as part of the assessment include collecting information about functional abilities and taking measurements of patients (i.e. popliteal height), fittings, and home furniture items, all of which is used to prescribe specific items of assistive equipment. Conventional paper-based guidance forms are used as a visual measurement aid to assist clinicians with the assessments, with the intention of ensuring that the correct information is recorded, and necessary associated patient data collected. These include measurement guidance presented in the form of two-dimensional (2D) illustrations of information that must be obtained about the patient, fittings, and home furniture. The paper-based (2D) illustrations are typically annotated with measurement arrows that serve as prompts to indicate the precise points in 3D space that must be accurately identified and measured to gather the data required to formulate an assessment and accurately prescribe the necessary assistive equipment [17].

Although the 2D paper-based guidance tool is regarded as valuable for the purpose of visualising the areas to measure, it is observed that its 2D format presents a challenge. It is limited in permitting sufficient visualisation of the 3D structures relative to their location and configuration for the measurements to be taken for equipment prescriptions. This can potentially result in the recording of inaccurate measurements, skewing the associated assessment data, and, potentially, rendering the prescribed equipment poorly fitted or incompatible to the patient needs/home. Approximately 50% of prescribed assistive equipment is abandoned by service users (SU) [18]. One of the principal reasons for this is 'poor fit' between the equipment and the patient using it [18, 19]. Inappropriate fitting of equipment has significant consequences on the effectiveness of care delivery, negatively impacts patient health outcomes, accelerates functional decline, increases overall exposure to fall risks in the home, and, more generally, unnecessarily depletes already scarce and valuable health care resources [20, 21]. Given the issues of 'poor fit' that already arise from trained OTs carrying out these tasks, it is likely that these will be exacerbated if patients and carers are given the responsibility for the EFAP [22].

In recognition of this, there is a need to explore whether innovative technology-based solutions can provide clearer and more effective assessment guidance to support and facilitate more accurate and reliable recording of measurements. The use of 3D visualisation technology has shown promise as an alternative to existing 2D paper-based tools used in healthcare, where limited visualisation capabilities impact stakeholders' ability to perceive aspects of treatment/rehabilitation. A review of 3D visualisation technologies in the medical and healthcare field is given in section 4.1.4. Furthermore, the employment of 3D visualisation provides an opportunity for interaction with tools that allow delivery to be perceived as in the natural environment. Introducing such technology in this sphere could tackle the 'poor fit' issue, and also help to address the pressing issue of self-assessment that lies at the frontier of healthcare delivery for older adults. The purpose of this research is to explore the use of 3D visualisation technology within the OT EFAP and identify its potential for augmenting existing 2D paper-based tools to provide a better aid for carrying out key measurement tasks in the EFAP.

1.3 Aim and Objectives

In light of the above, this research explores the potential value that mobile 3D visualisation technology could have in OT, and, specifically, the fall prevention technology domain, by supporting both clinicians and patients in the provision of assistive equipment in the home. This is achieved through co-designing a novel 3D visualisation application with clinicians and patients. By novel application, this refers to the use of 3D visualisation technology introduced in the OT field in the form of an application that augments the visual quality of existing 2D clinical guidance tools. Using a more enhanced visualisation of measurement guidance could improve interpretation/comprehension of crucial illustrations that aid the collection of information required for equipment prescriptions, which has not previously been explored. The primary **aim** of this research, therefore, was:

> **To develop and evaluate a novel application that utilises mobile 3D visualisation technology to assist patients and clinicians in carrying out more effective and efficient extrinsic home-based fall-risk assessments.**

The overall research aim is achieved through the following **six objectives** that are linked to the research studies reported in this thesis:

O1. Survey the fall prevention technology domain to conceptualise the state of the art systems, identify gaps, and explore the literature for a suitable approach to guide the research in the development of an artefact to address the identified gaps in the fall prevention domain;

O2. Explore the challenges and opportunities of the EFAP as a case example to address the limited efforts spent on environmental assessment interventions and the existing methods used to overcome extrinsic fall risks;

O3. Design and develop an alternative approach with stakeholders to overcome visualisation limitations of existing EFAP methods currently in use;

O4. Evaluate the research artefact through user-based studies (i.e. clinicians and patients) concerning its effectiveness in enabling accurate recording of measurements, efficiency, and perceived satisfaction of its general usability, compared to the conventional 2D method counterpart;

O5. Explore the artefact's functionality in assisting stakeholders with prescriptions of accurate equipment sizes based on a collection of assessments;

1.4 Research approach adopted

The research approach has been carefully selected for each stage of the data collection, taking into account the problem statement, the main aim and objectives, and the setup of the experimental studies. To fulfil the overall aim and objectives, the research employed design science research (DSR) [23, 24] as the overarching approach, while adopting a mixed method approach for each experimental study carried out in this research. The rationale for selecting this was premised upon it being a problem-solving approach, improving existing tools used in practice, and, as a result, designing technology-based solutions in the form of artefacts to address those problems [25, 26]. The data was gathered in four distinct research stages, with the outcomes of the preceding stage used to further develop the artefact for use and evaluation of the proximate stage. A more detailed overview of the research process is given in Chapter 3.

There is a debate in the literature regarding what an artefact represents. Put simply, March and Smith [27] classify artefacts as a construct, model, method, and instantiation. Given that the purpose of this research was to design a novel technology-based solution to address the defined problem, the artefact produced is classified as an instantiation. In order to implement the instantiation, a software development methodology was employed that allows for iterative prototypes of the artefact to be developed rapidly, in parallel to evaluating its performance and general usability at the end of each cycle. A DSR artefact is, by definition, a technological innovation that is functional and enhances existing systems, or proposes new ones to address a specified problem, which, in terms of what the artefact offers, is considered a contribution in its own right [23, 25]. The research artefact is, therefore, based on this definition in terms of how it contributes to the fall prevention technology domain. Furthermore, it is worth noting that the artefact is not a software development project. Whilst a software application is designed, the problem which it has been designed to solve is linked to a gap identified in the literature and is aligned with being able to undertake a task more easily. A more elaborate discussion of this is given in Chapter 3. All of the experimental studies reported upon in this thesis employed a mixed method approach. This research is divided into **five stages:**

Stage 1: this stage involved surveying the fall prevention technology literature to gain an understanding and conceptualise the sub-domain areas that make up its knowledge base (by developing a conceptual framework) and identify the various challenges that warrant attention (see Chapter 2 for more details).

Stage 2: studies 1 and 2 used *participatory design workshops*, *'think-aloud' semi-structured interviews*, *focus groups*, and a *questionnaire* to co-design a prototype, together with user cohorts to investigate the use of 3D visualisation technology in an EFAP context. A high-fidelity prototype was developed based on outcomes of the participatory design workshops. An evaluation was performed to gain insights into the perceptions and experiences of the two user cohorts and measure their subjective satisfaction of the proposed artefact.

Stage 3: studies 3 and 4 conducted user-based studies within a living lab setting to evaluate the measurement guidance module of the artefact against the 2D measurement guidance booklet currently in use, based on the established usability metrics [28] i.e. effectiveness, efficiency, and user satisfaction *(semi-structured interview and usability questionnaire)*.

Stage 4: study 5 conducted a user-based study to evaluate the equipment recommendation module, based on accuracy and consistent accuracy of recommendations generated by the app compared with conventional methods used for equipment prescriptions. Furthermore, this research employed technology acceptance theories to analyse the *semi-structured interviews* that were carried out at each stage of the research. A more detailed discussion of the overall research approach and the experimental studies undertaken is provided in Chapter 3. Carrying out these studies resulted in findings that impact the research domain and clinical practice within three high-level contributions, as presented briefly in the next section.

Stage 5: this stage draws conclusions from across the studies and establishes the overall contributions that this research work makes to the research sphere. Furthermore, the research findings have also been discussed and presented to other researchers and healthcare practitioners to determine its wider impact and ecological validity.

1.5 Research contributions in brief

The research presented in this thesis makes the following contributions to the domain areas of fall prevention technology, occupational therapy, and the wider healthcare provision arena:

- **A conceptual framework of the state of the art of fall prevention technology systems:** This first contribution provides a comprehensive literature survey of the falls prevention technology domain. A systematic approach was employed to search and synthesise the fall prevention technology studies that belong to the various sub-domains within the field, resulting in a conceptual framework. This was then unpacked and used to survey the research literature where a set of trends and challenges in the various sub-domains were identified and discussed. These contribute to a growing body of literature, as the findings provide a novel lens through which to view the research landscape; which, to the researcher's knowledge, did not exist prior to undertaking this work. It also provides other researchers with challenges which they can address to further advance the field of study. Furthermore, the systematic approach taken to survey the literature could also serve as a reference point for other researchers to conduct a literature survey of a similar nature.
- **A novel mobile 3D visualisation software artefact:** This primary contribution is a novel mobile 3D visualisation software artefact which is more effective, efficient, and usable than the conventional 2D paper-based guidance tools currently used as measurement guidance for equipment prescriptions. The Guidetomeasure app is adaptable for use by both clinicians and patients alike and could be redesigned for a different assessment purpose in healthcare.
- **Implications and recommendations for deployment in practice:** This research contributes to the enhancement of the healthcare provision through the employment of the mobile 3D visualisation approach for use by OTs and older adults by providing improved visualisation and equipment prescription capabilities to alleviate cost and societal implications as a result of equipment abandonment. The issues that the artefact is expected to highlight, and resolve could have implications for the use of similar technology in other neighbouring areas of healthcare.

Overall, this research has demonstrated that improving the visualisation of the measurement guidance and using a complementary algorithm to help prescribe assistive equipment sizes more accurately can be effective for ensuring successful fit of equipment. More broadly, it can be extrapolated to address other related areas in healthcare. A detailed discussion of the contributions presented above is provided in section 9.4.

1.6 Thesis roadmap

This thesis is divided into nine chapters. Figure 1-2 presents the roadmap of the thesis, in addition to the contents of each chapter that is subsequently provided.

Chapter 2 presents a comprehensive literature survey of the state of the art of the fall prevention technology landscape in order to understand this and develop a conceptual framework, using thematic analysis to examine the range of fall prevention systems proposed in the literature (O1). Each theme in the framework and findings from the survey are explained in detail. Subsequently, the various gaps in the literature are identified. The challenge of a lack of research effort expended on integrating environmental assessment interventions to overcome extrinsic risk factors forms the focus of this research.

Chapter 3 describes the research approach adopted, and the design, data collection, and analysis techniques employed at each stage of the research in support of addressing the overall aim and research objectives, previously outlined (O1). An overview of the design science research paradigm is provided. Subsequently, the design science approach applied to the research is discussed, with the research divided into stages and a mixed methods approach employed in the experimental studies. The role of theory in this research is also discussed. Further, the general and ethical considerations for this research are explained. Finally, this chapter provides a rationale for adopting the software development methodology for the intended purpose.

Chapter 4 presents the first user-centred design and exploratory study with OTs of a mobile 3D visualisation prototype to overcome visual quality limitations with 2D paper-based EFAP tools. Subsequently, the challenges and benefits of employing mobile 3D visualisation technology to facilitate EFAP in practice and how the prototype can be further adapted are explored (O2, O3). The chapter initially provides existing literature and a rationale for the study. A walkthrough of the prototype is given. The study procedure, data collection, and analysis methods employed for the study are presented. Then the results of the study are discussed. The key outcomes linked to the results are reviewed, resulting partly in user requirements to be implemented in a prototype to be evaluated further in a subsequent study. Finally, the conclusions of this study are drawn.

Chapter 5 provides the second study, similar to the first, but exploring the benefits and drawbacks of mobile 3D visualisation technology via a developed prototype (presented in Chapter 4, section 4.2) for EFAP with older adult service users (O2, O3). The data collection and analysis methods employed for the main study are presented. The usability evaluation and semi-structured interview results are discussed. Then the key outcomes of this study are reviewed, mapped to the results source with recommendations provided. This is followed by limitations encountered in the study. Finally, conclusions are drawn.

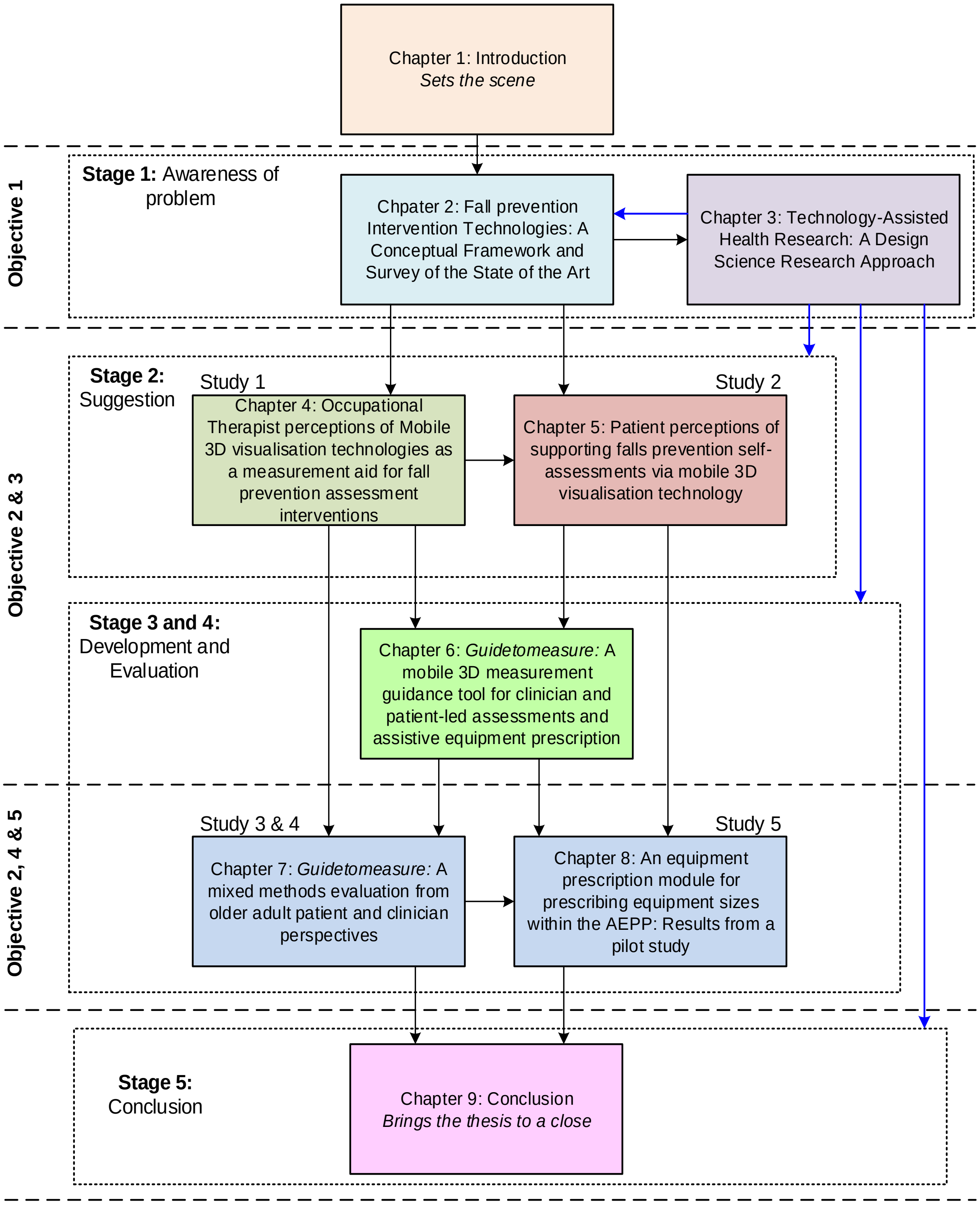


Figure 1-2: Thesis roadmap.

Chapter 6 explains the design and implementation process of the refined research artefact based upon user requirements collected from studies 1 and 2 (reported in Chapters 4 and 5). The revised system architecture is presented. The measurement guidance module and its components are described and a walkthrough of how to use it is given. The recommendation module and a walkthrough of how to use it are also described.

Chapter 7 presents the third and fourth studies, evaluating the performance of the Guidetomeasure app, compared with an existing 2D measurement guidance paper-based tool that is currently in use, within a living lab setting (O2, O4). First, an overview of the previous studies is presented and a rationale given for carrying out such evaluation with OTs and older adults. Then the protocol and methods used for data collection and analysis methods/techniques are described. The results of the evaluation in relation to the research questions outlined in this chapter are presented. The key findings associated to the research questions for each of the studies are discussed. Conclusions are then drawn and findings across studies are presented at the end of the chapter.

Chapter 8 presents the fifth study, evaluating the effectiveness of the recommendation module prescribing accurate minor equipment compared with existing approaches used by clinicians within the EFAP in practice (O2, O5). First, the chapter presents the outcome of the previous studies and how it provides the basis for this study. The design of the prescription algorithm which underlies the recommendation module is explained and presented. The study procedure, data collection, and analysis methods employed for this study are presented. Then the results of the study are reviewed. The findings related to the research questions are discussed. Conclusions to this chapter are then drawn.

Chapter 9 summaries the thesis and discusses the findings of the research carried out in relation to the objectives outlined in Chapter 1. The main contributions of this research and the value they provide are presented. Finally, the limitations encountered during the course of the research are acknowledged, and future research directions to address those limitations are examined.

Chapter 2
A Conceptual Framework and Literature Survey of the state of the art of Fall Prevention Technology Systems

2.1 Introduction

Falls prevention within the home environment has been a topic of research for over 30 years [29] and is recognised as an important health issue in the UK, Europe, North America, and Australia [16]. The frequency of falls increases with age, often as a result of physical, functional, and cognitive impairments, which are likely to emerge as a result of advanced ageing [30]. Consequently, it is estimated that 30% of older adults aged 65 and over fall at least once a year [1]. One in five falls result in bone fractures and the need for specialist medical attention [31]. Fall-related fractures may cause disabilities, and, in some extreme cases, premature death among older adults, which has a significant impact on demand for health and social care services, resulting in a cost of £1.8 billion per year to the NHS in the UK [32].

Falls prevention activities are carried out across a range of health disciplines, including occupational therapy, physiotherapy, general practice, nursing, geriatric, gerontology health and social care [33-35]. There is evidence in the falls prevention research literature which suggests that in excess of 50% of potential falls relating to older adults can be avoided as a result of ongoing falls prevention interventions [36]. There is a range of clinically established prevention interventions that target fall-related risk factors [29]. A number of recent meta analyses and systematic reviews considered a comprehensive range of falls prevention intervention studies for preventing falls in community-dwelling older people [2, 4, 37-39]. Figure 2-1 presents a diagrammatic summary of the key categories of intervention that are considered in these reviews and serves as a high-level overview of the key areas in which falls prevention research has been undertaken in recent years.

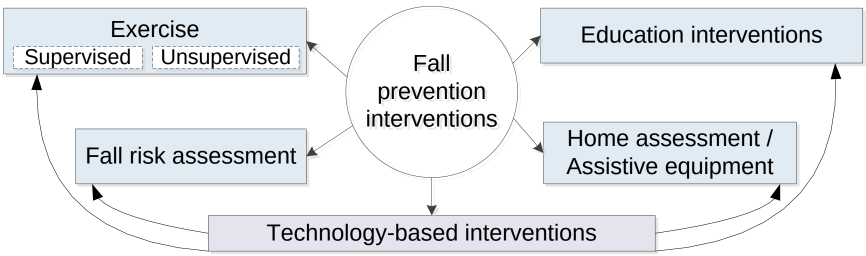


Figure 2-1: Overview of falls prevention interventions.

In recent years, one popular approach to falls prevention has been to explore ways of targeting the restoration of muscle strength and balance for prevention of fall risks [40, 41]. Exercise interventions are becoming an increasingly popular approach to falls prevention and there is an extensive body of evidence suggesting that these interventions can be effective in reducing falls and the risk of falling

[42]. There are many issues, however, with regards to adherence and acceptance of the range of existing *exercise* interventions. *Supervised* one-to-one interventions with the patient and the practitioner are resource-intensive in terms of cost and time, whilst supervised group exercise interventions require older adults to be able to travel to the location of exercise classes. Furthermore, there are many issues with regards to adherence and acceptance of existing *unsupervised* home-based exercise interventions, partly due to the lack of interactivity and personalisation that the paper-based exercise interventions typically use in these settings [43]. As such, 3D technology and games are increasingly being seen as having the potential for improving adherence, by providing patients with more tailored and interactive exercise programs to engage with [44, 45].

Fall risk assessment is an approach used to assess a number of risk factors, specifically mobility issues and physiological factors that include muscle strength, balance, stability, posture, and gait reaction time. There are many tests (e.g. Berg Balance Scale, Timed Up and Go test, and Turn 180° test) that have been developed to screen older people for fall risks in the community or in a clinical setting [46]. These tests are widely known, with research evidence that supports their effective use in predicting fall risks to uncover issues that may lead to falls. Older adults who are exposed to fall risks such as gait and balance abnormalities, admitted into hospital for medical attention as a result of falling are at higher risk of falling. Consequently, they are offered a singular or multifactorial fall risk assessment that is administered by clinicians in a clinical setting or within a specialist fall service. It is crucial that older adults who are at high risk of falling are identified using the fall risk assessment tests so that targeted falls prevention interventions can be prescribed. Conducting such assessments includes high cost equipment in specialist fall services. However, 3D technology and games have shown promise as a low cost solution to augment traditional fall risk assessments and to account for low adherence rates of self-assessment of fall risks done at home [47].

Education interventions are developed to increase knowledge about falls prevention and educate patients regarding their risk of falling and falls prevention strategies, based on the available evidence-based literature. This type of intervention, as a single component, is often part of a multifactorial falls prevention programme leading to positive outcomes, such as behavioural change, decreased fear of falling, and increased mobility. Education interventions typically take the form of fact sheets with evidence-based materials. These inform their readers about preventive measures to reduce falls or a checklist to help to identify fall hazards in the home and preventive measures that can be taken, such as change of behavioural patterns. In addition, patients are also offered information regarding where they can seek help and assistance in case of a fall to avoid 'long lie syndrome'. As such, there is little research evidence of education interventions as a single component intervention that reduces the risk and rate of falls [2].

Home assessments are carried out and *assistive equipment* is prescribed to reduce falls within the home environment. Typically, home assessments involve clinicians visiting older adults' homes to assess the suitability of the home environment in relation to the mobility of the patient. Clinicians then propose adaptations - often via the installation of assistive equipment - in order to facilitate independent living and mitigate any potential fall risks which could arise during performance of activities of daily living (ADLs). Accordingly, reviews in the falls literature have revealed that home assessments and adaptations as a single intervention do not, in general, significantly reduce the risk of falling. However, they do have some positive effect for those who are at higher risk of falling [2, 34]. Furthermore, identifying environmental risks and adapting the living environment accordingly may reduce fall risks among older adults significantly [5]. By definition, assistive equipment are systems or specialist devices prescribed by clinicians, that provide functional support to older adults to help with mobility, which would otherwise be proven difficult, maximises independent living and reduces falls. Assistive equipment includes grab rails, walking frames, hoists, raised toilet seats, stair rails, raised chairs and beds within the patient's home [48-53]. Notwithstanding the benefits of the extrinsic fall-risk assessment, there are issues which often persist with the use of equipment, as it is not always adopted successfully. Consequently, research evidence indicates that more than 50% of home modifications and equipment are rejected [54-56]. As a result, there has been an increase in functional decline, leaving older adults vulnerable to the risk of falling. Equipment abandonment is often associated with a number of factors, such as lack of knowledge about equipment use, involvement of users in the decision-making process, their attitudes towards the equipment, and a lack of fit of the equipment between service users and their environment [19, 55, 57, 58].

Technology-based interventions have been deployed in a wide range of falls prevention contexts and include diagnosing and treating fall risks [59-61], increasing adherence to interventions [62-64], detecting falls and alerting clinicians in case of falls [65-67]. Technology is also seen as having the potential to play a key role in enabling older adults to self-assess, which is in line with the personalisation agenda within the NHS in the UK, giving older adults the opportunity to perform self-assessments for extrinsic fall-risk assessment [68-72]. With an increasing pressure and demand on the NHS and with limited spending budgets, partly due to an unprecedented increase of life expectancy resulting in an ageing population [73], there is a need to find new ways to enable patients to provide effective self-care and further steps towards recognising patients as experts of their own care by giving them the chance to provide their own care [8].

Chapter 2

A Conceptual Framework and Literature Survey of the state of the art of Fall Prevention Technology Systems

Innovations in technology are seen as key to reducing costs and lessening the burden on the healthcare system, whilst also improving the quality and effectiveness of care provided [70], thus enabling patients to engage in the effectiveness of self-care to improve clinical outcomes. Encouraging the adoption of technology, particularly among the older population, however, has been a primary area of focus. There are contributing factors that include usability for the older adult cohort [74], exploring older users' perceptions and beliefs [75], intuitive interactions [76], and multisensory feedback [77], which play a central role in motivating older adults to engage in clinical interventions. These should be catered for if technological interventions are to be adopted by older adults. Therefore, deploying usable and effective ICTs in areas of assisted healthcare, specifically falls prevention within the home, has the potential to enable older adults to maintain their independence and engage in unsupervised interventions, remotely monitored by clinicians. Consequently, there is an urgent need to explore the extent to which technology has been developed for the falls prevention domain and to identify the areas in which work is still required, in order to respond positively to the broad range of challenges presented by this domain. Technology-based interventions have been identified as having valuable potential in the applied sub-domains highlighted in Figure 2-1; *exercise*, *fall risk*, *education* and *home assessment*. However, relatively little research has surveyed the extent to which technology has actually been applied to each of the sub-domains and the provision of collaborative care; specifically, the emerging patient-practitioner paradigm within the context of falls prevention. Furthermore, little research has covered the extent to which opportunities to support fall interventions have been explored respectively and the extent to which patients are being enabled to deliver effective self-care to improve clinical outcomes.

A number of systematic reviews have been carried out in the falls prevention domain, some of which include: (1) general reviews [13, 39]; (2) exercise interventions [37, 78]; (3) fall risk assessment [79, 80]; and (4) technology-based interventions [81]. Although a number of technology-based systematic reviews have been presented in the literature to-date, such reviews tend to focus mainly on specific sub-domains of a much broader context of technology-based interventions. To the best of the researcher's knowledge, there is no existing research which surveys and categorises across the full falls prevention intervention landscape, the types of existing technology-based fall prevention systems, their key collaboration functions, the technologies they exploit, and the specific types of falls prevention interventions they support. Furthermore, there is little existing research which, as a result of taking this holistic view, identifies the areas of clinical practice, which appear to be well-catered for and identifies areas which require more attention.

In light of the need to better understand the state of the art of the falls prevention technology landscape, this chapter provides a comprehensive review and a conceptual falls prevention technology framework, which was developed as a result of carrying out a survey of the range of fall technology systems presented in the literature. Section 2.2 outlines the research methods used to conduct the literature survey. Section 2.3 presents the conceptual framework and explains its component parts. Through presenting the conceptual model, sections 2.4-2.7 survey the falls technology systems - such as those in respect of pre-fall, post-fall, fall injury and cross-fall prevention systems found in the literature to date, respectively. Section 2.8 discusses challenges of existing falls technology systems and recommends future research directions based on the gaps that exist based on the survey of the state of the art in falls prevention technology research. Conclusions are drawn in Section 2.9.

2.2 Research Method

This section provides a detailed explanation of the methods employed for this literature survey. The steps taken to develop the conceptual framework and to carry out the survey of the state of the art are presented in Figure 2-2 and are described in more detail throughout this section.

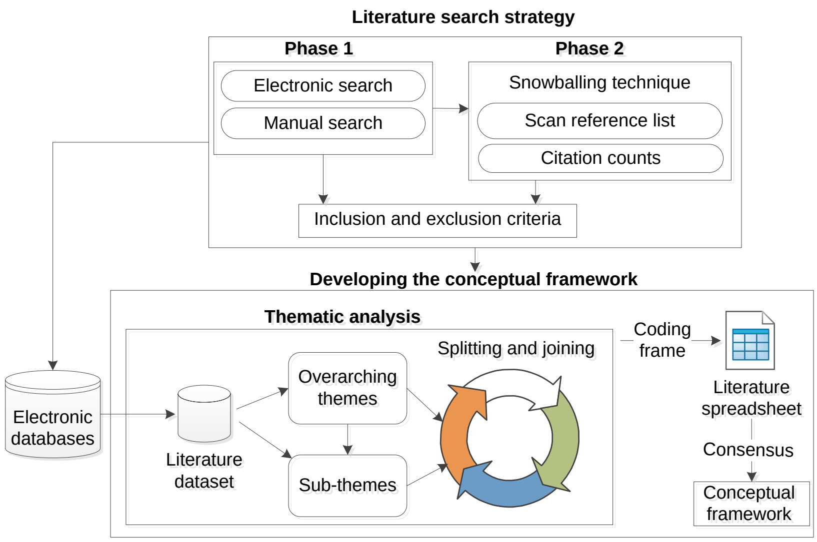


Figure 2-2: Literature survey research protocol adapted from Afzal *et al*. [82].

2.2.1 *Literature search strategy*

Initially, a number of survey papers were sourced to gain background knowledge of the research area. Part of the search strategy used for finding existing research was derived from reading previous survey papers such as [39, 78, 83-85]. This provided candidate search terms, keywords specific to the falls technology domain. The literature search strategy was a two-phase process. In *Phase 1*, *electronic search* and *manual search* was performed using electronic databases (IEEE Xplore, ACM, Pubmed, Web of Science, BioMed Central and ScienceDirect) to scan for papers that contain the search terms derived from the falls technology survey papers that had already been considered. For each paper, a manual scan of the title and abstract was conducted, and the paper was then included, if it was considered relevant (the inclusion criteria is specified in the next section). In *Phase 2*, each paper's *reference list*, found from the electronic search, was manually scanned in order to identify other potentially relevant studies. Thus, the *snowballing technique* [86, 87] was used in phase two to pursue additional papers from *citation counts* and the list of references in each paper; thus, essentially performing forward and backward searches. All searches conducted are based on a full screening of the studies, which were published between January 2010 and December 2014. The following search strings were used in the electronic databases:

- *Falls prevention technology* AND *older adults* OR *elderly*
- *Falls systems* AND *patients* OR *older adults* OR *elderly*
- *Falls management* AND *patients* OR *older adults*
- *Falls prevention assistive technology* AND *patients* OR *older adults*
- *Falls prevention approaches* AND *patients* OR *older adults*

Search terms that were used in this review were purposely kept general to avoid potential bias in identifying a candidate dataset of studies which represents the state of the art. To enhance the search, Boolean operators were used so that synonyms of the search terms were included when carrying out automated searches. Preliminary searches were conducted to identify search terms from existing reviews and to combine those search terms that derived from the reviews. Figure 2-3 presents the list of electronic databases used, the number of studies retrieved from the searches carried out using *search terms* with for each respective electronic database, the duplicate papers removed, and the total number of papers that were deemed relevant.

The *inclusion and exclusion criteria* were used to identify appropriate studies, which proposed technology-based systems/applications that aimed at: aiding in fall risk assessment and/or prevention activities, responding to falls, or reducing the risk of falling with or without the support of clinicians. Incomplete studies and studies written in a language other than English were excluded. To ensure that the literature dataset reflected recent developments in the field, whilst remaining manageable, all studies that appeared in the period 2010 to 2014 were included, whilst any studies that were outside this time period were excluded from the sample. Studies that did not involve the use of technology for falls prevention activity and not published research were also excluded from the corpus. Each study reference list was scanned for additional studies that met the inclusion criteria in order to gain more coverage of studies.

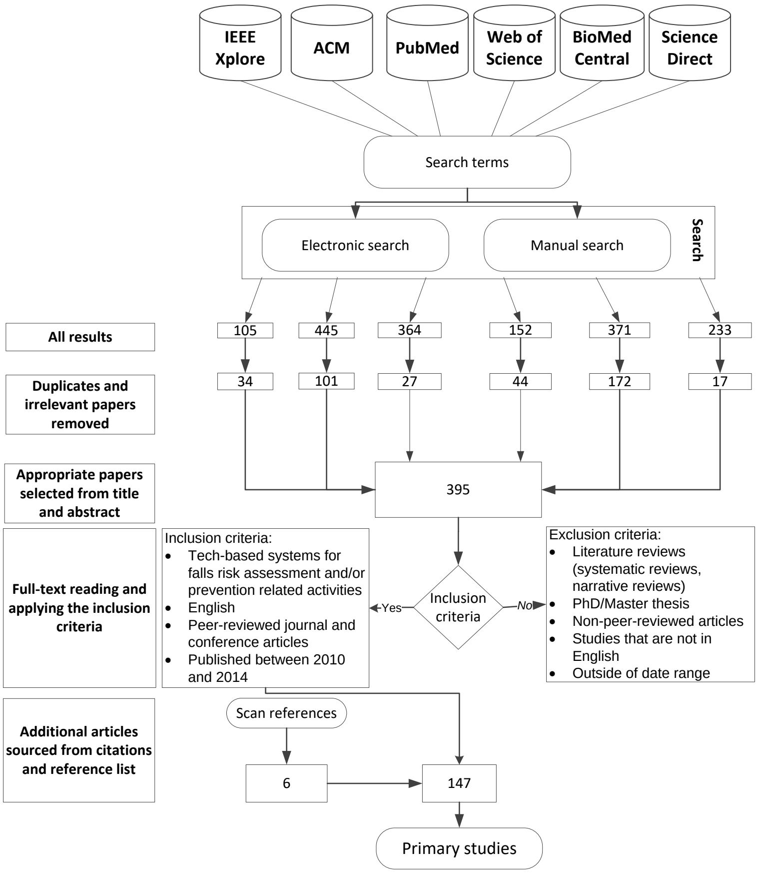


Figure 2-3: Literature search strategy, including the search strategy used to search through the falls prevention technology literature, inclusion criteria set to include relevant studies, and results obtained from the search.

2.2.2 *Developing the conceptual framework*

The conceptual framework was derived from surveying and analysing the *literature dataset* identified from deploying the literature search strategy presented in Figure 2-2. A *thematic analysis* of the literature dataset was then performed in order to review and categorise the studies that were included in the literature sample. Thematic analysis is a qualitative analysis method for searching, analysing, and representing the overarching themes and sub-themes that emerge from textual datasets [88]. Consequently, the themes and sub-themes and the observed interrelated structure, which emerged as a consequence of carrying out a thematic analysis on the literature dataset were articulated via the incremental development of a conceptual framework that represents the state of the art of the falls prevention technology landscape. The following steps were taken to analyse the literature dataset and develop the conceptual framework. Initially, all falls prevention technology studies were added into a spreadsheet (used as a data management tool for primary studies that met the inclusion criteria), making up the dataset. After studies were added, the individual studies listed in the dataset were initially examined and *overarching themes* that emerged from the dataset were recorded in the *literature spreadsheet*, which served as a coding frame for carrying out the thematic analysis. Each theme was allocated to the appropriate code name and extracts of text from the studies that fitted each concept were identified. The dataset was examined iteratively, to further develop themes and sub-themes. This was achieved via a process of *splitting and joining* together of themes and associated text that was related to themes and sub-themes. At this point, a list of themes and sub-themes was used to classify each study in the dataset within the coding frame. Several iterations of this reflective process were carried out until the themes and sub-themes reflected the representative literature dataset. Any inconsistencies were rectified, arriving at a *consensus* pool of themes and sub-themes that formed the conceptual framework in Figure 2-4. The resulting conceptual framework represents the falls prevention technology landscape, according to the literature dataset which was analysed. A detailed description of the conceptual framework and its component parts (themes and sub-themes) is now provided in the next section.

2.3 A conceptual framework of falls prevention technology

The conceptual framework of the state of the art for falls prevention technology is presented in Figure 2-4. The model is divided between *falls prevention technology systems in practice* (illustrated in the top part of the figure), which looks at the various falls prevention interventions in practice. The second part of the model considers *technology deployment*, which presents the range of falls technology systems proposed in the literature, the information sources they exploit, the types of user interface which they present, and their respective collaborative functions.

2.3.1 *Falls prevention technology systems in practice*

There are a wide range of falls prevention interventions and associated systems which aim to overcome falls and the risk of falling.

2.3.1.1 Pre-falls prevention intervention systems (Pre-FPIs)

Pre-FPIs are technology applications that focus on supporting patients who have not yet experienced a fall, but may be considered to be at risk of falling (see Figure 2-4). They take a pro-active approach via the development of applications, which support the delivery of targeted physical activities, exercises and *education* programmes that increase awareness of fall risks and help develop strategies to identify and overcome environmental fall hazards and the complications that may arise after having a fall.

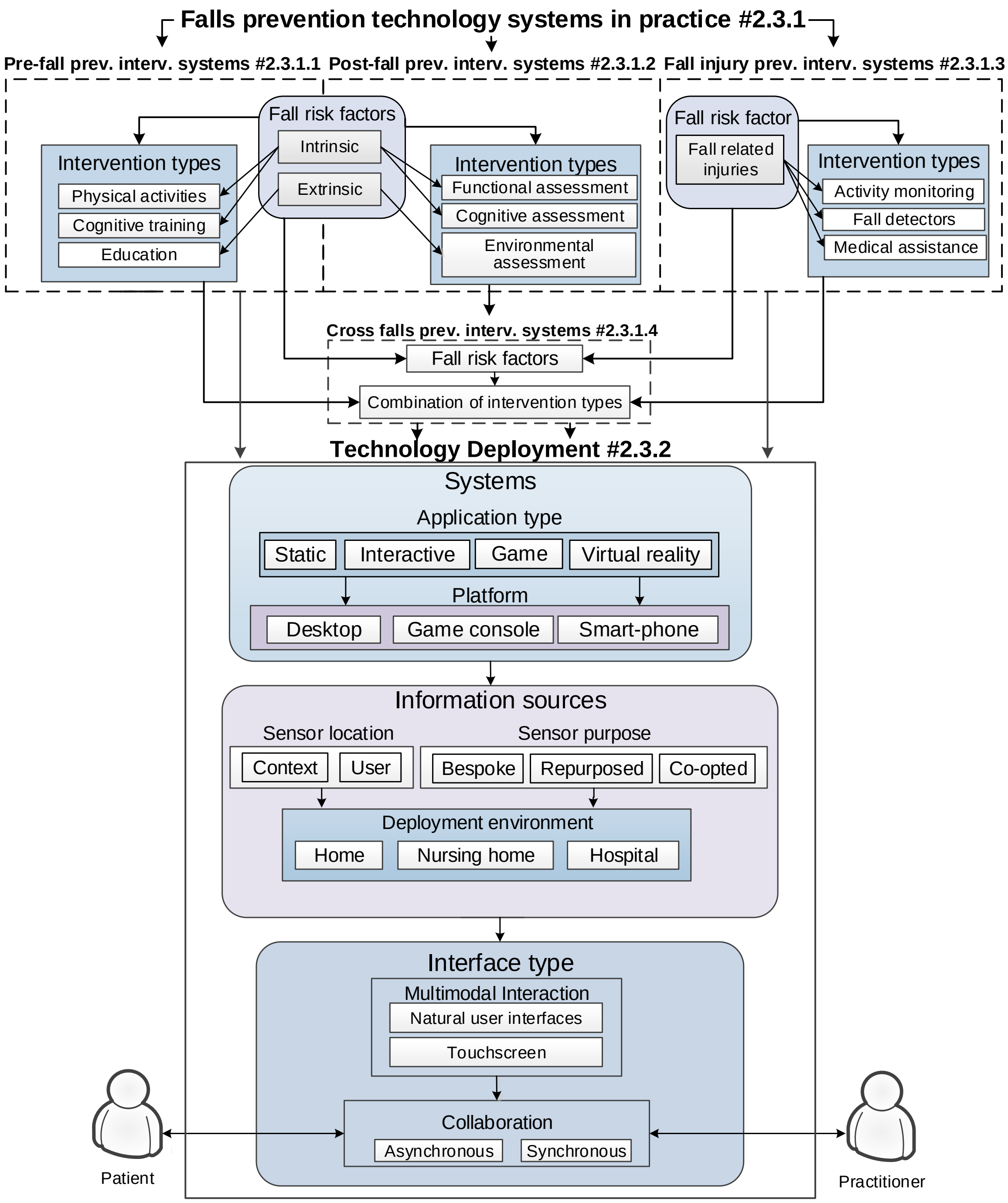


Figure 2-4: Conceptual model of falls prevention technology.

Cognitive training programmes are also deployed to encourage older adults to engage in activities that stimulate their cognition, hence slowing down the onset of age-related cognitive decline. Cognitive decline occurs as a natural part of the ageing process and can impact on functional ability and, therefore, lead to increased risk of falls [89-91]. *Fall risk factors* that Pre-FPIs aim to overcome, include *intrinsic risk factors* that relate to natural ageing changes that affect older adults' physical ability, vision, balance, muscle strength and changes to their cognition. Lack of mobility could also result in loss of muscle strength and balance impairments, leading to functional decline and resulting in a fall [3]. *Extrinsic risk factors* include factors that are external to older adults' physical health, functional ability and cognition. These include, for example, environmental hazards that are apparent within older adults' home environment [92] such as poor lighting, wet floor surfaces, loose rugs, slippery handrails, and seating, and toileting and bathing furniture, which is not optimally set up or fitted with suitable assistive equipment for an individual's mobility needs or to carry out ADLs safely.

2.3.1.2 Post-fall prevention intervention systems (Post-FPIs)

Post-FPIs are applications of technology which focus on individuals who have already experienced a fall and aim to help assess and deliver interventions to reduce the future risk of repeated falling episodes (see Figure 2-4). The strategies employed by Pre-FPI and Post-FPI often share similarities, i.e. applications that support the delivery of exercise and education programmes with a view to overcoming shared *intrinsic* and *extrinsic* fall risk factors. However, the user cohort and motivation for delivery of these interventions may be somewhat different in that Pre-FPI takes a pro-active approach and Post-FPI supports the delivery of more reactive interventions. Thus, many Post-FPIs initially involve fulfilling a diagnostic assessment function, whereby the cause of the fall, which triggered the post-fall intervention, is identified along with other intrinsic and extrinsic fall risks. There are a range of *intervention types* that are used to carry out *functional assessment* and *cognitive assessment* of post-fall patients to assess intrinsic risk factors. Functional assessment involves screening the patients' physical movement for risk factors. As such, this includes older adults performing intentional physical activities in order for a range of assessment tests to be performed to gather fall risk behaviour data, helping to determine the type of risk and appropriate preventive measure to take. *Cognitive assessment* includes tests performed to assess cognitive abilities and reduce the progression of cognitive impairments, which typically lead to falls. Delivering this particular intervention provides opportunities for clinicians to determine which preventive interventions are most appropriate to be carried out thereafter, and thus address the intrinsic risk factors identified as a result of the assessment. *Environmental assessment* involves systems developed to assess extrinsic risks that impact on older adults' ability to function independently within their living environment. This type of assessment aims to remove environmental hazards that obscure older adults' ability to perform ADLs and recommend equipment to aid mobility and reduce fall risks in the home.

2.3.1.3 Fall injury prevention intervention systems (FIPIs)

FIPIs focus attention on patients who are likely and expected to experience falls in the future (see Figure 2-4). Primarily, the aim of many such systems is to detect falls when they occur and to prevent/minimise the injuries that may occur after the event of falling. FIPIs, therefore, often aim to detect falls in order to prevent *fall related injuries* rather than address the risks that lead to falls. There are three main *intervention types* used to tackle these risks. *Activity monitoring* monitors patient movements obtrusively or unobtrusively whilst they perform ADLs and attempts to identify abnormalities, otherwise not apparent. *Fall detectors*, attempt to distinguish fall events from everyday activity signatures, so as to detect fall events when they occur. *Medical assistance* involves the provision of support provided by clinicians after a fall.

2.3.1.4 Cross fall prevention intervention systems (CFPIs)

CFPIs are technology applications which attempt to support and deliver a combination of pre-fall, post-fall and fall injury prevention interventions (see Figure 2-4). CFPIs propose technology applications which attempt to deliver system functionality across two or more groups of intervention types i.e. Pre-FPI, Post-FPI and FIPI. An example of a CFPIs that includes Post-FPIs and FIPIs is that of Shi and Wang [93] who develop a smart-phone application which assesses fall risks using traditional clinical tests and detects falls after they have occurred in order to prevent fall-related injuries. Another example which combines intervention types of Pre-FPIs and Post-FPIs is that of Silva et al. [59] who assess older adults for intrinsic risks and provide an exercise regime of dancing as a type of physical intervention to enhance the uptake and adherence to exercising more often in the older adult population, particularly those who are prone to falls, in an attempt to and reduce those intrinsic risks such as functional decline and a decline in muscle strength.

2.3.2 Technology deployment

The *systems* presented in the falls prevention domain host a range of application types and are deployed on a range of hardware platforms (see Figure 2-4). *Application type* refers to the range of applications which are presented to support fall interventions. *Interactive* applications allow the user to interact with the application in some manner, whereas *static* offers no form of interaction between the user and the system. For example, most fall prevention injury applications are static as their main purpose is to collect data and alert when a fall has occurred. *Games* are *interactive* applications that make up another group of falls prevention systems which are typically played by patients with the goal of educating and increasing awareness of fall risks, or to engage the user in exercise and physical activity which is designed to improve mobility and hence reduce the risk of falling. *Virtual reality* (VR) applications present simulated 3D *interactive* environments that allow the user to navigate through these environments and receive feedback in real-time based on multimodal user input. Physical activity interventions are also often augmented by VR applications to engage users in physical activity and fall related physical exercise. With regards to the *platforms* that falls prevention technology systems are deployed upon; *game consoles* are self-contained platforms in which specific game applications are utilised by falls prevention systems so as to deliver falls prevention related games. For intervention types such as physical activities, the game consoles and sensor devices such as Nintendo Wii and Microsoft Kinect are often used [94-97]. *Desktop computers* are another common platform that systems are often deployed on. In recent years, *smart-phones* have shown promise as an ideal candidate for the deployment of falls prevention applications partly due to advanced processing capability, integrated sensors and communication facilities that such devices now host. A *tablet* is a mobile touchscreen platform, which includes inertia measurement units, sensors (accelerometer, gyroscope, GPS), camera and touchscreen display (requiring touch gestures to interact), replacing the traditional devices such as a keyboard and mouse.

Information sources relate to the range of inputs that systems use to sense the users and the living environments they monitor in order to provide falls prevention system functions. *Sensor location* specifies where the sensors are located, either often as wearable sensors on the *user* or within the *context* of the environment in which the falls prevention system is being used. With regards to context, this may be for example in the form of sensors (camera-based and floor sensors) installed in the living environment which feed information back to the system about the user's interactions with that environment. *Sensor purpose* considers the sensors used by falls prevention systems as belonging to one of three discrete groups: *bespoke*, *repurposed* and *co-opted*. *Bespoke sensors* are developed specifically for falls prevention systems, which often gather physiological data from users. For example, Uzor et al. [63] propose a small sensor which included a big switch to turn the power on and off, light emitting diode (LED) light to show power on and a velcro strap case to enable users to attach the sensor to their body to interact with the falls prevention exercise games. *Repurposed* sensors are sensors, which were originally developed for a different function, but have since been adapted for use within the falls prevention context. For example, Kayama et al. [96] utilise the Microsoft Kinect which was originally developed for gaming, however, due to the natural gesture-based interaction paradigm this technology supports, the Kinect is repurposed to provide the platform for an application that promotes the uptake of a gesture-sensitive falls prevention exercise game. *Co-opted sensors* are typically built into popular devices. For example, the accelerometer and gyroscope that is often built into self-contained smart-phones. These may be used to obtain movement data in order to perform falls prevention interventions, as with the study of Ferreira et al. [98], which exploit the smart-phone platform with the built-in sensors available (e.g. the gyroscope, accelerometer and magnetic sensors) to detect movement by attaching the smart-phone to the user's body. *Deployment environment* reflects the range of living environments in which fall prevention technologies are typically designed to be deployed as specified in the surveyed literature sample. There are three key deployment environments which fall prevention systems are designed to be deployed within: the patient's own *home* living environment; the *hospital* environment, typically for hospitalised patients; and within the *nursing home* environment which may also take the form of an assisted living/ sheltered housing environment, whereby residential care is provided to older adults considered to be at risk of falling.

Interface type refers to the form of user interface that each respective falls prevention system provides to its users. *Multimodal interaction* considers the mechanisms that enable users to interact with fall prevention systems, whether the user is the patient or the practitioner. A common interface type used in fall prevention systems is *natural user interfaces*, which provide patients with a naturalistic way of interacting with fall prevention systems. This typically requires users' natural movements to be monitored and to serve as inputs, gathered via wearable or environmental sensors that are used to control fall prevention systems. This serves as an intuitive way of interacting with the system, particularly when considering that fall prevention systems typically strive to allow users to engage in an unrestricted manner and monitor the user's natural movements within their respective living environments. *Non-interactive interface* is an invisible interface, which relies on intermediary sensor devices to source data from older users and to save that data to a centralised system, with no feedback provided or interaction with the end-users. The other common interface used by fall prevention systems is a *touchscreen interface*, which enables users to interact with fall prevention systems deployed on smart-phones by providing touch gestures to touch an object on the screen. This interface is an evolution of the peripheral devices such as a keyboard and mouse that were used to interact with objects on the screen. Although touchscreens are inherently used for fall prevention systems as they are deployed on smart-phones, they are not part of sourcing of physiological data from users, but rather a means to operate low level tasks.

Users of the fall prevention systems consist of *patients* and *practitioners* interacting with the systems. Patients who use fall prevention systems tend to be older adults, i.e. people over the age of 65 years who experience advanced age changes, age related health decline, and age-related declines in physical and functional abilities. *Practitioners* are professionals (e.g. occupational therapists, physiotherapists, nurses, carers, social workers, general practitioners, accident and emergency staff) who deliver care to older adults in the hospital or community. *Collaboration* represents the means by which practitioners' work in partnership with patients to deliver an intervention. *Asynchronous* collaboration relates to activities that are performed in real-time, however, the response to these activities do not occur in the time in which they occurred. For example, in case where an older adults' movement data is gathered through the use of fall injury prevention interventions and if a fall event is detected an alert is sent to health care clinicians informing them of a fall. In this particular scenario, there is a time lag between the time of the fall event and the health response to a fall. On the other hand, s*ynchronous* refers to when users' movement data is gathered in real-time and the response of the movement data is also given in real-time in the form of visual feedback or biofeedback depending on the fall prevention systems that the patient is engaging with. For example, Reed-Jones et al. [99] utilise the Wii to improve balance and mobility in older people. The Wii Fit game was used in conjunction with the Wii balance board, which served as an input device to source movement data from older users to provide real-time visual feedback during game play in order to engage users and to better achieve precise body control as part of the exercise training.

In the following sections, the conceptual framework of falls prevention technology presented in this section is used to survey the systems that have been proposed in the literature. Section 2.4 reviews pre-falls prevention intervention systems; Section 2.5 reviews post-falls prevention intervention systems; Section 2.6 reviews falls injury prevention intervention systems; and Section 2.7 reviews cross-prevention intervention systems.

2.4 Pre-fall prevention intervention systems

Pre-fall prevention intervention systems (pre-FPIs) focus on supporting the prevention of falls by targeting risk factors, which if present, are known to be the cause of falls. Table 2-1 provides a summary of Pre-FPIs considered in this literature survey and which make up the sole focus of this section.

2.4.1 *Fall risk factors*

Pre-FPIs target *fall risk factors* that may be considered as a function of two distinct categories: *intrinsic* risk factors [42, 43, 62-64, 95-128]; and *extrinsic* risk factors [94, 129]. With regard to intrinsic risk factors, *functional ability deficits* are the sole focus of a number of studies [94, 98, 104, 114, 118-120]. In these examples, a range of technologies is used to proactively mitigate observed deficits in functional ability. The study, for example, by Visvanatha et al. [114] monitors the physical activity of patients who are hospitalised and considered to be at a high risk of falling as a result of

Table 2-1: Pre-fall prevention interventions.

	Pre-fall prevention interventions											
	Fall risk factors		Intervention types			Systems		Information sources			Interface type	
Pre-fall prevention system	Intrinsic	Extrinsic	Physical activities	Cognitive training	Education	Application type	Platform	Sensor location	Sensor purpose	Deployment environment	Multimodal interaction	Collaboration
Bailey and Buckley [119]	Fun		X				DC	U	Bs	He	NUI	Sync
Bainbridge et al. [110]	Fun		X			G	GC	C	Rp		NUI	Sync
Bell et al [94]	Fun	Eh	X		X	G	GC	U	Bs	Ns	NUI	Sync
Bieryla et al [113]	Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
Chao et al [95]	Fun+Bal		X			VR + G	GC	C	Rp	Ns	NUI	Sync
Chou et al. [104]	Fun		X			S	Sm	U+C	Co+Bs		Nii+Ts	Async
de Bruin et al [112]	Fun+Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
De Morais and Wickstrom [120]	Fun		X			G	DC	U	Bs		NUI	Sync
Doyle et al. [103]	Fun+Bal		X			VR	DC	U	Bs	He	NUI	Sync
Duclos et al. [108]	Bal		X			VR + G	GC	C	Rp		NUI	Sync
Ferreira et al. [98]	Fun+Bal		X			G	Sm	U	Co	He	NUI+Ts	Sync
Geraedts et al [43]	Fun		X			VR	Sm	U	Bs	He	NUI+Ts	Sync
Gerling et al. [111]	Bal		X			G	GC	C	Rp	He+Ns	NUI	Sync
Griffin et al. [127]	Fun		X			G	GC	C	Rp		NUI	Sync
Hardy et al. [101]	Fun+Bal		X			G	GC	C	Rp	He	NUI	Sync
Hilbe et al. [105]	Fun+Cog					S	DC	C	Bs	Hs+Ns	Nii	Aync
Horta et al. [118]	Fun		X				Sm	U	Co		NUI+Ts	Async
Jorgensen [42]	Fun+Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
Kayama et al. [96]	Fun+Cog		X	X		G	DC	C	Bs		NUI	Sync
Lange et al. [106]	Bal		X			G	DC	C	Bs	He	NUI	Sync
Majumder et al. [121]	Fun		X			S	Sm	U	Co		Nii+Ts	Async
Ferrari et al. [116]	Fun		X			S	DC	U	Bs	Hs	Nii+Ts	Async
Mirelman et al. [128]	Fun+Cog		X	X		VR	DC	C	Bs		NUI	Sync
Mirelman et al. [125]	Fun+Cog		X	X		VR	DC	C	Bs		NUI	Sync
Otis and Menelas [129]		Eh	X			S	Sm	U	Co		Nii	Async
Pisan et al. [97]	Fun+Cog		X	X		G	DC	C	Bs		NUI	Sync
Rajaratnam [107]	Fun+Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
Reed-Jones et al [99]	Fun+Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
Schoene et al. [117]	Fun+Cog		X	X		G	GC	C	Bs	He	NUI	Sync
Silveira et al. [124]	Fun+Bal		X			G	T		Co	He	Ts	Sync
Singh [109]	Fun+Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
Smith [122]	Fun+Bal		X			VR + G	GC	C	Rp	He	NUI	Sync
Sparrow et al [115]	Fun+Bal		X			S	DC			He	Nii	sync
Taylor et al [100]	Bal		X			VR + G	GC	C	Rp	He	NUI	sync
Taylor et al. [62]	Fun		X			G	GC	C	Bs		NUI	Sync
Uzor et al. [63]	Fun+Bal		X			VR+ G	DC	U	Bs	He	NUI	Sync
van Diest et al [123]	Fun+Bal		X			G	DC	C	Rp	He	NUI	Sync
Visvanatha et al. [114]	Fun		X			S	DC	U	Bs	Hs	Nii	Sync
Williams et al. [64]	Fun+Bal		X			G	DC	C	Bs		NUI	Sync
Young [102]	Fun+Bal		X			VR + G	GC	C	Rp		NUI	Sync

functional decline. This is achieved via the use of wearable sensors and a sensor network that detects signs of potential risks as a result of physically impaired patients moving around the hospital room without aid. De Morais and Wickstrom [120] develop a serious game based on tai chi, to help improve the stability of those who exhibit balance impairments and impaired mobility. Initially, older adults are given a demonstration of pre-recorded tai chi activities at the start of the game and are then required to mimic those movements during gameplay.

Functional ability deficits and *balance impairments* are the sole focus of many studies [42, 43, 62-64, 95, 98-103, 106-113, 115, 116, 118, 121-124, 127], which provide technology-based interventions to enable patients to retain their balance and improve functional abilities in order that physical activities can be performed safely within their normal living environments. For example, Uzor et al. [63] and Williams et al. [64] use 3D visualisation technologies and games to increase adherence rates and engagement with home-based exercises with the aim of improving muscle strength and balance. Another example of this is provided by Hardy et al. [101], who propose an exergame (i.e. exercise game) to reduce balance and gait impairments, thus encouraging older adults to exercise by providing a game that requires movements similar to that of activities found in evidence-based exercise programmes. Although many systems augment evidence-based exercises, some systems encourage users to engage in less structured exercise activities such as dancing. Lange et al. [106], for example, use an off-the-shelf game to help reduce impairments that impact on older adults' balance by encouraging patients to engage in dancing activities.

The systems presented in [96, 97, 105, 117, 125, 128] focus on alleviating *functional ability deficits* and *cognitive impairments* (Fun+Cog), which are typically targeted via the use of game applications. As such, cognitive impairments are considered to impact on the patients' functional ability. Some systems attempt to measure the extent to which cognition impacts upon functional ability. For example, Pisan et al. [97] integrate cognitively demanding tasks within a virtual environment, such as solving maths problems in a "simplified stroop test" whilst performing stepping exercises within an immersive virtual environment. The aim is to measure the patient reaction time whilst stepping, in order to uncover the severity of balance impairments whilst multitasking. Hilbe et al. [105] focus on patients in hospitals and nursing homes who are cognitively impaired. Patients are monitored to establish whether they leave their beds and, if so, the clinicians are informed so as to avoid falls in patients who are considered to be at high risk. Kayama et al. [96] and Mirelman et al. [125, 128] address the reduction of the dual-task ability, cognition, and balance impairments by executive function and delivering dual-task training as it is believed that such activity improves cognitive function. Dual tasks include users engaging in problem solving tasks and performing tai chi exercises simultaneously within an immersive virtual reality environment. Finally, Schoene et al. [117] propose a game deployed on a game console that includes stepping and balance control tasks to improve reaction time in order to improve physical and cognitive abilities of community-dwelling older adults.

The Pre-FPIs presented in [94, 129] both focus on reducing *extrinsic risk* factors, in addition to *intrinsic risk* factors. For example, Bell et al. [94] use a desktop-computer-based game and user-worn sensors to reduce impaired mobility via engaging users in exercise tasks and a gaming narrative which educates the player on environmental fall risk factors such as clutter, placement of furniture, and the dangers of spills on different types of flooring. Otis and Menelas [129] present a smart-phone application which is the only system that focuses solely on reducing extrinsic risk factors. It considers the environmental conditions in which older adults function and notifies them of potential risks. The environment is scanned for slippery surfaces and steep slope by means of a smart shoe with built-in sensors.

2.4.2 *Intervention types*

Intervention types used for preventing fall risks in [42, 43, 63, 64, 94-125, 127-129] are typically administered either by practitioners or self-administered by patients. *Physical activities* are intervention types targeted by [42, 43, 62-64, 95, 98-116, 118-124, 127, 129], to mitigate these intrinsic risk factors. Studies [42, 43, 62-64, 94-104, 106-125, 127, 128] all explore the value of VR and gaming technologies as a more interactive and engaging platform for patients to engage in exercise activity compared with more traditional approaches. For example, Chao et al [95] investigate the barriers that lead to a lack of adherence to falls rehabilitation exercises and issues concerning older adults' behaviour towards exercising. Their resulting system included the application of the self-efficacy theory to enhance exercise behaviour to engage older adults in physical activities to increase adherence rates of exercise programmes. The system made use of the Wii which provided both visual and audio feedback based on users performance during the game to encourage users to exercise whilst still using the original idea and purpose of the game to entertain users. Silveira et al. [124] explore the barriers to physical activities such as varying adherence rates to exercise programmes, behaviour towards physical activities and lack of social company whilst exercising. The proposed system is developed to specifically increase exercise adherence rates and behaviour by involving users in social groups to stimulate participation with training regimes and integrating the system into their daily routine. It also provides feedback on in-game performance and remote contact to supervise older adults during their exercise.

The systems presented in [96, 97, 117, 125, 128] use a combination of both *cognitive training* and *physical activities* intervention types to reduce fall risks. For example, Pisan et al. [97] present a balance training game that uses Microsoft Kinect to enable older adults to interact with the proposed game. The game involves a series of stepping exercises where squares appear randomly on the screen and the user is required to step on the squares as quickly as possible while solving basic arithmetical problems. The results from this study revealed that performance during the stepping exercises decreases when participants engage with physical and cognitive tasks simultaneously, indicating that users could potentially be at high risk of falling when multitasking. Schoene et al. [117] use exergames to address the issue of lack of adherence to exercise programmes in light of improving older adults' balance, stepping ability, cognition and other factors associated with falling. This exergame consists of a dancing gameplay, which provide instructions to perform dance moves using a step pad, with the aim of train balance, reaction and attention. *Education* and *physical activities* are intervention types in [94] which are used to reduce both intrinsic and extrinsic risk factors of falling. Bell et al. [94] , for example, investigate the benefits of utilising the Nintendo Wii game console for preventing falls in assisted-living environments. Participants in this study engaged in exercise training with the use of the Wii combined with falls prevention education sessions. The fall prevention education sessions focus particularly on reducing clutter, arrangement of furniture in the living area, positioning of the rug, flooring and spills within the home environment, lighting, and staircase and bathroom safety, presented in the format of checklists.

2.4.3 *Systems*

Pre-FPIs take the form of a range of *application types* and are deployed on a range of *platforms*. The application types presented in [104, 105, 115, 116, 121, 129] are all *static*; they are essentially data collection tools which issue an alert to notify users of potential fall risks as a consequence of abnormal walking/behavioural patterns, which are collected from sensors. For example, Majumder et al. [121] propose a system which includes a feature extraction technique to conduct an analysis of walking patterns collected in real-time to determine whether there is a potential risk of the user falling. This system does not involve any notable form of interaction, as it simply analyses and sends alerts based on the data that is collected from patients. Otis and Menelas [129] develop a prototype of an instrumented shoe with embedded sensors actuators which are positioned in certain parts of the shoe to collect data, categorise the fall risk status of the environment, and then broadcast this in real-time to a smart-phone application. Horta et al. [118] propose a smart-phone-based system using built-in sensors to collect physiological data from older adults to inform them of any abnormal behaviour in their walking pattern. Chou et al. [104] detect the position of patients from that of lying-to-sit and alert the user with a warning that there is a high risk of falling while getting out of bed. Once the transitions of the patients have been detected, a notification is sent to clinicians in order to provide care and prevent bedside falls.

All of the *game* applications presented in [62, 64, 94, 96-98, 101, 106, 110, 111, 117, 119, 120, 124, 127] make use of the Wii games console to detect user movements in real-time and enable users to interact with games and control in-game avatars. These studies explore the effects of such an interaction paradigm and evaluate its suitability to the fall and the prevention intervention domain. With regards to suitability, the Wii game console is a relatively low-cost solution and has the capability to simulate an array of physical activities; hence it has become a popular repurposed platform used in attempting to overcome the issue of uptake of and adherence to falls-related exercise interventions. Bainbridge et al. [110] examine the efficacy of a Wii Fit game for reducing balance impairments among community-dwelling older adults. Although the results in this study suggest that the Wii Fit game program can be an effective intervention for clinicians to prescribe to patients, it also reports that further research is needed to optimise its effectiveness and to better target the types of movement necessary to reduce fall risks. The most common sensor devices used with the Nintendo Wii are colloquially referred to as “Wii-motes”, which are handheld sensor devices with built-in infrared and accelerometer sensors and are similar in size to a TV remote control. The Wii balance board, with pressure sensors, is often used to monitor and assess patients balance. Williams et al. [64], Bell et al. [94] and Schoene et al. [117] use the Wii balance board with the Wii Fit game to assess its feasibility for improving the balance of older adults who had fallen previously, based on clinically established balance assessment tools such as the Berg Balance Score (BBS), Tinetti Test, Falls Efficacy Scale - International (FES-I), and Timed Up and Go Test (TUG). Pre-FPI systems presented in [43, 103, 125, 128] are VR applications. The use of the Wii balance board device appears to reduce the fall-related risks based on the outcome measures of balance and functional ability, as reported in the studies. However other systems, specifically [42, 63, 95, 99, 100, 102, 107-109, 112, 113, 122], are all interactive *virtual reality* and *game* applications which typically provide the user with a means of interacting with the application by the system responding to the user’s physical state, where aspects of the system are manipulated by their movement.

A number of Pre-FPIs [43, 98, 104, 118, 121, 124, 129] are deployed on *smart-phone platforms*. As a result of advancements in smart-phones, they are an ideal technology for tackling an issue like fall prevention, as data can be obtained via built-in sensors. An example of the use of smart-phones is that of Ferreira et al. [98] who propose a smart-phone-based falls prevention system operating based on user movement which was then translated to movements performed for exercises in a serious game application. The main purpose of the study is to increase adherence of older adults exercising within their home. Majumder et al. [121] propose a fall prevention system for identifying abnormal gait patterns in real-time to predict an imminent fall and prevent it from occurring by notifying the user on the likelihood of a fall occurring. This system was deployed on a smart-phone and used the embedded sensors. Horta et al. [118] and Majumder et al. [121] propose a smart-phone-based solution to obtain movement data from older adults in real-time to inform users of abnormal walking pattern behaviour identified by the system, thus helping to avoid the occurrence of falls. This data is also shared with other stakeholders, such as clinicians or carers. The remaining system [124] is deployed on a tablet. Silveira et al. [124] develop a tablet-based exercise intervention system as it provides a touchscreen display rather than keyboard and mouse and is reported to be more intuitive in providing feedback based on in-application performance. The Pre-FPIs presented in [42, 62, 95, 99-103, 107-113, 117, 122, 126, 127] are repurposed *game consoles*. Bell et al [94] and Lange et al. [106] investigate the utility of the Wii game console for preventing falls, particularly to educate older adults on exercise training and the environmental hazards that often contribute to falls. There are also Pre-FPIs [63, 64, 94, 96, 97, 105, 106, 114, 115, 119, 120, 123, 125, 128] that are deployed on *desktop computers*. This is exemplified in the study conducted by Uzor et al. [63] who develop both a game and VR application for desktop computer platform using bespoke sensors to control the system.

2.4.4 *Information sources*

The Pre-FPIs presented in [42, 43, 62-64, 94-125, 127-129] all use *information sources* to enable the patient and/or practitioner to interact with the systems in some manner. There are, however, differences in the information sources and the way in which information is sourced from the user of the system. *Sensor location* comprises of two distinct categories, namely, are *context* and *user*. *Context* sensors are the main devices used in [42, 62, 64, 95-97, 99-102, 105-113, 115, 117, 122-125, 127, 128] to source information from patients unobtrusively, without the need for users to wear a device to interact with VR or game applications. Kayama et al. [96] utilise Microsoft Kinect as an input device, deployed in the environment, to enable older adults to interact with a game application. Taylor et al. [62] utilise the Nintendo balance board as an input device where the user stands on the board to interact with the game. Hardy and Steinmetz [101] and Griffin et al. [127] utilise Nintendo balance board to improve balance by controlling in-game avatar and to move virtual objects in order to achieve the game objective and to physically engage the patient as part of an intervention. Finally, Mirelman et al. [128] and Mirelman et al. [125] use pressure on the treadmill to capture physical movement of older adults performing physical activities. On the other hand, *user-worn* sensors in

[43, 63, 94, 98, 114, 116, 118-121, 129] require users to wear them in order to obtain the movement and translate that motion to control the system for clinical use. For example, Uzor et al. [63] built a bespoke sensor device that was used to enable patients to control the game and was considered less intrusive than other devices such as Microsoft Kinect and Wii Remote, and also ideal due to its size to attach it to specific parts of the body to capture the movement. Bailey and Buckley [119] utilise bespoke sensors to collect data from older adults performing ADLs as an attempt to understand the cause of falls.

Sensor purpose refers to the type of sensing devices used to capture data from users and consists of bespoke, repurposed and co-opted sensors. *Bespoke* sensors [43, 62-64, 94, 96, 97, 103, 105, 106, 116, 117, 119, 120, 125, 128] are custom-built sensors developed specifically for fall prevention and deployed within the living environment or worn by older adults. For example, Hilbe et al. [105] propose a "Bed-exit" alarm used to reduce bedside falls. The pressure sensors were designed and integrated on the side rails of the patient's bed to track their attempt to get out of bed. The side rail is in a certain position so that if pressure is detected from the pressure sensor, with the value exceeding the threshold, an alarm is sent to clinicians (e.g. nurses) in order to prevent a fall from occurring. Williams et al. [64] use the Wii balance board as an input device with the Wii Fit game and balance assessment tools to improve the balance of older adults who are vulnerable to fall risks. Commercially available *repurposed* sensors are used to interact with falls prevention exercise games. For example, Pisan et al. [97] and Kayama et al. [96] utilise Microsoft Kinect with a game developed for older adults at risk of falling. The game measures changes to patients' functional and cognitive abilities by carrying out physical and cognitive tasks simultaneously, as reduction in multi-tasking is known to be a predictive factor of a risk of falling. In particular, using Kinect is ideal as it is a cost-effective means of obtaining data from patients unobtrusively without the need to wear or to control handheld devices.

Co-opted smart-phone sensors are now enabling applications such as fall prevention, detection and monitoring patients [130, 131]. The pre-fall prevention systems presented in [43, 98, 104, 116, 118, 121, 124, 129] made use of built-in sensors on smart-phones, which lend themselves well to tracking user movement in order to achieve outcomes of fall interventions. An example of a smart-phone application is that of Horta et al. [118] who use built-in sensors on smart-phones to capture physiological data from older adults in real-time. Otis and Menelas [129] propose a smartshoe to track the movement of patients and collect information from smart-phone sensors to the developed application. Smart-phones are considered an ideal tool for falls prevention due to their self-containing nature, size, portability and that they can also be used to communicate with other sensors making the applications more wide-reaching. Finally, Chou et al. [104] develop a system to detect the position of patients from lying to sit and alert the user with a warning that there is a high risk of falling while getting out of bed. Once the transitions of the patients have been detected, a notification is sent to alert clinicians in order to provide care and prevent a bedside fall.

2.4.5 *Interface types*

Natural user interfaces [42, 62-64, 94-97, 99-103, 106-113, 117, 119, 120, 122, 123, 125, 127, 128] enable users to interface with systems when performing physical activities during game-play and collect ambulatory/behavioural data from users unobtrusively. Mirelman et al. [128] augment treadmill exercise training with VR technology to improve functional ability and cognitive function, thereby reducing falls. Users perform exercises on the treadmill; those movements are then translated into inputs in a virtual environment which present users with obstacles, as well as other challenges, that they have to overcome. Feedback (visual and auditory) is presented to users based on errors that are made and tasks successfully completed. Systems presented in [43, 98] use *touchscreens* and *natural user interfaces*, which are a specialised way of interacting with technology-based interventions to reduce fall risks. Although this type of interaction does not involve nor measure any physiological parameters, it enables touch input in order to operate some systems. It is a required action to interact with some systems. Ferreira et al. [98] propose a falls prevention game that use embedded sensors on smart-phone to enable users to interact with the serious game application via the use of the built-in touchscreen.

Non-interactive interfaces [105, 114, 115, 129] enable interventions to be administered without an interactive interface to engage users. For example, Sparrow et al [115] propose an automated home-based exercise programme that provide voice response for real-time guidance whilst older adults performed their exercises. The programme is administered over the telephone with no interactive form of feedback or interface present to guide or engage users in a way that feedback is given of their performance during exercises. The remaining systems [104, 116, 121] use both non-interactive interface and *touchscreens* for Pre-FPI systems to perform fall prevention activities, such as gathering of data via built-in sensors and to use the platforms touchscreen to initiate the activities or to visualise analysis of the data that prevent fall risks. Chou et al. [104], for example, use sensors integrated into the patient's bed to detect when an attempt is made to leave the bed without aid. This system does not require any form of interaction, as it is a monitoring tool for clinicians to prevent hospitalised patients from attempting to leave the bed. Once the alarm is triggered, the system on the smart-phone receives the alarm signal and clinicians are notified by a text message alert, which gives details of data received from the bed sensors, such as codes that indicate posture position.

In terms of *collaboration*, the systems presented in [42, 43, 62-64, 94-103, 106-115, 117, 119, 120, 122-125, 127, 128] enable *synchronous collaboration* and engagement between patients and clinicians via a range of interface types. In the study by Marisa Ferrari et al. [116], clinicians supervise participants in an exercise training with the use of the Nintendo Wii in a nursing home. Users were provided with immediate feedback of their in-game performance to improve their functional ability and balance. Although it is not made clear if patients were involved in the decisions made in this intervention, the fact that both practitioners and patients are engaging in the intervention at the same time provides an opportunity for patients to be seen as more equal partners in their own care. Conversely, the remaining studies [104, 105, 116, 118, 121, 129] are considered as *asynchronous* in that response from sourced movement data does not occur in real-time. The studies of Hilbe et al. [105], Majumder et al. [121] and Marisa Ferrari et al. [116] monitor older adults physical activities in an attempt to predict the likelihood of falling. Data such as abnormalities in walking patterns and critical patients leaving their bed are sourced from patients to prevent falls. As these systems monitor to improve health outcomes such as reduced fall risks, clinicians only intervene when the data collected suggests that the patient is at high risk of falling. No feedback is provided, as the purpose of these systems is simply to unobtrusively collect data that reflects ADLs, rather than perform activities to improve functional ability and balance to undertake ADLs.

2.4.6 *Discussion*

Pre-FPIs provide a useful way of preventing the onset of risks and treating fall risks using intervention types to reduce: functional ability deficits [62, 94, 110, 114, 116, 118-121, 127]; functional ability deficits and balance impairments [42, 63, 64, 95, 98-103, 106-109, 111-113, 115, 122-124]; and functional ability deficits and cognitive impairments [96, 97, 105, 117, 125, 128]. However, limited attention is given to reducing both functional ability deficits and extrinsic risk factors [94] or focusing solely on reducing extrinsic risk factors [129]. A considerable number of Pre-FPIs have focused their efforts on alleviating intrinsic risks, with limited effort invested into providing support for overcoming extrinsic fall risks and the process of provision of assistive equipment in order to mitigate some of these extrinsic fall risk factors. This is despite the provision of specialist assistive equipment being one of the key interventions used to mitigate fall risks associated with functional decline.

The consensus of the fall technology literature reviewed indicates the increasing popularity and reusability of VR and game applications which aim to address the limitations of clinical interventions, particularly adherence and uptake issues. Based on results of studies presented in [62, 64, 94, 96-98, 101, 106, 110, 111, 117, 119, 120, 124, 127], games are often proposed as an adjunct to traditional interventions and are not typically designed to replace existing interventions. It seems that users are motivated by the use of exercise games as they can provide feedback on performance, thus creating a more stimulating and entertaining experience. Employing such technology reduces travel costs for older adults who travel to rehabilitation centres [132] and increases patient motivation to engage with proposed falls prevention intervention programmes. From the corpus of research reviewed [42, 43, 62-64, 94-125, 127-129], it seems that there are limited research efforts that utilise VR technology and games to augment fall education interventions aimed at reducing extrinsic fall risks with the exception of [94, 129], which also lack the use of such technology.

Surprisingly, given the ever-increasing ubiquity of smart-phones with patients and clinicians, a relatively small number of Pre-FPI are deployed on smart-phones [43, 98, 104, 118, 121, 124, 129] compared to the majority, which are on desktop computers [63, 64, 94, 96, 97, 103, 105, 106, 114, 115, 119, 120, 123, 125, 128] or repurposed game consoles [42, 62, 95, 99-103, 107-113, 117, 122, 126, 127]. A possible explanation for this may be that game consoles more naturally possess the requirements and functionality that can be more readily repurposed for the function of developing rehabilitation exercise intervention applications. Nonetheless, smart-phones have shown promise in deploying Pre-FPIs, especially to help capture physiological data [42, 43, 62-64, 94-114, 116-118, 120-123, 125, 127-129], but also in a much broader sphere, hence the need to further explore their use to tackle both intrinsic and extrinsic risk factors. The advancements of smart-phones have increasingly become a portable device with unprecedented computational power similar to that of desktop computers.

One issue that stands out is the extent to which these systems allow patients and practitioners to collaborate. Whilst some of Pre-FPIs support asynchronous collaboration (i.e. not real-time collaboration) [43, 98, 99, 107, 109, 113, 115, 117, 118, 121, 129], the remaining studies [42, 62-64, 94-97, 101, 104-106, 110, 112, 114, 116, 119, 120, 124, 125, 127, 128] are synchronous, thereby giving an opportunity for patient and practitioner to collaborate as they are in the same environment, during the intervention. Given the long-term goal of health care delivery, particularly within the UK, to increase the extent to which patients are more equal partners in the delivery of care [69-71, 133], it seems many Pre-FPIs are creating opportunities to support patient engagement in care and the decision-making that is required whilst providing this care.

2.5 Post-fall prevention intervention systems

Post-fall prevention intervention systems (Post-FPIs) are typically used in the first instance to screen patients for fall risks after they have experienced a fall. Fall assessments are traditionally conducted within controlled environments, such as within a specialised falls clinic environment or alternatively within uncontrolled environments. The latter are often carried out as longitudinal assessments, where older adults are remotely monitored over a period of time in order to identify activity signatures that correspond to fall risks. Although Pre-FPIs have yielded many benefits for promoting health promotion activities to prevent the onset of fall risks, similar fall risk factors are diagnosed and treated via Post-FPIs. Table 2-2 provides a summary of Post-FPIs and their respective characteristics.

2.5.1 *Fall risk factors*

Post-FPIs and technologies that focus on preventing falls by screening and assessing for fall risks may also be considered as a function of two *fall risk factor* categories: *intrinsic* risk factors [61, 134-150]; and *extrinsic* risk factors [60]. With regards to intrinsic risk factors, *functional ability deficits* are the sole focus of assessment in [134-139, 141-146, 148-150]. Majumder et al. [145] detect abnormalities in gait patterns, which are considered to be a common cause of falling in the older adult population. Users are notified of the likelihood of falling based on data collected and classified to determine whether or not the patterns of ADLs are abnormal. Redmond et al. [135] provide an unsupervised continuous fall risk assessment for older adults who live independently with a high risk of falling and who have been selected for clinical intervention. Staranowicz et al. [143] and Weiss et al. [141] present systems which monitor older adults' gait in real-time from ADLs and collate the motion data in order to predict falls so that older adults can receive early intervention. Zijlstra et al. [137] and Greene et al. [138] present approaches to monitor and assess fall risks for older adults performing clinical tests which emulate ADLs. Riva *et al.* [142] and Soaz and Daumer [144] analyse gait patterns to determine the association between features extracted from gait patterns with a history of falls in order to target older adults who are in need of clinical interventions. Almer et al. [134] develop a framework which was evaluated with a series of assessment tests (2-Minute Walk, Sit-to-Stand 5 and Timed Up and Go) by recoding movement data and using feature extraction techniques to determine fall risks in the movement data. Cuddihy et al. [149] monitor gait in older adults and notifies caregivers of any changes as they also carry out assessments remotely and take preventive measures to alleviate fall risks. Singh et al. [148] and Barelle and Koutsouris [136] present an approach in extracting gait features from the walking patterns of older adults' to perform early diagnosis of functional decline for a more accurate estimation of fall risks. Post-FPIs presented in [61, 140, 147] address both *functional ability deficits* and *cognitive impairments* via the use of dual-tasking. Schoene et al. [147] introduce a device that serves as a proxy to measure older adults with severe cognitive and physical impairments. Reaction time of stepping ability is used to predict potential risk of falls.

Table 2-2: Post-fall prevention interventions.

	Post-fall prevention interventions											
	Fall risk factors		**Intervention types**			**Systems**		**Information sources**			**Interface type**	
Post-fall prevention system	Intrinsic	Extrinsic	Functional assessment	Cognitive assessment	Environmental assessment	Application type	Platform	Sensor location	Sensor purpose	Deployment environment	Multimodal interaction	Collaboration
Almer et al. [134]	Fun		X			S	Sm	U	Co	He+Hs	Nii+Ts	Async
Barelle and D. Koutsours [136]	Fun		X			S	DC	C	BS	He	Nii	Async
Brell et al. [146]	Fun		X			S	DC	C	BS	He	Nii	Async
Cuddihy et al. [149]	Fun		X			S	DC	C	Rp	He	Nii	Async
Du et al. [60]		EH			X	S	DC	C	BS	He	Nii	Async
Garcia et al. [61]	Fun+Cog		X	X		VR	DC	C	Rp	-	Nii	Sync
Greene et al. [138]	Fun		X			S	DC	U	BS	He+Hs	Nii	Async
Majumder et al. [145]	Fun		X			S	Sm	U	Co	He	Nii+Ts	Async
Rawashdeh et al. [140]	Fun+Cog		X	X		VR	DC	U	BS	Hs	NUI	Async
Redmond et al. [135]	Fun		X			S	DC	U	BS	He	Nii	Async
Regterschot et al. [150]	Fun		X			S	DC	U	BS	He	Nii	Async
Riva et al. [142]	Fun		X			S	DC	U	BS	.	Nii	Async
Schoene et al. [147]	Fun+Cog		X	X		G	DC	C	Rp	He+Hs	NUI	Sync
Singh et al. [148]	Fun		X			G	DC	C		He	NUI	Sync
Soaz and Daumer [144]	Fun		X			S	DC	U	BS	He+Hs	Nii	Async
Staranowicz et al. [143]	Fun		X			S	Sm	C	Co	He+Hs	Nii+Ts	Async
Weiss et al. [141]	Fun		X			S	Sm	U	Co	He	Nii+Ts	Async
Zhang et al. [139]	Fun		X			S	DC	U	BS	He	Nii	Async
Zijlstra et al. [137]	Fun		X			S	DC	U	BS	He	Nii	Async

The remaining Post-FPIs [60] focuses solely on the *extrinsic* risk factors. Du et al. [60] develop a robot to screen older adults' living environment for typical *environmental hazards* such as, to name a few, poor lighting, unstable furniture, lack of equipment in the bathroom and then provides that information to clinicians.

2.5.2 *Intervention types*

Post-FPIs *intervention types* consist of *functional assessment*, *cognitive assessment* and *environmental assessment*. In particular, functional assessment is the main intervention type presented in [134-139, 141-146, 148-150] in order to determine intrinsic risk factors such as *functional ability deficits* . Majumder et al. [145] develop a smart-phone-based fall assessment system to monitor abnormal gait patterns from older adults performing physical activities that are constituted as ADLs. The gait patterns are collected from users over a period of time from walking and carrying out ADLs. Staranowicz et al. [143] propose a system which monitors the walking patterns of older adults' during their ADLs at home and identifies functional decline via the use of an autonomous robot. The systems proposed in [61, 140, 147] use cognitive assessment and functional assessment to assess functional ability deficits, balance and cognitive impairments. Patients are encouraged to conduct physical activities and cognitively demanding tasks to determine fall risks. Garcia et al. [61], for example, present a Kinect-based system to gather timing of movement to measure the reaction time of stepping ability tasks. This is referred to in this study as choice stepping reaction time (CSRT) and it is used to predict falls. As such, this approach measures physical abilities including strength and balance, and cognitive abilities such as attention and speed of processing. The remaining system presented in [60] conducts *environmental assessment* for fall risks. Du et al. [60] develop a robotic system that screens the patient's home, operated remotely by clinicians, with the robot being navigated around the home whilst checking for fall hazards. Essentially, this system automates home assessments that are typically conducted by clinicians.

2.5.3 *Systems*

Post-FPIs presented in [60, 134-139, 141-146, 149, 150] are all *static* systems, i.e. they do not provide the user with an interactive interface. Cuddihy et al. [149] propose a static system that measures gait based on ADLs performed by older adults. The system requires no form of interaction as its main function is to unobtrusively collect data in order to analyse gait patterns. Riva et al. [142] Soaz and Daumer [144] and Greene et al. [151] use wearable sensors, with no interface, to assess users' physical activities and balance to predict the potential risk of falling. Robinovitc et al. [152] use video cameras to record footage to identify falls or the environmental and behavioural factors that lead to falls. Almer et al. [134] and Majumder et al. [145] develop static applications to collect fall-like data from users to assess the data for fall-related behaviour. The applications used smart-phone sensors to extract features that are fall-like behaviour; however, the interface on the smart-phone was not used. Conversely, g*ame* and *VR* applications presented in [61, 140, 147, 148] are purpose-built or repurposed to screen older adults for intrinsic risks through game-play or simulation. Singh *et al.* [148] provide a balance game using the Nintendo Wii balance board to measure agility and balance in older adults. This system can also be used to reduce balance impairments as it empowers older adults to train frequently by providing visual feedback based on movement performed, converting real-life movement into virtual movement as part of an in-game narrative. The majority of the systems presented in [60, 61, 135-140, 142, 144, 146-150] are deployed a on desktop computer platform, whilst the remaining systems in [134, 141, 143, 145] are deployed on a smart-phone platform.

2.5.4 *Information sources*

The Post-FPIs presented in [60, 61, 134-150] exploit a range of *information sources* to gather data from patients. In particular, *users* one of the key *sensor locations* in [134, 135, 137-142, 144, 145, 150] to gather information relating to the users' physical movement and to reduce the progression of fall risks. For example, Weiss et al. [141] use a bespoke wearable sensor to collect long-term gait patterns from older adults performing their ADL routine in order to capture properties and characteristics of fall risks in a real-life setting and complement conventional performance-based tests. Providing such a solution not only enables fall risks to be assessed remotely, but it also uncovers useful information regarding the quality and quantity of ambulation performed by older adults in the home. Conversely, *context* is exploited in [60, 61, 136, 143, 146-149] to source information unobtrusively from patients. Barelle and D. Koutsouris [136] develop an ICT-based home care system to monitor patients with gait impairments in order to diagnose early potential fall risks before a fall occurs and to respond with appropriate interventions. The system enables independent living at home by use of biomechanics data and indicators of gait impairments recorded in a schedule agreed with medical staff and patients based on health status and ADLs.

Sensor purpose consists of sensors tailored for reducing falls or built-in sensors repurposed for technology-based interventions. In particular, systems presented in [134, 141, 143, 145] use *co-opted* smart-phone sensors as wearable devices to collect data from users. For example, Staranowicz et al. [143] and Weiss et al. [141] use accelerometer and gyroscope sensors on smart-phones to assess users' gait patterns for any abnormalities to notify users of potential falls. Users are not required to wear the smart-phone on any particular part of their body, however, it has to be on their person as the built-in sensors gather acceleration and movement data while users are walking. Almer et al. [134] present a smart-phone-based falls assessment application. The application collects data from built-in sensors such as accelerometer and gyroscope; it was evaluated using clinical assessment tests: the "2-Minute Walk", "Sit-to-Stand" and "Timed Up and Go" (TUG). *Bespoke* sensors are used in [60, 135-140, 142, 144, 146, 150] to identify risk factors. For example, Greene et al. [138] propose bespoke body worn sensors to gather older adults movement data. The sensors are attached to the older adults' body whilst performing the berg balance scale (BBS) and the TUG tests. PostFPIs presented in [61, 147, 149] use *repurposed* sensors. For example, Singh et al. [148] use the Wii balance board as an input device to interact with a balance game to assess older adults balance.

Deployment environment refers to the range of environments in which Post-FPIs are deployed within, namely; the home environment, hospital setting or nursing home setting. The systems presented in [134, 138, 143, 144, 147] are deployed within the *home environment* and *hospitals*. The Post-FPIs presented in [60, 135-137, 139, 141, 145, 146, 148-150] are all deployed solely within the *home environment*. Brell et al. [146] conduct clinical tests using a robot to collect data from patients performing ADLs in their home in order to diagnose fall risks. Other systems are deployed solely within the *hospital setting* [61, 140]. Rawashdeh et al. [140], for example, propose a virtual 3D avatar system which reflects the movement of hospitalised patients that are prone to falls. There are no Post-FPIs that are deployed solely within the nursing home environment.

2.5.5 *Interface type*

Post-FPIs use *natural user interfaces* [140, 147, 148] to enable the user to interact with the system. Schoene et al. [147] propose a game which requires natural interactions such as foot movements to interact with the proposed game application. Singh et al. [148] provide an interactive interface to engage older adults to exercise independently and frequently without therapist intervention. The interface provides visual feedback during the intervention to enhance compliance to exercise more often and real-time feedback with regards to users' ability to maintain their balance.

Post-FPI systems presented in [60, 61, 135-139, 142, 144, 146, 149, 150] are *non-interactive interface* which provide a one-directional flow of data, without presenting feedback of the sourced data to patients. Regterschot et al. [150] use sensors to identify changes in mobility and fall risks to perform clinical tests, without providing an interactive medium to engage users in fall prevention interventions. Zhang et al. [139] use a pendant-worn sensor to detect chair transfers in order to unobtrusively assess fall risks in a non-interactive way. Older adults wear the pendant around their neck like a necklace for continuous monitoring. ADLs, particularly chair transfers, performed by older adults are the system's sole input to conduct fall risk assessments. A system's interface is often driven by the platform it is deployed on.

Systems presented in [134, 141, 143, 145], for example, use a combination of non-interactive interface and *touchscreen* built into smart-phones as the sensors collect data from patients, who use the touchscreen to activate in-system functions. Almer et al. [134] develop a smart-phone application with non-interactive interface to conduct assessment tests by obtaining motion data from patients using built-in sensors such as accelerometer and gyroscope, and touchscreen for users to authenticate into the system and to display the system's status and users information. The developed iOS application requires little interaction as it displays the current user and information about the device.

The main engine, running the assessment tests, is deployed in the background, indicated by a green light, whilst the tests being performed are also displayed.

The systems presented in [61, 147, 148] enable *synchronous collaboration* between patients and practitioners. Garcia et al. [61] and Singh et al. [148] carry out assessments through patients performing physical activities. Patients are presented with real-time feedback of balance scores and progress made during the assessment programmes. This real-time feedback component improves compliance for patients to regularly assess for fall risks. The remaining systems [60, 134-146, 149, 150] provide *asynchronous* collaboration. Zijlstra et al. [137] monitor patients with mobility issues and fall risks whilst they perform sit-to-stand movements during chair transfers. Data is sourced from patient to provide a longitudinal profile of changes to ambulation and mobility issues during transfers in order to determine potential fall risks. No interface is presented to users, however, sensors are located on the torso of the patients and in and around their home furniture in order to measure power exertion and movement. Collecting longitudinal datasets such as [146] enables patients' movement data to be considered over a period of time. Conducting assessments in patients' homes enables both parties to collaborate to some extent, as patients are assessed remotely by clinicians without both parties having to physically be in the same environment. Rawashdeh et al. [140] develop a system that senses patients' movement and posture data from sensors attached to different parts of the body (wrist, ankle and chest). The data is sent to a base station in which it is processed in real-time. The processed data is used to animate a 3D avatar that mirrors patients movement. Clinicians respond to abnormalities on the 3D avatar that indicate that patients are at risk of falling. However, no data is directly fed back to patients as its sole purpose is to monitor movement.

2.5.6 *Discussion*

Post-FPIs assess patients for intrinsic and extrinsic fall risks using physical, cognitive and environmental assessment interventions. After reviewing these systems, the following observations are drawn with regards to assessing fall risks. The majority of the post-fall prevention systems assesses intrinsic risk factors such as functional ability deficits [134-139, 141-146, 148-150]; functional ability deficits and cognitive impairments [61, 140, 147], with limited attention given to extrinsic risk factors [60] which can also result in serious fall injuries. Post-FPIs use a range of intervention types to assess fall risks. Functional assessments [134-139, 141-146, 148-150] were solely used to assess functional ability to determine risks of falling, whereas [61, 140, 147] use both functional assessments and cognitive assessments to assess multifactor risks.

While Post-FPI systems play a crucial role in reducing the risk of falling, particularly assessing fall risks, few systems address extrinsic factors [60]. In fact, only one system, [60] has focused on assessing the home environment for extrinsic risks. This system involves a robot to assess the patient's home. A clinician is able to operate the system remotely by navigating the robot around the home whilst going through a checklist of factors. Despite the apparent benefits, the system is not fully autonomous, which makes it prone to handling errors that can affect its reliability, in addition to still needing clinicians time to conduct the assessment tasks remotely.

The consensus of the Post-FIP systems indicates that majority of systems are static in nature and offer no means for users to interact with the systems [60, 61, 134-139, 141-146, 149, 150]. Therefore, it appears, that limited efforts are spent on systems which provide an interactive means to assess fall risks [140, 147, 148]. Another challenge yet to be explored in this domain is the patient-clinician collaboration. The majority of systems provide synchronous collaboration [60, 61, 134, 136-145, 148-150] where data is sourced from older adults and the response is provided in real-time. The rest of the studies reviewed here present systems that are asynchronous [135, 146, 147], meaning that data sourced from older adults is not clinically assessed at the time it was performed.

2.6 Fall injury prevention intervention systems

Fall injury prevention intervention systems (FIPIs) aim to detect and respond to falls after they have occurred and prevent or minimise *fall related injuries* that may occur as a consequence of falling. Unlike Pre-FPIs and Post-FPIs, they do not typically focus on overcoming the intrinsic and extrinsic risk factors that may lead to a fall occurring, but rather focus on responding to a fall after it has occurred. These systems typically aim to monitor patient activity with the goal of providing a channel of communication between older adults and clinicians. There are three main *intervention types* that these systems target.

Activity monitoring involves monitoring patient movements either obtrusively or unobtrusively while they perform ADLs to identify abnormalities in patient daily occupations. *Fall detectors* monitor patient activity in order to identify the discrete occurrence of a fall. In the event of abnormalities or the occurrence of a fall, clinicians can be alerted via an alert for *medical assistance* after a fall has occurred [83]. Many systems have been proposed over the years and categorised based on their sensors, underlying algorithms and computational techniques used to detect this phenomenon. Table 2-3 summarises fall injury prevention systems proposed in the falls technology domain.

Table 2-3: Fall injury prevention interventions.

	Fall injury prevention interventions										
	Fall risk factors	**Intervention types**			**Systems**		**Information sources**			**Interface types**	
Fall injury prevention systems	Fall related injuries	Activity monitoring	Fall detector	Medical assistance	Application type	Platform	Sensor location	Sensor purpose	Deployment environment	Multimodal interaction	Collaboration
Abbate et al. [65]	X	X	X	X	S	DC+Sm	C+U	Co+BS	He	Nii+Ts	Async
Abbate et al. [153]	X	X	X	X	S	Sm	C+U	Co	He	Nii+Ts	Async
Albert et al. [154]	X	X	X	X	S	DC+Sm	U	ES	He	Nii+Ts	Async
Aud et al. [155]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Bagnasco et al. [156]	X	X	X	X	S	DC	U	BS	He	Nii	Async
Busching et al. [157]	X	X	X	X	S	Sm	U	Co+BS	He	Nii+Ts	Async
Cabestany et al. [158]	X	X	X	X	S	DC+Sm	C+U	Co+BS	He	Nii+Ts	Async
Cao et al. [66]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Dai et al. [159]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Della Toffola et al. [160]	X	X	X	X	S	Sm	C+U	Co	He	Nii+Ts	Async
Fahmi et al. [161]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Fang et al. [162]	X	X	X	X	S	Sm	U	Co+BS	He	Nii+Ts	Async
Ferrari et al. [163]	X	X	X	X	S	DC	U	BS	He	Nii	Async
Fourlas and Maglogiannis [164]	X	X	X	X	S	DC	U	BS	He	Nii	Async
He et al. [165]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
He et al. [166]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Kepski and Kwolek [167]	X	X	X	X	S	DC+Sm	C+U	Co+BS	He	Nii	Async
Kepski and Kwolek [168]	X	X	X	X	S	DC	C	Rp	He	Nii	Async
Koshmak et al. [169]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Laguna and Finat [170]	X	X	X	X	S	DC+Sm	U	Co	He	Nii+Ts	Async
Lee and Carlisle [171]	X	X	X	X	S	DC+Sm	U	Co+BS	He	Nii+Ts	Async
Leone et al. [172]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Li et al. [173]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Martín et al. [174]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Mastorakis and Makris [175]	X	X	X	X	S	Sm	C	Co	He	Nii	Async
Mehner et al. [176]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Paoli et al. [177]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Papadopoulos and Crump [178]	X	X	X	X	S	DC	U	BS	He	Nii	Async
Planinc and Kampel [179]	X	X	X	X	S	DC	C		He	Nii	Async
Rantz et al. [180]	X	X	X	X	S	DC	C	Rp	He	Nii	Async
Ren et al. [181]	X	X	X	X	S	DC	U	BS	He	Nii	Async
Sahota et al. [182]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Shieh et al. [183]	X	X	X	X	S	DC	C		He	Nii	Async
Shim et al. [184]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Tang et al. [185]	X	X	X	X	S	Sm	U	BS	He	Nii+Ts	Async
Terroso et al. [186]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Viet et al. [187]	X	X	X	X	S	Sm	U	Co	He	Nii+Ts	Async
Werner et al. [188]	X	X	X	X	S	DC	C	BS	He	Nii	Async
Yu et al. [67]	X	X	X	X	S	Sm	C	Co	He	Nii	Async
Zhang et al. [189]	X	X	X	X	S	DC	C	BS	He	Nii	Async

2.6.1 *Fall risk factors*

All FIPIs presented in [65-67, 153-191] focus on minimising *fall related injuries* that may occur as a result of experiencing a fall. For example, Abbate et al. [65] propose a system to monitor patient movement automatically using an artificial neural network and feature extraction machine learning technique which alerts emergency services and other preloaded emergency contacts after a fall has been detected. Mastorakis and Makris [175] present a system using an algorithm which uses a large training dataset which includes falls data and a range ADLs in order to more accurately detect falls when they occur and avoid false positives. Ferrari et al. [163] monitor and track patient movement in hospital, if a fall is detected, the system automatically sends an alarm to clinicians when patients attempt to leave their beds without aid or displays an increase in activity levels. Transmitting this type of data to nurses in the hospital enables them to provide care and assistance when it is needed. Zhang et al. [189] put forward a system that unobtrusively detect falls that occur at night-time where the older adult is unconscious and hence may find it difficult to move without aid. An alarm is generated to inform clinicians of a fall. Cao et al. [66] prevent injuries which occur as a result of lying on the floor after a fall for a long period of time, this is achieved by patients wearing the smart-phone and using the built-in accelerometer sensor to detect falls when they occur. A threshold algorithm was developed which can be adapted to the patient demographic information, such as age, gender, height and weight to increase the detection accuracy of motion outputted from patients' movement.

2.6.2 *Intervention types*

The FIPIs presented in [65-67, 153-191] use a full range of *intervention types* i.e. *activity monitoring*, *fall detector* and *medical assistance* to detect and reduce fall related injuries occurring. For example, Abbate, Avvenutia, Bonatesta, Colaa, Corsinia and Vecchioa [40] and Abbate, Avvenuti and Light. [153] develop filtering techniques to distinguish falls from ADLs in order to specifically identify falls when they occur, gather data profiles about older adult's movements, and automatically send alerts to clinicians in the event of a fall. Cao et al. [66] monitor older adults' activities and acceleration of movement to determine if the older adult is currently experiencing a fall. If a fall is identified, an SMS message is sent to the older adult's carer provide immediate assistance to their client. Bagnasco et al. [156] classifies three different fall types which are front fall, backward fall and lateral fall, which occur as a result of performing ADLs. This approach increases the accuracy of identifying fall events so that they can receive adequate support from clinicians. Kepski and Kwolek [167] [168],Yu et al. [67] and Koshmak et al. [169] all provide a means of either obtrusively or unobtrusively monitoring older adults within their living environment to identify falls. Once a fall has been identified, an alarm is triggered for caregivers to provide medical support to older adults who have fallen. Laguna and Finat [170], Werner et al. [188] and Koshmak et al. [169] monitor older adults movement remotely and detect falls when they occur. Paoli et al. [177] and Leone et al. [172] provide notifications to caregivers in the case of a fall and enable them to have authorised access to monitor older adults. Mastorakis and Makris [175] monitor older adults activities to identify a fall by using an algorithm with a 3D bounding box which calculates the velocity of width, height and depth in order to establish if the activity performed by users is a fall or an ADL. An alarm is sent to clinicians in order to provide immediate assistance to fallers.

Mehner et al. [176] detect falls automatically in order to provide rapid medical support so that fall related injuries will be reduced and to physically help older adults off the ground, particularly in cases where older adults knock their head and are unconscious or not able to seek help. He et al. [165] classify data sourced from monitoring older adult activity. The motion is then split into five sub-patterns which include vertical and horizontal motion, lying, sitting, standing, and falls in order to accurately detect falls by employing a feature extraction technique. Once a fall is detected, an automatic multimedia messaging service (MMS) is sent to preloaded contacts which include the patient's GPS coordinates and auto-generated image of a Google map pinpointing the location of the fall. Cabestany et al. [158] automatically detect falls both inside and outside the living environment and then sends an alert to a call centre, informing them that a fall has occurred. Shim et al. [184] monitor patients in bed in order to detect bed-side falls in an assisted living environment. If patient movement is detected around the bed, it is then necessary to consider it as a potential fall and a caregiver is then notified. Lee and Carlisle [171] provide a mechanism that sources data about the activities of older adults; if a fall occurs, it is then reported to emergency services. Terroso et al. [186] detect a fall, either in or out of the home and send an automatic message to family members and other stakeholders involved in the patient's care. Ren et al. [181] enable caregivers of patients to have access to a centralised cloud server, where data sourced from patients activities are transmitted to it. This enables patients to receive medical attention, in some cases, prior to a fall occurring or soon after the event. A fall is detected by distinguishing ADLs from simulated activities that are stored in the cloud server as fall events. Finally, Sahota et al. [182] reduce bedside falls of patients in hospital by monitoring their activities. If the patients leave the bed, an alarm is triggered and sent to the nursing team of the hospital, providing the location of the patient who has fallen.

2.6.3 *Systems*

Application types of all FIPIs presented in [65-67, 153-189, 191] are *static* typically offering no form of rich interaction or visual feedback based on the activity monitored by these systems. Martín et al. [174], Dia et al. [159], Tang et al. [185] and Fang et al. [162] all gather data from older adults through mechanisms which detect falls based on the movements being made by older adults in real-time. There is no interface present, as the sole purpose is to detect falls and send an automatic message or call automatically to preloaded emergency contacts. FIPIs appear to be heterogeneous with regards to the devices, systems and techniques that underpin them. One of the main objectives of successful

FIPIs is to distinguish fall events from ADLs. This has proven to be an on-going challenge and often the primary point of focus of contemporary systems. Much effort has been invested in improving classification algorithms and detection techniques to be able to consistently distinguish fall events from ADLs; however, this is perhaps at the expense of focusing attention on developing more interactive, analytical and informative user interfaces for such systems.

FIPIs are deployed on a range of *platforms* including *desktop computer* [154-156, 163, 164, 168, 172, 173, 177-184, 188, 189]; *smart-phone* [66, 67, 153, 157, 159-162, 165, 166, 169, 174-176, 185-187, 191] platforms. Unlike other system categories, there appear to be no FIPIs deployed on game console platforms. An example of systems deployed on a smart-phone platform is that of Abbate et al. [65] and Abbate et al. [153] who develop a fall detection system on a smart-phone where patients are required to have the smart-phone on their person as a wearable device. The system consists of three fundamental components: (1) a device that collects physiological data via wearable and environmentally embedded sensors; (2) a filtering technique to process the sensor data to distinguish it between falls and ADLs; and (3) communication of an alert in the event of a fall occurring.

2.6.4 *Information sources*

FIPIs exploit a range of *information sources* in order to detect falls. *Sensor location* defines where the sensors are located to source information typically located either on the u*ser* or are embedded within the *context* or environment in which the falls are being detected. The sole location of sensors used by the FIPIs presented in [66, 154, 156, 157, 159, 161-166, 169-171, 174, 176, 178, 181, 185-187, 191] is on the user. For example, Cao et al. [66] require users to wear a smart-phone device on their body, repurposing the built-in accelerometer in order to monitor the movement of the patient. Another example, that of Terroso et al. [186] uses a wearable accelerometer sensor which sends data on patient movement to the smart-phone application and server. The sensor communicates to the smart-phone application via Bluetooth in order to enable the analysis to be carried out, the geographical location to be logged via the smart-phone GPS sensor, and the message to be sent. Fang et al. [162] propose an android-based fall detection system which requires users to either attach the smart-phone to their chest, waist or thigh to detect the significant change in acceleration in order to accurately detect a fall. Fahmi et al. [161] use built-in accelerometer and orientation sensors which are built into the mobile device to measure the position and acceleration of the user to understand a range of fall characteristics and accurately detect a fall when it occurs.

Context is the main information source used in [67, 155, 168, 172, 173, 175, 177, 179, 180, 182-184, 188, 189]. Data is unobtrusively collected from patients and is arguably less intrusive than approaches which place sensors on the body of the patient. For example, Kepski and Kwolek [168] use the Kinect to detect falls in a living environment. This approach enables older adults to be tracked in 3D, and is a low-cost solution. Although environmentally embedded sensors unobtrusively source information based on user movement, the system is limited by spatial coverage and is unable to monitor patient movement wherever they go, unless the environment is instrumented by a number of sensors; although this may address such a challenge, doing so is often not practical. Yu et al. [67] use a single camera to monitor community-dwelling older adults in their home in order to detect a fall based on posture. However, in some scenarios wearable sensors and context sensors are used to improve the level of accuracy of detecting falls. The systems proposed in [65, 153, 158, 160, 167] all use both the *user* and *context* as an information source. For example, Cabestany et al. [158] propose a small sensor device which require users to attach around their waist or hip to achieve optimal accuracy using a developed algorithm. The device is developed so that it is easy for users to wear while performing ADLs. The context-based device is deployed as a bed sensor to detect falls that occur in instances where users are not wearing their sensor. If a fall has occurred, an alarm will be generated. If there is no physical response from the user, a notification from the sensors is sent to the smart-phone application and a message is then sent to emergency services.

All fall injury prevention systems use devices that have different *sensor purpose* to sense activity signatures that represent fall events. *Bespoke sensors* are used in [155, 156, 163, 164, 172, 173, 177, 178, 181, 182, 184, 185, 188, 189] to identify fall events. For example, Bagnasco et al. [156] design a bespoke wearable device that triggers an alarm after a fall, then transmits the data to a base station via Zigbee, a communication protocol that creates a wireless personal area network with low-powered devices. On the other hand, systems presented in [66, 67, 153, 159-161, 165, 166, 169, 170, 174-176, 186, 187, 191] use *co-opt* smart-phone sensors to detect falls. For example, Abbate et al. [65] develop a fall detection system on smart-phones that track the movement of patients, identifies a fall and then automatically sends a notification to emergency services. Although there are benefits in using smart-phone sensors, for example, the built-in accelerometer and gyroscope to obtain information from the patient, it is recognised that users have to be willing to wear the device, which can be considered intrusive. Alternatively, there are sensors repurposed to suit detecting falls. *Repurposed* sensors in [168, 180] have various forms, such as camera, pressure, and audio or are devices that are brand specific, for example, the Microsoft Kinect. For example, Kepski and Kwolek [168] develop a fall detection system which repurposed the Kinect as an input device to source information from older adults functioning in their living environment. The systems presented in [65, 157, 158, 162, 167, 171] use *co-opted sensors* and *bespoke sensors* and are considered as distributed systems.

Deployment environment refers to the living environment in which FIPIs are deployed. *Home environment* [65-67, 153-189, 191] relate to FIPIs that are developed to detect fall events among community-dwelling older adults. For example, Della Toffola et al. [160] develop a robotic system to be deployed in the patient home. This system monitors older adults and responds rapidly to fall events that occur in the home. A sensor network, which is part of the system, is used to determine where the patient has fallen in the home. The nodes within the network are connected via wireless signal which sends an alert to the robot in case of a fall. The robot then communicates the alert to the clinicians who intervene with medical assistance.

2.6.5 *Interface types*

All FIPIs use *multimodal interaction* which comprises the way in which information is collected from users, how they control the system, and the in-built touch mechanisms that are embedded into handheld devices. *Non-interactive interface* are used in [65-67, 153-191] with no interface presented to the user, but uses sensor devices to source information from users and is employed to control the fall prevention system. For example, Kepski and Kwolek [168] develop a fall detection system using the Kinect as an input sensor device that was used to source information from users in the living environment. Although in a gaming context the Kinect provides users with feedback based on their performance, this system is a non-game application and is used purely for monitoring user movements, hence no specific input required nor an interface presented for users to control the system. Shieh et al. [183] develop a video-like surveillance system which uses cameras to monitor high risk locations within the home to capture daily movement performed by users. This system is uni-directional as no user interaction is required as multiple cameras are unobtrusively deployed throughout the living environment for a wider coverage and to collect vision data from users in order to detect falls. Li et al. [173] focus on detecting a fall using acoustics in the living environment and automatically sends a notification to the caregiver when the detected fall occurs. Della Toffola et al. [160] monitor ADLs of older adults who are at risk of falling. The system detects falls, but recognises that fall detection is prone to false positives, and hence, a robot is deployed in the environment in an attempt to address these issues and to intervene if a fall is detected. An alarm is sent out to emergency services, caregivers and clinicians. Rantz et al. [180] deploy a camera-based intervention to prevent falls in hospital rooms, preserving patients' privacy and unobtrusively capturing activities that lead to a fall and notify clinicians of a fall.

The systems presented in [65, 66, 154, 157-159, 162, 165, 166, 169-171, 174, 176, 185-187, 191] use both *non-interactive interface* and *touchscreen* to enable users to use the systems via movement and touchscreen gestures. An example of this is He et al. [165] who present a fall detection system on the Android smart-phone. The embedded sensors on the smart-phone are utilised to collect information on the user's movement. If a fall is detected an alarm message with the time and the patient's location is sent out to clinicians and other preloaded contacts. This system has a natural user interface, as the sensors are embedded into the smart-phone; the user is required to attach the smart-phone to their waist, as required for the built-in accelerometer. On the other hand, the touchscreen function gives the user the option of disabling the system by closing the application or an alert is automatically sent to practitioners.

Collaboration between patients and practitioners in FIPIs occurs as a result of data being sent to practitioners as a consequence of a fall event being detected. However, the collaboration between the two parties is *asynchronous* [65-67, 153-191]; these systems do not offer any real-time communication functions to the practitioner in order to communicate with the patient immediately after the fall has occurred. All systems simply alert the practitioner that a fall has occurred, but do not provide any further scope for communication, within the bounds of the system, after the alert has been sent. An example of this is Abbate et al. [65] and Dai et al. [159] who develop systems which enable asynchronous collaboration between the faller and clinician as a notification is sent to the clinician in case of a fall. Even if an older adult has fallen, an opportunity for collaboration does not occur in real-time, but rather when clinicians respond by providing medical assistance to patients.

2.6.6 *Discussion*

FIPIs are all commonly used to detect falls and prevent fall-related injuries with the use of intervention types such as activity monitoring, fall detector and medical assistance, which all are interdependent. The falls prevention technology literature appears to be saturated with systems developed to monitor activity, detect falls, and send an alert if a fall is detected. Despite the abundance of FIPI systems in the research literature and the significant benefits in the deployment of such systems, there are a number of challenges that may potentially impact their use in practice. Accurate detection of falls is one such challenge particularly distinguishing the kinematic differences between ADLs and fall events is an on-going area of research. Preserving users' privacy is also considered challenging [180]. Repurposed camera sensors have an advantage over wearable sensor devices as image processing techniques can be applied to preserve users' privacy. This also offers an unobtrusive way of sourcing information and creates a means of monitoring patients to verify whether or not they have fallen. Repurposed camera sensors are only able to monitor predefined spaces within the living space, however, this can be a benefit in comparison to wearable sensors as, they can source data directly from users without users having to attach a device to their body [168].

Whilst the risk of falling cannot be eradicated due to the inevitable nature of falls occurring as a result of ageing, effective fall prevention measures can be implemented to help minimise the risks from the outset. The majority of the research efforts in falls preventing technology have focused on using and developing machine learning techniques and optimising algorithms to enhance the sensitivity and specificity of accurate fall detection when they occur, with limited efforts expended on the design and interface functionality of these systems. The consensus of the FIPI studies indicate that these systems provide static applications with the sole purpose of detecting falls when they occur, rather than providing interactive applications that engage patients in interventions that would reduce fall risks. In most FIPI studies, there is a singular focus on reducing fall-related injuries as such injuries happen in the event of fall.

2.7 Cross falls prevention intervention systems

Cross falls prevention intervention systems (CFPIs) target the full range of interventions covered by Pre-FPIs, Post-FPIs and FPIs, thus providing an integrated approach to the delivery of falls prevention interventions to patients. Table 2-4 presents a summary of CFPIs proposed in the research literature.

2.7.1 *Fall risk factors*

All CFPIs solely target intrinsic fall risk factors [59, 93, 192-194], with the exception of [93] which targets both intrinsic and extrinsic fall risk factors. With regard to CFPIs that solely target intrinsic risk factors [59, 192-194] , *functional ability deficits* are the sole focus of these studies. They are also considered in the study of Shi and Wang [93], which also addresses extrinsic factors.

Table 2-4: Cross falls prevention interventions.

	Cross falls prevention interventions											
	Fall risk factors		Combination of intervention types			System		Information sources			Interface type	
Cross fall prevention systems	Intrinsic	Extrinsic	Pre-Fall prevention	Post-Fall prevention	Fall injury prevention	Application types	Platform	Sensor location	Sensor purpose	Deployment environment	Collaboration	Multimodal interaction
Chen and Gwin [192]	Fun			X	X	S	DC	U	Bs	-	Async	Nii
Cortés et al. [193]	Fun		X		X	S	DC	C+U	Bs	He	Async	Nii
Ranasinghe et al. [194]	Fun			X	X	S	DC	U	Bs	Hs	Async	Nii
Shi and Wang [93]	Fun	Eh	X		X	S	Sm	U	Co	He	Async	Nii+Ts
Silva et al. [59]	Fun		X	X		G	Sm	U	Co	He	Async	NUI+Ts

An example of a study which focused on intrinsic risk factors is that by Silva et al. [59] who propose a game to assess older adults' gait in order to delay onset of strength and functional decline. Similarly, Chen and Gwin [192] and Ranasinghe et al. [194] focus on intrinsic factors such as poor postural transition, gait, history of falling, and other fall-related risk activities, which affect one's functional ability and ultimately may lead to falls.

The cross falls prevention interventions presented in [93] focus on both intrinsic and extrinsic risk factors, especially *environmental hazards*. This is exemplified in the work undertaken by Shi and Wang [93] who develop a smart-phone application that provided tips to increase awareness of fall hazards in the home. The tips include illustrations of exercises and ideas about how to improve the home so as to avoid environmental hazards such as poor lighting in the hallway, kitchen and bathroom.

2.7.2 *Combination of intervention types*

A few systems [93, 193] use *intervention types* often associated with Pre-FPIs and FIPIs to prevent the onset of fall risks or identifying risks to avoid fall-related injuries. For example, Shi and Wang [93] increase awareness of environmental fall risks, assess and detect fall risks when they occur and alert older adults and carers to take preventive measures in a timely fashion. Cortés et al. [193] develop assistive technology to increase independence around the home and to help alleviate the burden on caregivers and family members. The proposed walking aid has embedded sensors, which collects the usage data and sends it to clinicians. Two of the five CFPIs [192, 194] use intervention types that are often employed by Post-FPIs and FIPIs. For example, Chen and Gwin [192] and Ranasinghe et al. [194] propose systems that monitor older adults' physical activities to identify fall risks. Once a fall has occurred clinicians are sent a notification to either reduce the potential risk or to assist in the case of a fall. Silva et al. [59] assess the intrinsic risk factors such as functional ability deficits, and more specifically walking patterns, for quality and to provide a form of exercising, (for example, dancing) to encourage physical activity to counter the potential risk of falling.

2.7.3 *Systems*

The *application types* employed by [93, 192-194] are all *static* and the remaining system [59] is an interactive *game* application, which provides a form of interaction and feedback to the user. Ranasinghe et al. [194] propose a static system to be used within hospitals and residential care homes. Users are required to wear a device to enable monitoring of movement in the environment. Shi and Wang [93] develop a smart-phone application, using built-in sensors, which did not require any form of user interaction as it was merely a data collection tool coupled with suggesting knowledge tips on reducing environmental risks within the home and how to get into a recovery position after a fall to prevent any adverse effects thereafter. Chen and Gwin [192] design a wearable sensor device, which collects data from users' performing ADLs and an algorithm to detect fall events. There is no interactivity required for this device to function, as the device's function is to collect data. Finally, Cortés et al. [193] develop a system to assist users living independently by attaching sensors on assisted equipment for clinicians to monitor the usage of the equipment. Silva et al. [59] develop a game-based application, which require users to interact with the dancing game using the built-in sensors on a smart-phone to enable older adults to interact with the game application, ensuring that the physiological data of users matches the movement required in the dancing game. The game then provides the user with visual and audio feedback.

Two out of five systems [59, 93] are deployed on a *smart-phone platform*. Shi and Wang [93] and Silva et al. [59] develop systems that use built-in smart-phone sensors to source data directly from users. Systems in [194] are deployed on the *desktop computer* platform. Ranasinghe et al. [194] develop a desktop application used to identify activity signatures of fall risks in real-time from wireless sensors and deployed within the living environment, to process and store the data and alert clinicians to address a fall risk.

2.7.4 *Information sources*

The i*nformation sources* in [59, 93, 192-194] support a wide range of fall prevention activity. Sensors are often used to gather information from various sources and therefore have different *sensor locations*. The majority of CFPIs [59, 93, 192, 194] source information directly from *users*. Chen and Gwin [192], for example, propose a device that automatically assesses and detects fall risk factors by older adults wearing the device on their body to continuously monitor physical activities. The device gathers acceleration data in 3D space and plots this to X, Y and Z axes, reflecting the body pose of the user respectively. Ranasinghe et al. [194] propose a wearable sensor. Users are required to attach it to a piece of clothing to enable the device to monitor their activities in real-time to classify high risk tasks. Silva et al. [59] present a smart-phone-based system where a accelerometer sensor is used to source data from older adults. The smart-phone is attached to their lower back so that the system recognises physical activities being performed during game play. The remaining system, that of Cortés et al., [193] uses *context* in which user functions coupled with movement to collect data. The same study proposes a system that uses wearable devices to capture data from users and the context to ascertain the state of users in order to respond with support. Sensors are also attached to assistive equipment, such as walking aids, to help keep track of movement and general use of the equipment and to keep clinicians informed.

All sensors capture data directly from users or the context in which they function. With regards to *sensor purpose,* a range of systems [192-194] use *bespoke sensors*, which are developed specifically for gathering data obtrusively or unobtrusively to track users' movement. For example, Ranasinghe et al. [194] utilise a wearable sensor device to unobtrusively monitor older adults in real-time, preserving their privacy, and enabling clinicians to source data from them remotely. Chen and Gwin [192] and Cortés et al. [193] both propose bespoke devices which require older adults to attach the devices to their body. Cortés et al. [193] built-in sensors into assistive equipment to enable monitoring of fall risks. The remaining systems [59, 93] use *co-opted* of smart-phones sensors to source information from users. For example, Silva et al. [59] require users to wear their smart-phone as a wearable device to provide movement to control and interact with the game. Shi and Wang [93] also exploit built-in smart-phone sensors to monitor older adults in order to detect fall events as and when they occur.

In terms of *deployment* environment, the majority of CFPIs [59, 93, 193] are deployed within the users' *home environment*. Silva et al. [59] propose a hybrid system to be deployed within the older adults' home to enable clinicians to administer clinical tests and monitor adherence to unsupervised exercises. Cortés et al. [193] deploy a system, within the patients' home to reduce fall risks and increase assisted living via the use of artificial intelligence and robotic solutions. Conversely, the study by Ranasinghe et al. [194] deploys technology-based interventions to reduce risks in *hospitals* for older adults who are admitted into acute care, especially if they are cognitively impaired, which therefore warrants the need to monitor them during their stay in hospital or residential care.

2.7.5 *Interface types*

The *collaboration* which is afforded by CFPIs [59, 93, 192-194], as with other fall prevention systems, is *asynchronous*. Patients (typically in an unobtrusive way) generate physiological and movement data which is sent to clinicians who respond with medical assistance or establish the likelihood of users falling. Shi and Wang [93] develop a game to increase levels of engagement with home-based exercises to reduce fall risks and enable clinicians to monitor those risks and carry out clinical tests. Ranasinghe et al. [194] enable nurses to respond with help to patients who attempt to transfer on and off items of furniture, such as the toilet and bed unassisted without caregivers' help, which could lead to falls.

All systems [59, 93, 192-194] use a particular form of *multimodal interaction* to interact with technology-based interventions. *Natural User Interface* appear to be a common form of interaction [59, 93, 192-194] as it enables users to perform physical activities and gestures to control an in-game avatar and various objects in a virtual environment. CFPIs in [59] uses *touchscreen* and *natural user* *interface* for users to manipulate the systems by performing gestures to interact with the touchscreen on a smart-phone. The system responds to those gestures by providing feedback to users. In the study of Silva et al. [59], the user attaches the smart-phone to their body so that the system can track their dance moves. Users are provided with both audio and visual feedback, as data their dance moves is transmitted to the movement of a character during gameplay. Shi and Wang [93] develop a smart-phone application for the user to interact with via the built-in touchscreen. Chen and Gwin [192] require natural gestures and movement from older adults to operate their system, enabling clinicians to monitor patients remotely.

2.7.6 *Discussion*

The CFPIs presented in this section [59, 93, 192-194] deploy a full range of techniques typically associated with Pre-FPIs, Post-FPIs and FIPIs to assess, detect, and respond to fall risks. As a result of combining these techniques, multiple fall risks are responded to, often allowing for more comprehensive interventions to be provided compared with systems that target one particular intervention type. The only cross fall prevention system that reduces both intrinsic and extrinsic risks is [93], which enhances awareness of environmental fall hazards supplemented with guidance of how to conduct exercise movements to increase adherence. All cross-prevention systems [59, 93, 192-194] use a natural user interface, enabling users to interact with computerised content by performing a range of natural gestures [195]. Movement data is analysed, for signatures that correspond to fall risks, via the use of computational techniques and advanced processing capabilities. CFPIs that are deployed on smart-phones [59, 93, 192-194] exploit their inherent natural user interface and touchscreen interface. From the systems presented here [59, 93, 192-194], it can be inferred that patients play a major role in their care by engaging with these interventions via the use of sensors and the communication functions of the systems. Perhaps the complexity of these systems and the increased overhead required to design and deploy such systems are the reasons that only a small number of such systems have been presented in the research literature to date.

2.8 Challenges and recommendations

In summary, taking a broader view of the typical functions that each category of system fulfils, the majority of Pre-FPIs [42, 43, 62-64, 94-103, 106-113, 117, 120, 122-125, 127, 128] deploy 3D technology and games as a means to augment evidence-based exercises, focusing on intrinsic fall risk factors, such as functional ability deficits and balance impairments. A large number of Pre-FPIs [42, 43, 63, 98-101, 103, 106, 107, 109, 112, 113, 115, 117, 119, 122-124] are deployed within the home environment to overcome issues of non-compliance with exercising and eradicate the travelling costs to rehabilitation centres. Most of the post-FPI systems are static [60, 61, 134-139, 141-146, 149, 150]. However, the remaining systems provide an interactive means of engaging older adults during fall risk assessment programmes [140, 147, 148]; specifically focusing on intrinsic fall risks. Post-FPI systems [60, 134-141, 143-150] are also often deployed within the home environment. With regards to FIPIs, the majority of these systems focus on falls detection, often via a database of simulated fall behaviour to help distinguish between fall events and ADLs. All approaches, to some extent, detect falls obtrusively or unobtrusively focusing on older patients. Technology-based falls prevention research has tended to focus on detecting falls as a result of its inevitable occurrence, particularly in older people. Nevertheless, Pre-FPI and Post-FPI systems have shown promise in reducing the onset of fall risks, rather than injuries that occur in the event of a fall. CFPI systems provide a comprehensive fall prevention approach as they include a combination of intervention types of Pre-FPI, Post-FPI and FIPI [59, 93, 192-194]. Smart-phone features are strongly being used across all system types. These portable, low cost, and increasingly ubiquitous devices are being used as a solution in deploying fall prevention systems, which is in line with a growing number of older adults now becoming more familiar with smart-phones [196], and consequently one can assume that smart-phones will continue to be part of future fall prevention systems.

Effective management of falls is a complex endeavour, particularly when considering the multiple intrinsic risks, namely social and physical factors and extrinsic risks such as slippery surfaces, poorly fitted or abandoning assistive equipment, poor lighting, unsafe stairs and loose rugs [16, 52]. It is recognised that in order to reduce the risk of falling, particularly in an older adult population, targeting extrinsic risk factors is equally as important as targeting intrinsic risk factors [16]. The effective management of fall risks in order to enable older adults to live independently within their homes for longer is seen as being extremely beneficial to the patient in terms of maintaining independence and quality of life [44]. Despite the key role extrinsic fall risk factors play in ensuring that the goal of independent living is realised, and that fall risk factors are suitably managed, it is apparent that extrinsic risk factors are rarely considered and targeted by contemporary fall prevention intervention systems. Of the 104 fall prevention systems [42, 43, 59-67, 93-125, 127-129, 134-150, 153-189, 192-194], only 4 systems [60, 93, 94, 129] target extrinsic risk factors. FIPI systems in particular, by definition, do not target extrinsic factors at all, as their sole focus is to detect falls so as to reduce fall-related injuries.

There is a need for new research to explore how technology-based applications can be applied to better address and manage extrinsic fall risk factors. Furthermore, when exploring the extent to which existing systems facilitate the process of collaboration and shared decision making between patient and practitioner, it seems that the majority of systems do not invest significantly into delivering such functionality. Pre-FPIs appear to be the category delivering the largest proportion of systems which offer synchronous communication between patient and practitioner and hence patient-practitioner collaboration [42, 43, 62-64, 94-103, 106-115, 117, 119, 120, 122-125, 127, 128]. The collaboration which is supported, however, is synchronous and hence does not optimally support real-time patient-practitioner discussions/interactions about the fall risks encountered or indeed how these may be better managed and overcome. In the rare cases that the system does facilitate asynchronous patient-practitioner communications [104, 105, 116, 118, 121, 129], the system functionality does not tend to actively support and facilitate shared decisions to be made about the patient's care or enable the patient to provide input into the decisions made about their care.

As a consequence of carrying out this survey, a number of challenges have emerged which should be addressed by the falls prevention technology research domain.

2.8.1 *Challenges to Pre-FPIs*

Challenge 1: *Lack of research effort focused on reducing extrinsic risk factors, which are of equally major concern for patients who exhibit intrinsic risks and live independently.* In many instances, falls occur as a result of multiple risk factors including intrinsic and extrinsic risk factors. Many interventions prevent both types of risks in order to increase the effectiveness of preventing a fall. Although there are Pre-FPIs that have produced promising results for addressing intrinsic fall risk factors to date, there are a limited number of systems that reduce both functional ability deficits and extrinsic fall risks and solely reduce extrinsic fall risks.

Challenge 2: *Lack of fall education interventions used in Pre-FPIs to reduce fall risks*. There are a small number of Pre-FPIs that use fall education interventions to reduce fall risks, not least as a singular intervention system. While the vast majority of Pre-FPIs that utilise 3D technology and games for preventing intrinsic fall risks has shown promising results, there is an absence of using such technology to augment fall education interventions, with the exception of two [94, 129]. These two systems specifically provide advice for patients to avoid environmental hazards. Bell et al [94], as well as focusing on reducing functional ability deficits, also addressed environmental risks, noted down in paper-based form, such as decreasing clutter, furniture, spills and the impact these could have on older adults in their living environment. Otis and Menelas [129] look at specific characteristics of the environmental conditions in which older adults function and notified them of a potential risk of falling. Despite this, Pre-FPI systems enable patients to self-manage and reduce falls by engaging in unsupervised health promotion activities. Fully realising the patient-practitioner collaboration paradigm is a challenge, as patients are not given the opportunity to be involved in any decision-making or interventions that reduce extrinsic factors of falling. Furthermore, Pre-FPI systems are of major benefit in that they provide an intuitive way for patients to engage in home-based exercises, and give practitioners the ability to monitor patient's physical health remotely.

In response to Pre-FPI challenges, the following research directions and recommendations are proposed:

Recommendation 1: *Identify new opportunities and develop new technology-based applications to support patients and practitioners in their efforts to overcome extrinsic risk factors.* One promising area of technology that may provide opportunities to overcome this challenge may be found within the interactive 3D virtual reality and gaming domain. For example, interactive 3D gaming applications which simulate the range of extrinsic fall risks that occur at a patient's home may help to improve patient's awareness of risks and encourage the development of strategies to overcome these risks if they occur in real-life. However, it is important that such solutions are applied in a meaningful way in order to target extrinsic risk factors that relate to patients personal home environment in which they function. This is particularly important when considering the notion of ageing-in-place, which focuses on enabling patients to remain in their home for longer. Therefore, addressing extrinsic risk factors via the use of technology could reduce fall events that occur as a result of multiple risk factors or solely based on extrinsic risk factors.

Recommendation 2: *Develop technology-based applications which enable and support fall prevention intervention education and promotion activity.* Taking a pro-active approach to educating patients, who may still be at low risk of falling, around fall risks is likely to increase their awareness of potential risks and encourage behaviour change that may reduce their risk of falling in the future. Given the distinct lack of applications which take such an approach, coupled with the potential benefits, there is a need for more focused technology-based research in this area. Furthermore, for those who have been prescribed assistive equipment to help with performing daily activities and reduce fall risks, educating patients on the need for equipment might be developed to increase adherence and successful uptake of assistive equipment in the home to help with mobility issues and the onset of fall risks. Interactive 3D gaming and virtual reality simulations of fall risks again, may offer promising platforms to deliver educational interventions. Educational interventions deployed on mobile platforms such as smart-phones and tablet-based applications may also be an area of potential opportunity for such applications, particularly given the popularity and ever-increasing ubiquity of such devices.

2.8.2 *Challenges to Post-FPIs*

Challenge 3: *Current systems do not consider or support the delivery of environmental assessment interventions to reduce fall risks.* The majority of the systems produce personalised applications by sourcing information obtrusively or unobtrusively, using sensors, directly from the patient's physical movement in accordance with clinical assessment tests. Although these systems enable patients to self-assess their functional abilities and cognitive function, there is little consideration given to assessing the environment in which they function, with the exception of one system [60]. This is particularly important as systems proposed in the literature are directing their efforts to ageing-in-place, independent living, and remote assessment but they do not take into account the fall hazards that may be apparent within the patient's home environment.

Challenge 4: *Existing Post-FPI systems do not enable patients and practitioners to interact and collaborate whilst fall risk assessments are carried out using Post-FPIs.* The majority of Post-FPI systems provide remote synchronous but static communication mechanisms and hence do not provide patients or practitioners with a means of interacting with each other whilst using these systems. Typically, systems produce static reports on the predefined criteria the system is set up to report on, with no option for the patient to provide additional contextual detail which may be useful for interpreting the data in a more personalised and appropriate way. Post-FPI systems, therefore, would benefit from offering more collaborative functions that provide an opportunity to enable patients, to some extent, to collaborate with clinicians and help interpret the data that these systems generate.

In response to these challenges, the following future research direction recommendations are proposed:

Recommendation 3: *Incorporate environmental assessment interventions into Post-FPI systems*. Whilst falls often occur as a result of multiple fall risks, it appears that Post-FPIs would benefit greatly from assessing extrinsic risk factors by incorporating environmental assessment interventions into Post-FPIs.

Recommendation 4: *Develop Post-FPIs which allow patients and practitioners to engage and collaborate with each other as part of the assessment process*. From the falls prevention systems reviewed, it appears that providing patients with an interactive means could help to increase compliance to fall risk assessments by presenting real-time feedback and a mechanism that supports richer interactions and collaboration between patients and practitioners.

2.8.3 *Challenges to FIPIs*

Challenge 5: *Existing FIPIs are often unable to demonstrate effective and reliable differentiation between fall events and daily activities in order to accurately detect falls, particularly within real-life settings.* As such, much effort has been expended on developing algorithms and computational techniques to improve the level of sensitivity and specificity in accurately detecting falls via user-worn or camera-based sensors. This still, however, remains an on-going research challenge. There are a small number of FIPI systems that have been evaluated with real-life falls due to ethical reasons, however, the remaining systems are unable to demonstrate the effectiveness and reliability of the proposed system in real-life settings. Hence, this raises issues relating to the ecological validity of the proposed systems. In overcoming such issues, most FIPI systems simulate fall-like behaviour in order to gather signatures of fall events in a database to increase detection accuracy.

Challenge 6: *Preserving the privacy of patients when using FIPI systems that utilise cameras to detect falls*. While the use of cameras as an alternative to user-worn sensors provides an unobtrusive way of monitoring patients, there still remains the challenge of users' privacy being breached.

Challenge 7: *FIPI systems that use cameras to monitor patients only cover a limited space within the monitored environment*. Using cameras as an alternative to user-worn sensors presents no restriction of where it is installed, however, the camera devices are limited in covering a certain amount of space in its view. Instrumenting the environment with multiple cameras may increase space coverage of the environment, but will increase in cost, and, in some instances, it may not be feasible to do so. Monitoring patients and detecting falls using camera sensors still remains an on-going research challenge, with limited coverage and effort in optimising image processing techniques to mask user privacy. Also, older adults may forget to wear user-worn sensors, which require effort in reminding users to wear the user-worn sensors.

Challenge 8: *The majority of FIPIs are static and provide no form of user interaction.* In most studies, developing machine learning techniques and optimised algorithms has been the focus in order to increase the accuracy of fall detection, however little consideration has been given to the interface functionality of the systems. There is a lack of interactive applications to engage patients during interventions that could reduce fall risks. However, much less effort regarding the interaction has been explored in this intervention. All systems attempt to alleviate fall related injuries that occur after a fall, these injuries are more severe upon the impact.

In response to these challenges, the following recommendations are proposed:

Recommendation 5: *Develop, deploy and evaluate FIPI systems under real-life conditions*. Falls are a complex phenomenon and are yet to be fully understood. Patients' physiology in relation to real-life falls differs, which makes gathering simulated fall like behaviour problematic and the robustness of which may be considered to be questionable. Therefore, if FIPI systems are to be ecologically valid, accurate and reliable such systems would need to be evaluated within real-world settings.

Recommendation 6: *New approaches to deploying camera-based digital video footage of patients within their home environment, whilst also protecting and preserving privacy of patients must be developed.* Some promising avenues via which this may be achieved lie within the image processing and face recognition research domain. For instance, there needs to be more development of algorithms that dynamically remove and selectively scramble or distort image detail at the point of capture, which may be considered to potentially compromise the patient's privacy. Furthermore, providing clear prompts of when cameras are monitoring to reassure users that their privacy is not being breached at other times may help with the acceptance of such technology. Developing techniques to selectively activate cameras or broadcast footage, only when a potential fall is detected, could also be a potential solution for preserving user privacy.

Recommendation 7: *Invest effort into developing hybrid sensor networks to detect falls*. Instrumenting the patients' living environments with multiple types of sensors has shown promise in the research literature as a potential solution and addresses drawbacks of certain sensors by installing another. Camera sensors that are used by fall prevention systems are deployed in the patient's environment to detect fall events or fall related injuries, however such sensors are limited in coverage, which in some cases, depending on the location of the fall, render it ineffective. However, the advantage of using cameras is that users are not required to wear any sensors on their body. User-worn sensors are not limited in covering the environment, but require users to attach a device on their body in order to detect falls.

Recommendation 8: *Develop systems which support richer and more engaging mechanisms for user interaction*. Little effort seems to have been invested into considering the user interface design of FIPIs, or indeed the specific user-centred interaction requirements of older adult users and clinicians. Systems do not appear to make any significant attempt to develop system interfaces that support patient/practitioner collaboration and interactive information sharing. Therefore, investing effort into user-centred design of system interfaces is likely to improve the level of engagement and acceptance of such systems, which in turn is likely to impact on their longer term success.

2.8.4 *Challenges to CFPIs*

Challenge 9: *CFPI systems face similar challenges to other fall prevention systems in that there is a lack of effort in reducing extrinsic risk factors*. Fall risks are categorised as intrinsic and extrinsic, both of which are equally of major concern and become a risk to older patients who live independently.

Challenge 10: *CFPIs incorporate intervention techniques associated with Pre-FPIs, Post-FPIs and FIPIs as a comprehensive prevention that can target multiple fall risk factors*. The majority of CFPIs prevent multiple fall risks by utilising Pre-FPIs, Post-FPIs and FIPIs intervention techniques. Although multiple fall risks are responded to, developing CFPI systems is an overly complex task which brings with it significant time and cost overheads.

In response to these challenges, the following recommendations are proposed:

Recommendation 9: *Develop CFPIs which support patients and practitioners in their efforts to overcome extrinsic risk factors.*

Recommendation 10: *Develop pragmatic CFPI systems which reduce multiple fall risks whilst also minimising the development and deployment overhead associated with such systems*. Combining intervention techniques to target multiple fall risks often provides more effective falls prevention as fall events occur as a result of multiple risk factors. However, the challenge is to identify CFPIs which also minimise the resource overhead required for developing these comprehensive solutions.

While there were several challenges identified and corresponding recommendations proposed as possible directions for future research, the focus of this research work is mainly to address challenges 1, 3 and 4 by implementing recommendations 1, 3 and 4. The challenges selected for the research focus address the prominent evidence from the literature survey of the increasing need to target environmental assessments to alleviate extrinsic fall risks. Particularly, by enabling clinicians to accurately prescribe assistive equipment to fit the needs of older adults, and for older adults to be able to self-assess their needs for equipment through a means that provides them such capabilities, without clinical intervention. Furthermore, it also focuses on delivering functions to enable patient-practitioner collaboration for patients to provide assessment data, allowing clinicians to prescribe equipment more accurately, without a home visit. To this end, exploring environmental assessments in OT context could ensure that the correct equipment fit the needs of the patient and their home environment, which could lead to better uptake of equipment use for ADLs in the home. The challenges that this research focuses on by implementing the respective proposed recommendations linked to the Objectives O2-O5 that Chapters 4-8 address is presented in Figure 2-5.

2.9 Concluding discussion

This chapter presents a conceptual falls prevention technology framework, which includes fall prevention interventions, the information sources they exploit, and their collaboration functions. The conceptual framework of falls prevention technology was derived from and used to survey a range of fall prevention technology systems that have been proposed within the literature in a specified time period. Fall prevention interventions were found to belong to one of four system sub-types; *pre-fall prevention* (mitigating the early stages of fall risks through health promotion), *post-fall prevention* (assessing fall risks), *fall injury prevention* (reduces post-fall injuries), and *cross-prevention* (combination of multiple interventions used to reduce fall risks) used in practice.

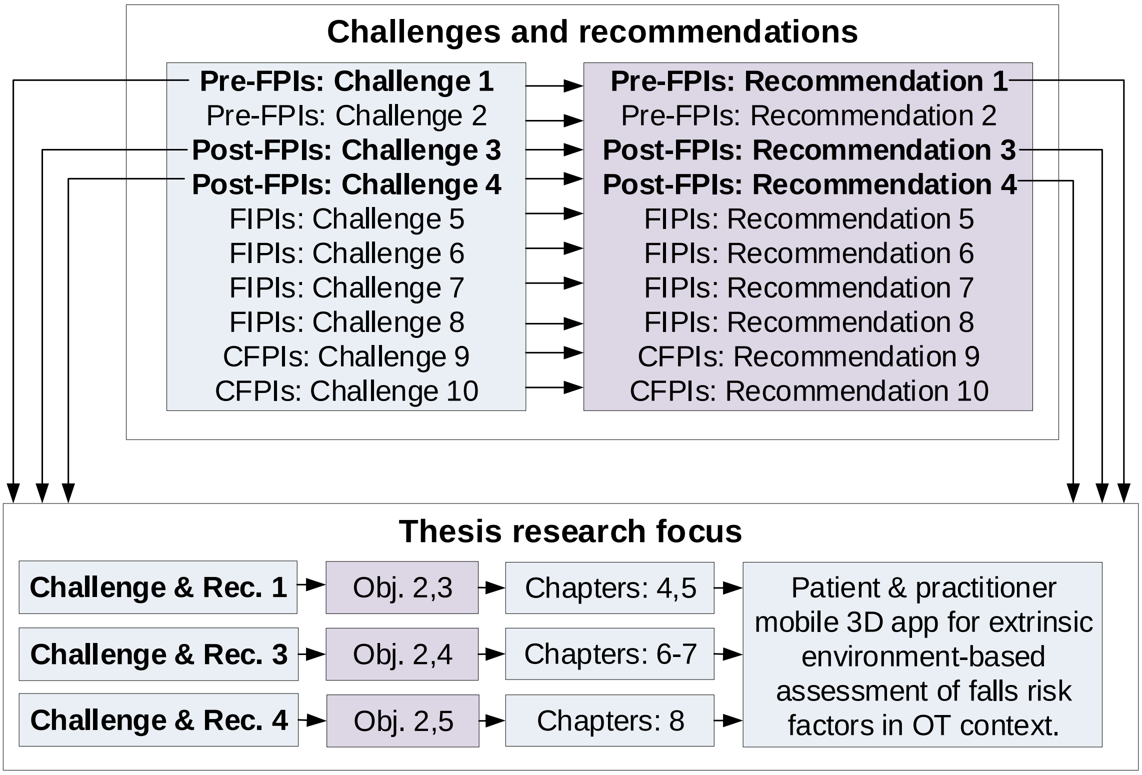


Figure 2-5: Research focus for this thesis.

The *application types* are categorised (*static*, *interactive*, *games* and *virtual reality*) and the *platforms* (*desktop computer*, *game console* and *smart-phones*) in which they are deployed. The fall prevention technology systems that exploit *information sources* were also categorised (user and context) and the purpose of sensors used to source information (*bespoke*, *repurposed* and *co-opted*), and *deployment environments* where the systems are installed (*home*, *nursing home* and *hospital*). The interface type that each system used were also categorised (*natural user interface* and *touchscreen*) and their respective *collaboration* functions (*synchronous* and *asynchronous*) which occurred between older adults and clinicians either offline, sharing an interface during an intervention, or online sourcing data remotely.

Although pre-fall prevention systems have shown promise in reducing intrinsic risk factors, relatively little attention has been paid to reducing extrinsic risks, expect from utilising education interventions, mainly as a component of a multifactorial intervention, to increase fall hazard awareness. This is due to the sole focus of such systems aiming to increase adherence to and uptake of exercise interventions.

Post-fall prevention systems are prominent for augmenting traditional clinical tests used to assess functional abilities and cognition. However, there appears to be benefits to reducing extrinsic risks in order to make these systems more of a comprehensive prevention, due to the collaborative nature of existing systems that are deployed in older adults' home to self-administer assessments. As such, post-fall prevention systems enable older adults to self-assess for intrinsic risks, which, in turn, enable clinicians to conduct their assessments remotely by deploying a system in the patients' homes. However, extrinsic risks and personalising the home to aid mobility and reduce fall risks by self-assessment have yet to be explored.

Fall injury prevention systems appear to be prominent in the literature amongst other systems as it is focusing mainly on detecting falls. As such, falls are inevitable and detecting falls when they occur to prevent fall-related injuries is essential, however, other areas of preventing fall risks are of major concern.

To address and overcome the challenges faced by pre-fall, post-fall, fall injury and cross fall prevention systems, this survey study has proposed a range of recommendations for fall prevention systems. It is proposed that future fall prevention systems would benefit even more from addressing extrinsic risks, particularly how equipment could be successfully adopted by clinicians conducting home assessments effectively and older adults being able to self-assess their needs for assistive equipment in the absence of clinicians in the home. To this end, exploring how home furniture are accurately measured by stakeholders involved in home assessments could ensure the correct fit of equipment in the home, which could lead to successful uptake of and adherence to using equipment. Providing an innovative way of educating fall prevention to older adults encountering fall hazards that are typically found in the home has also been suggested as a potential area of research. Moreover, systems would benefit from focusing on enabling patients to self-assess and provide self-care against fall risks and to enable collaboration for shared-decision making between patients and practitioners.

2.10 Chapter summary

This chapter provided a literature survey and conceptual framework of the state of the art fall prevention technology research landscape and identified challenges in the domain, which provides the motivation for this research work. The various gaps identified are positioned within the number of sub-domain areas that make up the knowledge base in the fall prevention technology domain. Evidence from the literature showed that there is a lack of research effort spent on targeting environmental assessments to overcome extrinsic fall risk factors (i.e. address challenges 1, 3 and 4 by implementing recommendations 1, 3 and 4), which this research addresses. The findings also highlighted the need for developing systems to accommodate the patient self-care activities and ways in which clinicians and patient can collaborate for more effective and comprehensive assessment of fall risks in patients that live independently. The next chapter discusses the research approach used to achieve the overall aim and objectives previously stated in Chapter 1, and a breakdown of each stage in the research to develop and evaluate the proposed research artefact.

Chapter 3
Technology-assisted Healthcare Research: A Design Science Research Approach

3.1 Introduction

The previous chapter provided a conceptual framework and a comprehensive literature survey of the state of the art in the fall prevention technology landscape. A number of challenges were identified in the research literature, specifically, the lack of research efforts invested in addressing extrinsic risk factors and how 3D visualisation technology could be applied to overcome such issues (see Chapter 2 for more detail). Furthermore, the consensus of the clinical literature shows increasing evidence that there are a number of barriers (e.g. inaccurate measurements and the diverse practices of measuring home furniture specifically in occupational therapy) that impact assistive equipment being prescribed and adopted successfully. This research, therefore, addresses this challenge by exploring 3D visualisation technology and how it could be effectively customised in a way to support clinicians and patients alike within the EFAP.

In order to achieve this, there is a need to seek and design an assistive tool which best supports both user cohorts as an alternative solution for home-based fall prevention in the EFAP; and, also, gain an in-depth understanding of the causal factors of equipment rejection and the impact in designing the proposed technology-assisted solution. Consequently, the perspectives of the user cohorts must be considered and explored in the design of the artefact, if this is to be of any clinical value and relevance to the respective purposes. To enable this, the research employs a design science research (DSR) approach [197, 198], including three research stages, using a mixed methods approach, to explore how the use of 3D visualisation technology can assist patients and clinicians through enhanced measurement guidance and equipment prescription in the EFAP.

This chapter explains the research approach employed and the process followed to achieve the aim and objectives of this research work (highlighted in Chapter 1). Furthermore, it also provides the rationale for the choice of methods and tools utilised in the research. This chapter proceeds as follows. Section 3.2 starts with a discussion of the multidisciplinary nature of the computer science field, describing the various research paradigms in the literature and their respective underlying philosophical assumptions. Section 3.3 provides an overview of the DSR approach and the rationale for selecting it for this research work; it presents the DSR cycle steps mapped to outputs to address the research problem; and provides a description of the Hevner's DSR guidelines. Section 3.4 explains the data collection and analysis techniques and the mixed methods approach employed in the research. Section 3.5 presents a diagrammatic representation of the research process, including the various stages of the research (mapped to the DSR cycle steps), and highlights the associated DSR guidelines, methods and tools, data source and outputs of each stage, and how these relate to one another. Section 3.6 explains the role of theory in qualitative data analysis to help explain insights gained from the views of the user cohort and how these could be appropriately integrated into the design of the artefact. Section 3.7 discusses the general and ethical considerations taken into account in the research. Section 3.8 provides the rationale for employing a software development methodology for this research. Conclusions are then drawn in Section 3.9.

3.2 Research Paradigm

The field of computer science (CS) is considered to be a multidisciplinary field which draws on a number of paradigms and methodologies from the natural and social sciences fields to make up its knowledge base and the increasing diversity of its practice [199, 200].

In Herbert Simon's [201] seminal book entitled *The Sciences of the Artificial* (1996), he recognises the clear distinction between the types of research that occur in science, namely *'natural science or behavioural science'* and *'sciences of the artificial'* (known formally as design science research). The first of these types focuses on understanding reality and how a particular phenomenon (natural or social) function within the domains of natural or behavioural science; however, the latter is concerned with designing artefacts to achieve a particular purpose [27].

Researchers that subscribe to the *'sciences of the artificial'* tradition are concerned with designing artefacts, which aim to manipulate and impact upon reality [202]; conducting such research requires seeking out new opportunities, as well as investing in efforts to understand the past. In so doing, artefacts are designed to shape phenomena in the real world, based on the interests, assumptions and values of researchers [203] and driven by their chosen philosophy or paradigm.

According to Mingers [204], the definition of a research paradigm is "a construct that specifies a general set of philosophical assumptions covering, for example, ontology (what is assumed to exist), epistemology (the nature of valid knowledge) ethics or axiology (what is valued or considered right), and methodology". Put simply, the adopted paradigm provides a lens through which the researcher's worldview is shaped [205]. There are a number of paradigms that have been discussed within technical disciplines such as computer science and engineering; these include the interpretivist, positivist, and design science research approaches (for a more detailed description, see [206] and [207]). If one subscribes to a particular paradigm when embarking on a research investigation, it is necessary to be mindful of the underlying philosophical assumptions that pertain to it when exploring a specific phenomenon. Broadly speaking, there are four distinct underlying beliefs to a research paradigm: (1) ontology; (2) epistemology; (3) methodology; and (4) axiology. *Ontology* refers to how one perceives reality; it addresses what reality is and is not; *epistemology* deals with how knowledge is constructed and what is known of it; in respect of *methodology*, the techniques used to collect data – for example, the techniques to detect and determine; and, finally, *axiology* relates to the values held by the researchers. This research employs the philosophical assumptions of the three broad research paradigms: positivism, interpretivism and design science research.

The *positivist research* is defined by understanding of a single reality by obtaining truth through objective testing via experimentation and mathematical proofing. In this research paradigm, researchers subscribe to the view that the research is independent of social reality and removes the researcher from gaining truth. An example of the positivist paradigm is in the natural and applied sciences where scientists conduct experiments to create, prove or disprove a theory/hypothesis as a way of predicting and explaining phenomena. One of the aims of an experimental study underpinned by this paradigm is for it to be repeatable/ reproducible albeit not always the case. Carrying out experiments and collection of quantitative datasets are usually associated with the positivist research paradigm. The quantitative results are typically subjected to statistical analysis. Findings from a quantitative study are reported objectively with the aim to generalise [27, 208].

The *interpretivist paradigm* is concerned with making sense of phenomena through examination and interpretation of participants' perspectives and actions in a socially constructed context, and how these meanings are understood by researchers [209]. Hence, researchers that subscribe to this paradigm aims to gain an understanding through interpreting the participants' perspectives that is related to the phenomenon under study [210]. Interpretive researchers are also of the belief that there are multiple realities and that truth is gained through subjective interpretation and recognise their involvement in the research. Examples of the gathering data under this paradigm is the use of qualitative methods such as interviews, focus groups and observations where the meaning of the phenomenon is investigated through the use of actions and use of language [23, 211].

Design science research (DSR) is an established paradigm in the area of Computer Science (CS), and its recognition as an approach is ever increasing [23, 24] (complementing and promoting shift between other paradigms namely, positivist and interpretivism). It involves the creation of knowledge through designing novel and innovative artefacts. Innovative artefacts are effectively designed to solve real-world problems by way of improving existing information systems that are currently in use [212]. DSR is also concerned with understanding the use of the artefact and where it is implemented. Such artefacts typically take the form of technology-based solutions to be applied to the technical disciplines that are responsible for DSR's conception. This paradigm asserts that the creation of knowledge through designing an artefact is linked with multiple realities and is socio-technologically enabled. Epistemologically, DSR researchers' belief of the relationship between the researcher and the phenomenon under study is best described as "knowing through making" [212]. A more detailed overview of the DSR is provided in section 3.3. Table 3-1 presents the three research paradigms commonly used in the field of CS [26] and details of their respective underlying philosophical assumptions, namely: ontology, epistemology, methodology and axiology.

Table 3-1: Research Paradigms in CS (adopted by Vaishnavi and Kuechler [26]).

	Research Paradigms		
Philosophical Assumptions	**Positivist**	**Interpretivist**	**Design science research**
Ontology	A single reality. Knowable, probabilistic	Multiple realities, socially constructed, subjective interpretation of the world	Multiple realities. Contextually situated alternative world-states. Socio-technologically enabled.
Epistemology	Objective and dispassionate. Detached observer of truth.	Subjective i.e. its values and knowledge emerge from the researcher-participant interaction.	Knowing through making: objectively constrained construction within a context iterative circumscription reveals meaning.
Methodology	Observation; quantitative, statistical	Participation; qualitative. Hermeneutical, dialectical.	Developmental. Measures artefactual impacts on the composite system.
Axiology	Truth: universal and beautiful; predictive.	Understanding: situational and descriptive.	Control; creation; progress (i.e. improvement); understanding.

Given the number of well-established paradigms, design science research is the high-level paradigm chosen for this research, considering the problem statement and the aim of the research which takes the form of an artefact deployed within a context closely tied to the problem it has been constructed to solve. Further, while other paradigms are concerned with understanding reality, DSR expends effort into creating things that serve a purpose in reality [201]. However, DSR is multi-paradigmatic in the sense that the constructing and validating/evaluating artefacts are achieved through adopting the philosophical assumptions from that of the interpretivist and positivist paradigms. As this research aims to design/instantiate a software artefact to improve existing clinical methods in the EFAP, which takes place over different iterations employing a shift between the two paradigms.

The *positivist* paradigm is employed to evaluate the extent to which the artefact improves existing tools and its usefulness in a way that assists users with gathering of more improved assessments and prescription of equipment. The *interpretivist* paradigm is adopted for obtaining participants experiences with using prototypes of the research artefact, and their views relating its clinical value, use in practice and the benefits it provides over existing tools. *Design science research* (DSR) is the overall approach adopted in this research as an artefact is developed to enhance the existing 2D measurement guidance and prescription paper-based tools. The following passage relates the DSR's underlying philosophical assumptions to this present research.

In terms of ontology, the needs/requirements and views from OTs and older adult patients are collected (multiple realities) to design the artefact, involving OTs from different NHS trusts and adults over the age of 50 (different world views). With regards to epistemology, knowledge was gained from integrating two distinct user group needs into the design of the artefact and fed into the subsequent steps/iteration in the DSR cycle; this revealed that the artefact shapes the context in which it is intended to be used and the perceived parameters of the context shape the design of the artefact. In terms of methodology, the purpose of this research calls for a mixed method approach for gathering both qualitative and quantitative datasets, by means of appropriate data collection methods and techniques, to inform the construction and evaluation of the artefact. In addition, establish the impact and improvement that the artefact has over the 2D booklet using approach evaluation metrics. In reference to axiology, the design of an artefact solves a known problem and improves the collection of accurate assessments by affording clinicians and patients with the capabilities to better comprehend what to collect in the EFAP. Apart from understanding the problem space, designing the artefact implies the improvement of existing approaches currently use.

In this research, a bespoke artefact is designed to investigate the utility of mobile 3D visualisation technology in occupational therapy, particularly for the provision of assistive equipment to prevent fall risks; also, to allow patients and clinicians to better visualise and interpret the measurement guidance in a virtual environment that emulates the real world. Improved understanding of clinical guidance is achieved through the use of navigational controls that enable intuitive interactions with 3D models to view the position of crucial prompts that conceptualise the necessary measurements to be taken by the end-user. It is worth noting at this point in the discussion that the research artefact is a novel technology-based solution to augment the visual quality limitations of measurement guidance in the existing 2D paper-based tools. This artefact should also be distinguished from what could be classified as a software development project.

Artefact contributions in DSR and HCI are instantiated as novel prototypes that are functional and offer new knowledge by either accomplishing new things previously impossible or accomplishing previously possible things more efficiently [213], and also "learning by doing" [214]. This is, therefore, what is being provided in this research. The next section provides details of the DSR as the chosen approach for this research. An explanation of how DSR is applied to this research is provided in section 3.5. Details of the stages of the research and how they are mapped to the objectives outlined in section 1.3 and relate to interpretivism and positivism paradigms is evidenced in subsections 3.5.1-3.5.4. First, an overview of the DSR approach is needed as it frames the research reported in this thesis, before delving into its application to this research.

3.3 DSR approach

3.3.1 Overview of DSR

DSR is an established paradigm that has been used in a number of disciplines, particularly in CS [23, 24] where it is widely used in this area and complements other approaches namely, the interpretivist and positivist. It involves the creation of knowledge through designing novel and innovative artefacts. These are effectively constructed to solve real-world problems by way of improving the existing information systems that are currently in use [197]. The DSR approach proposed by Vanishnai and Kuechler [26] represents an extension of existing paradigms to be employed for the creation and evaluation of the artefact via this approach. The adoption of a multi-methodological approach has been advocated for many years [204, 215]. As discussed previously, creating and evaluating artefacts is a fundamental part of DSR [27] as suggested by the two processes of build *(constructing a purposeful and innovative artefact to address unsolved problems)* and evaluation *(appraise the extent to which the artefact performs and how it solve the specified problem)*. While the rationale for developing an artefact for this research has been presented previously, taking the form of an instantiation of the proposed solution, it is crucial to highlight the number of outputs that were also produced which equally took the form of artefacts in their own right. Figure 3-1 presents a diagrammatic representation of how the DSR outputs are linked to the DSR cycle steps to address the research problem. Each of the steps is conducted independently of each other with the outputs developed in one step fed into the next. The DSR process steps are applied to this research.

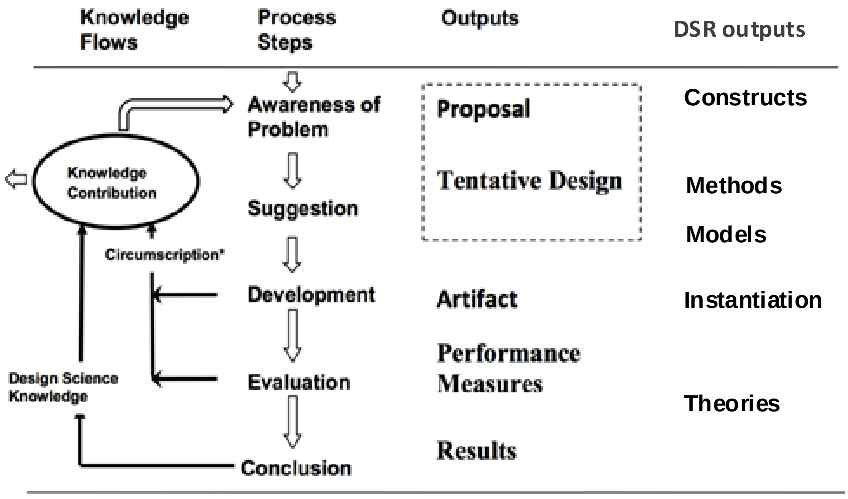


Figure 3-1: Mapping the DSR outputs to the Design Science Research Methodology cycle (adapted from Vijay Vaishnavi and Bill Kuechler 2004 [26] and March and Storey 2008 [216]).

In terms of DSR outputs, *Models* provide an understanding of reality/real world problems and allow for the effects of design decisions to be explored for the impact they could have within a real-world context. *Methods* provide a framework of guidance about how to solve problems. *Constructs* refer to the problems and solutions that are defined and presented using language. *Instantiations* refer to the implementation and intended purposes of the artefact and demonstrate its feasibility and impact in a real-world context. Each form of an artefact is considered a contribution to knowledge [197].

While the knowledge base of DSR provides the appropriate tools through and from which the creation and evaluation of the artefacts is achieved, rigor is also obtained by use of appropriate methods and theories. Hevner et al. [197] propose seven guidelines which are derived from the underlying principle of DSR; namely, that developing an understanding of a problem and its respective solution is acquired in constructing and applying an artefact. It is said that the purpose of establishing these guidelines is to enable researchers to apply them to DSR-related research projects and address each in some way in order for the DSR project to be considered 'complete' [217]. Table 3-2 provides a summary of the seven guidelines and their corresponding descriptions for the purpose of carrying out good design science research and constructing artefacts. Each of the guidelines is applied and discussed in detail in the subsequent sections.

Table 3-2: Hevner's seven DSR guidelines (adopted by [197]).

Guideline	Description
#G1: Design as an artefact	Design-science research must produce a viable artefact in the form of a construct, model, method, or instantiation.
#G2: Problem relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
#G3: Design evaluation	The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.
#G4: Research contributions	Effective design-science research must provide a clear and verifiable contribution in the areas of the design artefact, design foundation, and/or design methodology.
#G5: Research rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.
#G6: Design as a search process	The search for an effective artefact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
#G7: Communication of research	Design-science research must be presented effectively to both technology- and management-oriented audiences.

The following briefly expands on the guideline definitions presented in Table 3-2. DSR includes creating an innovative artefact (#G1) for a specified problem statement (#G2). The artefact is designed for a particular purpose and must have value and benefit for the specified problem that it is designed to solve. Thus, a thorough evaluation of the proposed artefact is essential (#G3). That the artefact is novel is similarly vital, as it must be innovative to solve either unsolved problems or address known problems more effectively and efficiently (#G4). DSR is distinguished from the practice of design; the artefact must be designed, created, and evaluated rigorously using appropriate methods (#G5). Designing an effective artefact involves a search process using available means to achieve a purpose, whilst operating within the boundaries of the problem space (#G6). As the final guideline, the results of the DSR project must be communicated to a variety of audiences (e.g. academia and industry) and presented in dissemination venues (e.g. workshops, doctoral consortium, and journals) (#G7). Section 3.5 demonstrates how the guidelines are applied this research, specifically in each stage.

In light of what has been discussed thus far with respect to the nature and overall aim of this research, the design science research paradigm was deemed suitable to be applied, as it offers a paradigm shift (between interpretivist and positivist positions). It also allows for techniques and methods associated with other paradigms to be used, to enable innovative artefacts to be constructed to address the research problem from multiple perspectives. The next section discusses mixed method approach used for data collection and analysis in this research.

3.4 Data collection and analysis techniques

Data collection is a fundamental step in any research enterprise, irrespective of the selection of techniques employed to extract information from the participants. A number of research instruments were employed to collect qualitative and quantitative data generated from the user studies in this research work (presented in each self-contained chapter). The data was gathered using interviews, focus groups, questionnaires, usability and 'think-aloud' studies, and HCI tools. Each of the specific methods, tools and instruments for each study is described in the following sections and in detail in the subsequent chapters (in sections 4.3.3, 5.2.4, 7.1.3 and 8.3.3). The analysis of the qualitative data included extensive reading of transcriptions to enable immersion within the dataset, and, thus, get 'a feel' for the data and understand the phenomenon under study in-depth. This could optimise the prevention of introducing bias or preconceived notions that could compromise the investigation of the problem. The quantitative datasets collected via questionnaire instruments and experiments in this research was subjected to both descriptive and inferential statistical analysis. Statistical tests for inferential analysis were chosen depending on the purpose of the study.

Typically, in the DSR paradigm, various data collection and analysis techniques are adopted from the two research methodologies (qualitative and quantitative) that co-occur within DSR. Combining these research methodologies is often an approach taken, as suggested by Mingers [204], as it allows one methodology to capitalise on the shortcomings of the other by exploring aspects of the problem/phenomenon under study to yield a better understanding. Given that the nature of problem in this research involves interacting directly with participants, a mixed-methods approach using qualitative and quantitative techniques was employed to provide flexibility in the application of methods and tools. A mixed-method approach provides the researcher with the opportunity to employ the most appropriate methods to address the research problem. Further, in order to increase the credibility and validity of the research and evaluation findings, triangulation was employed [218, 219]. Triangulation is the process of using multiple methods and tools, data sources, and researchers' perspectives to enhance the validity of the study. Irrespective of the underlying philosophical beliefs to which a researcher subscribes, it is essential for data to be gathered from multiple sources using a variety of methods in order to substantiate research findings or demonstrate that the independent measures are not contradictory [220]. This has been applied throughout the studies in this research; for example, the evaluation of the clinical utility of 3D visualisation for measurement guidance was investigated through the use of the different forms of interviews, questionnaires, and measures of efficiency. Utilising such an approach may assist in reducing bias and contradiction, such that validated findings can be proposed [221, 222]. Mackay and Fayard [223] argue that triangulation is particularly valuable in scientific disciplines that investigate HCI. Table 3-3 presents the four triangulation approaches [224] and provides a brief rationale of how each approach is applied to the research.

Table 3-3: Triangulation approaches used in the research.

Triangulation approaches [224, 225]	Rationale for employing the approach in this research
Triangulation of data: Data collected from multiple sources to facilitate assessment of the generalisability of the research findings.	Data was collected from clinicians and patient cohorts and was carried out within living labs that include features of the natural setting (e.g. home furniture and assistive devices), so as to improve validity of the study in examining it under a variety of conditions.
Investigator triangulation: Multiple researchers are involved in the collection and interpretation of the data; very similar to multiple coders involved as encouraged by Miles and Huberman (1994). In so doing, it is crucial that other researchers are able to inspect the interpretations in order to assess the study's validity and generalisability if it is to contribute to the research in an informed way.	Given the nature of doctoral research as an independent piece of research work, analysis of the datasets generated at each stage of the research was discussed with the supervisory team, as involving multiple researchers is considered good practice. This demonstrates that rigor was taken into account for the analysis of qualitative data.
Triangulation of theories: Using different theoretical frameworks as lenses on the data or findings.	A number of user acceptance of technology theories were utilised as theoretical lenses to facilitate the analysis of the qualitative data gathered from each study in the research.
Methodological triangulation: Employing multiple data collection techniques can help to ensure that the results are not simply a function of the protocol used to gather the data.	Using a mixed methods approach and triangulation allows one method to capitalise on the shortcomings of the other method, but also complements the outputs of the data streams. The drawbacks of one method is the benefit of the other and merging the two can result in valid research findings [222, 224].

Quantitative and qualitative methods are viewed as complementary and beneficial to selecting method(s) deemed suitable for addressing the research problem [226, 227]. Adopting this approach is of value, given that the research aim is to involve and obtain the views of clinicians and patients alike for the purpose of designing and evaluating a customised tool to enhance practices within a healthcare context. It is also crucial to acknowledge the appropriateness of when to employ different methods, as there is no single correct method or means to apply these, but, rather, they should be used in way that is fitting and addresses the purpose of the study [228, 229]. Qualitative research is principally exploratory as it provides flexibility to investigate in-depth, and to better understand the phenomenon under study by gaining insights or developing new concepts [230]. Further, qualitative research is subjective in nature, with multiple avenues of interpretation, which is why it is often associated with the interpretivist paradigm. While the goal of qualitative research is not to generalise, transferability is a concept frequently used to improve the generalisability of the results through 'thick description' of the context and processing of the data collection and analysis [231]. The problem posed by this research can be understood through designing the artefact based on the nature of techniques employed; therefore, qualitative techniques were applied to understand the needs, requirements, and perceptions of the user cohort and inform the design and evaluation of the situated use of the artefact. Quantitative research includes an empirical investigation of the phenomenon under study through the use of statistical and mathematical techniques [232], and is thus often associated with the positivist paradigm. Qualitative techniques are used to supplement quantitative data to help understand the 'why' and 'how', and to shed light on the heterogeneous and varied practices of the fall prevention pathway within which the artefact could potentially be used.

3.5 Applying DSR to this research

This section provides details of the DSR cycle steps and outputs and includes the seven guidelines that are applied to each stage of the research for data collection and analysis. Figure 3-2 presents an overview of the research process (divided via the DSR cycle steps [26]), methods and tools employed, data sources, the form of outputs produced at each stage, and where Hevner's seven guidelines (that were introduced in subsection 3.3.1 previously) are appropriately applied to each stage in the research. In addition, a description of the three iterations in terms of data collection, artefact design and evaluation, and data analysis and how the stages relate to the research paradigms (either positivism or interpretivism) is provided in the proceeding subsections.

3.5.1 Stage 1: Awareness of the problem

This stage of the research involved surveying the falls prevention technology landscape, conceptualising the various sub-domain areas within the research literature which resulted in a conceptual framework, enabling gaps to be identified, and advancing a set of recommendations *(constructs)* to address those gaps (see Chapter 2 for more details). A *thematic analysis* of the literature dataset (Microsoft Excel to facilitate this) was then performed in order to survey and categorise the studies that were included in the literature sample (see section 2.2 for details of how the thematic analysis was performed for the literature survey). Inductive approach was taken as it was linked directly to the data in the literature spreadsheet. The knowledge gaps were identified in fall prevention sub-domain areas in the literature survey with recommendations proposed to address those gaps that have valuable potential for technology-assisted interventions across the fall prevention technology landscape O1. From surveying the sub-domain areas, a number of challenges emerged. A selection of those challenges *(research problem)* was then chosen as the focus of this research (see section 2.8). To address these challenges, recommendations were proposed *(proposal)* to exploit opportunities of applying technology in areas which lacked research efforts. This is related to the *#G2 guideline – problem relevance,* with the sole purpose in producing technology-based solutions to the specified problem.

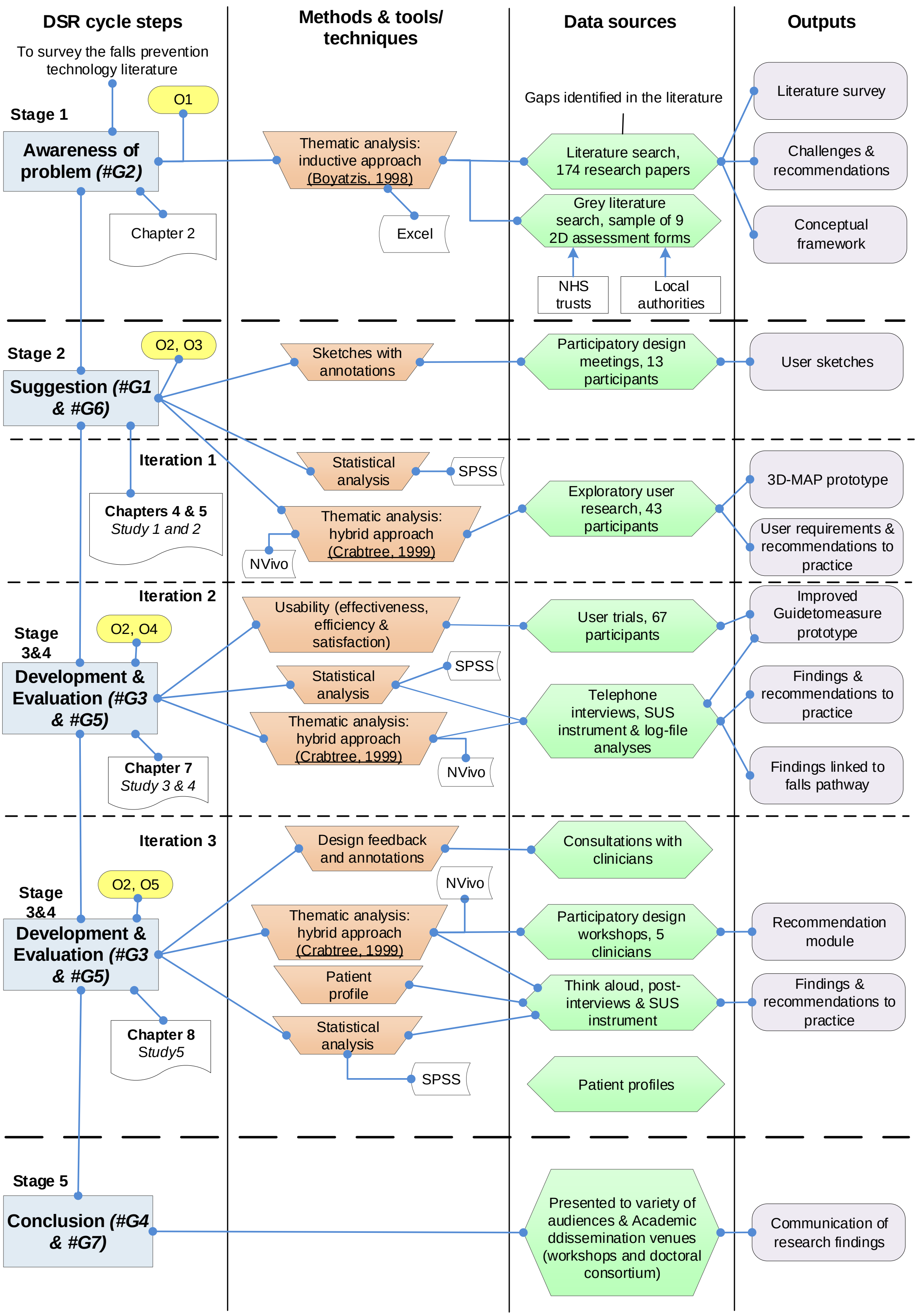


Figure 3-2: Research workflow process model.

3.5.2 Stage 2: Suggestion

Through a comprehensive survey of the research literature related to the problem, a set of recommendations was proposed to bridge the identified gaps in the area *(proposal)*. By employing guideline *#G6*, an additional survey of the 'grey' literature was performed; in particular, searching for established clinical tools related to the EFAP context that are used across the different NHS trusts and community-based practices within the UK (see Chapter 4, background section 4.1). Limited dimensionality of clinical tools was identified as limitations in the literature and the 3D visualisation technology in the form of a software artefact was proposed as a means to resolve those limitations. In a set of participatory design workshops, the design and development of an alternative approach to improve visualisation, with stakeholders were conducted, to overcome limitations of existing methods currently in use in the EFAP (responds to Objectives O2 and O3). Based on the findings, improvement of existing tools in the form of a technology-based solution is suggested, employing the *#G1* guidelines (*design as an artefact*). A low-fidelity prototype *(tentative design),* accompanied by a list of user requirements, was produced as an output of this stage following participatory design workshops with clinicians and patients alike (in section 4.2). Instantiation in the form of a high-fidelity evolutionary prototype *(Guidetomeasure-beta)* was then developed in accordance with user requirements gathered from the concept design phase and evaluation of the low-fidelity prototype. This study employed a qualitative approach to the design of the initial artefact and to allow user requirements with regard to its viability to be empirically tested.

3.5.3 Stage 3 and 4: Development and Evaluation – iteration 1-3

As mentioned previously, the main output when following the DSR approach is to develop a viable artefact. In achievement of this, it is crucial for *#G1 (Design as an artefact)* and *#G6 (Design as a search process)* guidelines to be followed during the process. Moreover, the proposed technology-based solution designed together with user cohorts in the previous stage was instantiated over three iterations within this stage, by using a software development methodology.

3.5.3.1 Iteration 1

A high-fidelity prototype (*Guidetomeasure-beta prototype*) was instantiated based on the findings and user requirements identified from the initial concept design phase. It was developed by utilising a prominent software development methodology *(RAD)*. This was then evaluated with the intended user cohorts, presented in study 1 and 2 (reported in Chapters 4 and 5, respectively) and addressed objectives O2 and O3 outlined in section 1.3. They employed a mixed-methods approach for the evaluation of the prototype. These studies employed a quantitative technique to measures the user cohorts' subjective satisfaction of the prototype interface's usability via a usability questionnaire instrument (associated with the positivist paradigm as it involved numerical data). The prototype was evaluated for its utility, quality, and efficacy (in accordance to the *#G3 guideline - Design evaluation*) in resolving the problem and augmenting the inherently known limitations of the clinical guidance tools. The nature of quantitative data calls for quantitative techniques such as statistical analysis to be employed to evaluate the datasets extracted from sources such as questionnaires, log-files, clinical measurements, and recommendations. To this end, IBM SPSS v20.0.1 was used for analysis of the quantitative dataset. SPSS is a statistical software package developed by IBM and is deemed appropriate for analysing the quantitative data gathered from methods that will be used for data collection and evaluation of the artefact. The quantitative ratings of the prototype interface's usability were complemented and qualified by open-ended.

Follow-up semi-structured interviews (study 1) and focus groups (study 2) were conducted (which was associated with the interpretivist paradigm) to obtain participants views and experiences of the prototype and its clinical utility, voice any usability issues and explore factors that influence acceptance of the proposed technology-based solution. During the interviews and focus groups, notes were taken, with follow-up questions seeking clarification, where necessary. At the end, participants would be presented with the notes to ensure that they accurately reflected what was discussed in the interview. Codes for participant responses (e.g. #P1 or #F1 for participant 1) were used for analysis, whilst at the same time protecting participants' anonymity. Lastly, the analysis of the interview results involved the use of the transcriptions that contained responses that participants gave to the questions on the interview schedule.

A number of theoretical frameworks (e.g., user acceptance technology theories) were used as lenses on the qualitative datasets generated from the empirical work in the research. As user acceptance theoretical frameworks have been used increasingly to structure discussions and gain insights into patient/clinician acceptance as part of interview studies relating to the key constructs found to be associated with user technology acceptance [233], a qualitative analysis technique, using a hybrid approach [234], was applied to make sense of and analyse qualitative datasets. This approach was both inductive (as some of the core, and sub-themes were linked directly to the data) and deductive (as the core themes were driven by the chosen theory and analytical interest of the researcher) [235]. NVivo 11 and Microsoft Visio were supporting software tools used to facilitate the thematic template analysis process and diagramming the resultant high-level themes and sub-themes in a thematic mind map. Details of how the qualitative and quantitative data analysis for study 1 and 2 were performed are discussed in subsections 4.3.3 and 5.2.4, respectively.

3.5.3.2 Iteration 2

In this iteration, study 3 and 4 (in Chapter 7) evaluated the revised prototype (Guidetomeasure, measurement guidance module) performance compared with existing 2D paper-based measurement guidance tools used in clinical practice in relation to effectiveness, efficiency and user satisfaction of usability (O2 and O4). Quantitative techniques were employed to measure the effectiveness, efficiency, and the users' subjective satisfaction (based on the ISO 9241 usability metrics [28]) of the Guidetomeasure app compared with an evidence-based 2D measurement guidance booklet. As the data generated from these studies are numerical and subsequently subjected to statistical analysis is means that this part of the studies is related to the positivist paradigm. Recruiting OT and older adult participants that are representative of the intended user cohort was done with due regard for informed consent, confidentiality, and safety. A probability sampling strategy was employed in the recruitment of study participants to achieve statistical power and an acceptable sample size to carry out the studies. Details of the sample size calculation are provided in section 7.1.1 for both user cohorts.

Semi-structured interview techniques were used to collect qualitative data to uncover insights into user perceptions of both tools to support standard measurement tasks as part of the extrinsic fall-risk assessment process (this part of the studies is associated with the interpretivist paradigm as they collect qualitative data). These studies are multi-paradigmatic in nature, as they have the hallmarks of methods that are philosophically positioned within interpretivism or positivism. Based on the output of the previous stage, research questions were posed to measure the three usability metrics – effectiveness, efficiency, and satisfaction. By definition, a research question is a phrase that focuses a particular line of enquiry and attempts to elicit information associated with a problem that the research study is trying to answer. Defining research questions include variables that the researcher wants to measure and control, user population of interest and phenomenon investigated as part of an experiment [208]. In this research study, the research questions were formulated to empirically evaluate the app compared with an existing 2D measurement guidance booklet in relation to the usability criteria and through an experiment [236] designed to address the research questions.

Experiments involve a number of conditions to which participants were assigned; variables are controlled and measured. There are three types of experiment: those (1) conducted in a laboratory setting; (2) carried out in the field in a context of where a particular phenomenon is deployed (also referred to as being "in the wild" or 'real world' [237]), and, finally, (3) simulation labs [238]. The setting in which the study takes place can significantly affect the result. When an experiment is performed in a laboratory, participants are being observed whilst using a system in a controlled setting. However, purely laboratory-based experiments are limited in their capacity to emulate issues in real life use. The living labs environment, however, are spaces that emulate a natural setting, where the participants have access to certain features that are found in a natural setting or in a particular context where the technology of interest is potentially going to be employed. A benefit of living labs is that they allow naturalistic features to be incorporated into the setting to control order effects in order to measure the cause and effect of the technology of interest [239]. For example, each participant was assigned to the two conditions where their order was alternated in order to reduce bias that is introduced in the different conditions to which participants were exposed. The principal reason as to why this experiment was performed in such an environment was to achieve consistency in the participants' measurement of the home furniture items, in addition to the resource, cost, and ethical reasons mentioned previously. Furthermore, it is essential that the researcher collect the data accurately during the experiment. Therefore, setting up the experiment in a living lab (which includes the required home furniture items) rather than conducting the experiment in the field was preferred. This allowed a number of measures to be performed more correctly in like-for-like conditions. Considering the nature of the research, conducting fieldwork meant visiting patients' homes. This raised some ethical issues concerning this endeavour (more details described in section 3.7).

3.5.3.2.1 Living labs

It is essential to define the research setting and the naturalistic features that are incorporated into the living lab experiment [239]. This includes the five home furniture items that are known to be associated with high occurrence of fall incidents, assistive devices, the observer, and participants. The lab environment was equipped with the necessary study instruments (home furniture, internet access, and accessibility to the required tablet devices). Additionally, the Guidetomeasure app was preloaded onto the tablet device before the commencement of the experimental study (specific details of the living lab setup are described in section 7.1.2). Figure 3-3 shows the living lab setting in which the studies reported in Chapter 7 were carried out.

3.5.3.3 Iteration 3

In this iteration, study 5 (in Chapter 8) evaluated the equipment recommendation module performance compared with existing recommendation guidance tools used in clinical practice. Recruiting OT participants that are representative of the intended user cohort was done with due regard for informed consent, confidentiality, and safety. In order to address objectives O2 and O5 outlined in Chapter 1, a user-based study was conducted which used quantitative data collection techniques to measure the accuracy of recommendations by clinicians and those provided by the app. It was also crucial to measure and gain valuable insights into the user subjective satisfaction of the improved Guidetomeasure app, as it evolved in support of other aspects of home assessment rather than just a collection/guidance tool.

Figure 3-3: Living lab of where the study 3 and 4 (in Chapter 7) took place.

Statistical analysis techniques were employed to analyse the quantitative data collected. This lends itself to the positivist paradigm, where truth (as in evaluation based on defined criteria) is obtained through experimentation and objective testing. Section 8.3.3 provides the data analysis protocol carried out on the quantitative datasets collected for study 5. Follow-up semi-structured interviews as a qualitative data collection technique were used to explore clinician views and experiences with respect to using the app. Adopting this technique is associated with the interpretivist ontological assumptions which suggests that "reality is socially constructed" [240] through understanding the view of participants. In this study, this relates to the perceptions of clinicians regarding the perceived challenges, benefits and clinicians intentions to adopt/accept the app in clinical practice. A series of artefact prototypes were evaluated throughout the research in terms of their clinical utility, effectiveness, efficiency, and satisfaction-rating (in accordance to the *#G3 guideline – design evaluation* and usability principles) in order to address the limitations of current practice identified in previous stages. A number of well-established and rigorous methods were employed to evaluate the artefact in accordance with *#G5 guideline – research rigour*.

3.5.4 Stage 5: Conclusion

At this stage, results are consolidated and presented to a variety of audiences, published (in peer-reviewed journals) and presented at academic dissemination venues (workshops and doctoral consortium) towards the end of the research effort or cycle. Communication is crucial in research [197]. A strong case for the knowledge contribution that each research effort makes must be defined and produced in the form of a DSR output [241]. This is in line with the *#G7* guideline - *communication of research*. Furthermore, the contribution that this research has made to the area of scholarship has also been presented to and discussed with healthcare practitioners who possess the necessary clinical expertise within the healthcare field, which is in accordance with the guideline of *research contributions* and also discussed in the final chapter of this thesis.

3.6 The role of theory in qualitative data analysis for artefact design and evaluation

The design, development and use of the novel artefact provide an understanding of how the phenomenon of interest is facilitated and improved. For the artefact to improve existing approaches and tailored to the needs of the target users, it is imperative for valuable insights into factors that ensure they accept and adopt it is considered. This is captured in the form of qualitative data. Technology acceptance theories are used to guide this research for this data to be captured in a meaningful way. To this end, the researcher embraces two of Gregor's [200] classification of the purpose of theory, which is to analyse and explain, particularly as the theories employed in this research plays a role in analysing and explaining the phenomenon under study. A theory is used to describe the phenomenon, provide analysis of connections between constructs that mediate the acceptance and adoption of technology in clinical practice. It was also adopted to explain 'how' and 'why' to gain a greater understanding of users' preferences and perspectives into the phenomenon of interest, which influences the design and use of the artefact.

3.7 General and ethical considerations

Careful attention was paid to ensure that the research complied with best practice. Providing assurance that participants' safety and rights were of great importance adds credence to the research protocol and subsequent results. Further, ethical issues surrounding privacy, security, and anonymity of participants' data have to be taken into account when involving human beings in research (especially service users who may have complex needs which this research involves). It is also worth noting at this point that financial incentives were issued for the exploratory and user design studies (reported in Chapters 4 and 5) in exchange for participants' time.

Gathering high-quality and valuable data from the older adult population require some adaptations to research methods and techniques used in the research enterprise. As there were a range of literacy levels in the older adult population under study (due to sensory and cognitive changes), it was important to ensure that the language used in the consent forms/written material were free from any technical jargon and that verbal description about the study was offered. The characteristics of the older adult population have an impact on the way in which an experiment is designed or an alternative choice of method is used. An example of this (from Chapter 5) is the choice of using the retrospective think-aloud method for users to provide their thoughts subsequent to task engagement rather than the use of the conventional concurrent think-aloud method were thoughts are verbalised simultaneously which could interfere with the completion of the task. It is also important to recruitment a sample of diverse group of older adults to accurately reflect the reality of the demographic in the population.

'Older' covers any person that is over the age of 50 which is a criterion used in the recruitment of participants in the studies reported in this thesis.

Ethical clearance was obtained from Brunel University Research Ethics Committee prior to commencing the data collection (refer to Appendix A for the ethics approval letter). Informed consent was sought from each participant prior to their taking part in the research (refer to Appendix B for the consent form used in the research). Each participant who participated was guaranteed anonymity and confidentiality and was informed both verbally and in writing of their right to withdraw from the study at any time without justifying their reason(s). All participants volunteered to take part on an anonymous basis and were briefed on the aim of the research and the protocols for each respective study reported in this thesis.

Best practice for research governance and data storage was followed in this research. Participants were given the information sheets for each study before they were asked to participate so as to allow time for the participants to think about it before making the decision to take part. Storage of the data collected is crucial, particularly when involving large amounts of paper-based questionnaires and audio recordings from the various stages of the data collection. With the potential risks of data loss or theft, the audio recordings and transcriptions were stored on a networked computer and on an encrypted portable hard drive. These devices were password protected to prevent unauthorised access. Questionnaires used in this research were entered manually onto SPSS and the transcriptions were uploaded onto the NVivo software. The hard copies of the paper-based questionnaires and transcriptions were appropriately labelled and stored securely. All interviews in the research were transcribed verbatim by a professional transcriber, with careful attention paid to confidentiality and anonymity.

3.8 Employing a software development methodology to this research

As the research artefact in this research takes the form of a software application, the discussion that follows will primarily focus on the development of the software application, specifically on the rationale to employ a software development methodology that is deemed appropriate and prefaces the implementation described in the subsequent sections.

Why do we need a software development methodology? To best answer this question, it is important to refer to the purpose of a software development methodology (SDM). By definition, SDM is a formal process in which software is designed and developed within distinct phases in a lifecycle, typically from design to deployment [242]. In the context of this research, an SDM is required to guide the development aspects of and aligning user needs and requirements that contribute to the design of the artefact. There are a number of software development methodologies that have been proposed in the software engineering literature, each of which belongs to software development paradigms, which guide the design of a software application from requirements gathering to production/deployment [242]. Given that the approach that underpins this research is iterative, in nature, where outputs of each phase contribute to the design of the artefact, it is necessary to employ a development methodology that advocates iterative prototyping until a satisfied artefact is produced. To this end, the rapid application development (RAD) methodology was considered most suitable and that fits this research, as it enables rapid development of prototypes of the artefact and is therefore employed in designing and developing the research artefact. RAD is an SDM approach that allows for rapid development of prototypes in an iterative development cycle, whilst involving users in the design through to the evaluation of the software artefact. Using this approach enables an initial version of the software to be developed and evaluated continuously with prospective end-users. Feedback (i.e. improved functionality and features, and user preferences) received from these end-users are then continuously fed into the next prototype of the software artefact, until an acceptable version of the prototype is produced. Figure 3-4 shows the RAD lifecycle that is used in this research work.

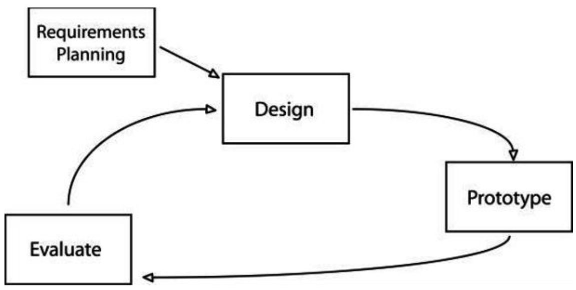


Figure 3-4: RAD lifecycle followed in this research adapted from Córdova *et al.* [243].

3.9 Conclusion

In conclusion, this chapter has explained the research approach used to achieve the overall aim and objectives of the research and to illustrate the choice of methods. Further, it has discussed how the research was designed using the design science research paradigm, employing a mixed-methods approach of qualitative and quantitative data collection techniques. The three iterations of the research have been summarised. Living labs were introduced as the sites in which the studies reported in Chapter 7 were conducted. Gaining access to older adults' homes was seen as resource intensive and problematic, and would require formal NHS ethical clearance, given the issues that surround this endeavour. The living labs chosen were seen as a suitable site for data collection and contained the home furniture items and assistive devices that are representative of what is typically found in the homes of older adults, which is measured by clinicians. The role of theory in this research was also explained. An acknowledgment of general considerations, in addition to the ethical issues encountered during the course of this research was discussed. The chapter concludes with a discussion of a software development methodology (RAD) employed to design and develop the research artefact and provided a rationale for its selection.

3.10 Chapter summary

This chapter has explained the research approach employed to address the overall research aim and objectives and provided a rationale for the methodological decisions made. Furthermore, it described how the design science research paradigm was applied to the research, utilising a mixed method approach for the data collection and analysis. Each stage of the research, methods employed, type and location of the user-centred design and experimental studies that were carried out have been outlined. The role of theory used for analysis of qualitative data collected for the design and evaluation of the research artefact was discussed. The general and ethical considerations were explained concerning the practices followed in the data collection and analysis process and the ethical issues encountered in the research. Subsequently, this chapter describes RAD, as the software development methodology, used in this research to design/develop the artefact. The subsequent chapters that follow will deal with the studies undertaken within the three research iterations (Chapters 4, 5, 7 and 8), and demonstrate how the research approach is used within a healthcare context.

Chapter 4
Occupational Therapist perceptions of Mobile 3D visualisation technologies as a measurement aid for fall prevention assessment interventions

4.1 Background

Chapter 2 proposed a conceptual framework of the state of the art fall prevention technology systems and surveyed the research literature. The conceptual framework was developed as a result of employing an inductive thematic analysis approach to examine the existing fall prevention technology research. The analysis revealed that existing fall prevention interventions were found to belong to one of four system sub-types that mitigate the different fall risk factors: (1) pre-fall prevention (mitigating the early stages of fall risks through health promotion); (2) post-fall prevention (assessing fall risks); (3) fall injury prevention (reduces post-fall injuries) and (4) cross-prevention (mixture of multiple interventions used to reduce fall risks) used in practice. Other categories of how these systems are used include: application type, technology deployment platform, information sources, deployment environment, user interface type and collaborative function.

Through surveying the existing falls prevention technology research, it was concluded that although all fall prevention systems are valuable in reducing the different stages of fall risks, there is a lack of systems that target environmental assessment interventions to overcome extrinsic risk factors. Further, developing fall prevention systems would benefit even more from addressing extrinsic risks, particularly given the increasing need to support patients to age-in-place and live independently whilst reducing fall risks. In response to this finding, it was proposed that augmenting environmental assessment interventions via a technology-based solution may serve as a valuable means to address extrinsic fall risk factors, which is equally as important as targeting intrinsic risk factors [16]. The *research focus* in this thesis, therefore, is to address the *environmental assessment interventions (challenges 1, 3 and 4)* by investigating the EFAP in the field of OT and explore the ways in which clinicians and patients could better collaborate to perform more effective assessments in this intervention via a *technology-based solution* to augment assessments for equipment *(recommendations 1, 3 and 4)*. Figure 4-1 presents the link between the literature survey findings to the OT EFAP context that is investigated in this research.

4.1.1 Occupational therapy, EFAP

In the field of OT, the EFAP is routinely carried out to prevent falls in the older patient's home environment. Numerous other benefits may be realised as a consequence of the extrinsic fall-risk assessment, this includes enabling ageing-in-place and independent living, improved facilitation of care, increased self-esteem, and overall improvement of the quality of life [10]. In the context of OT, falls prevention activities are carried out as part of the EFAP.

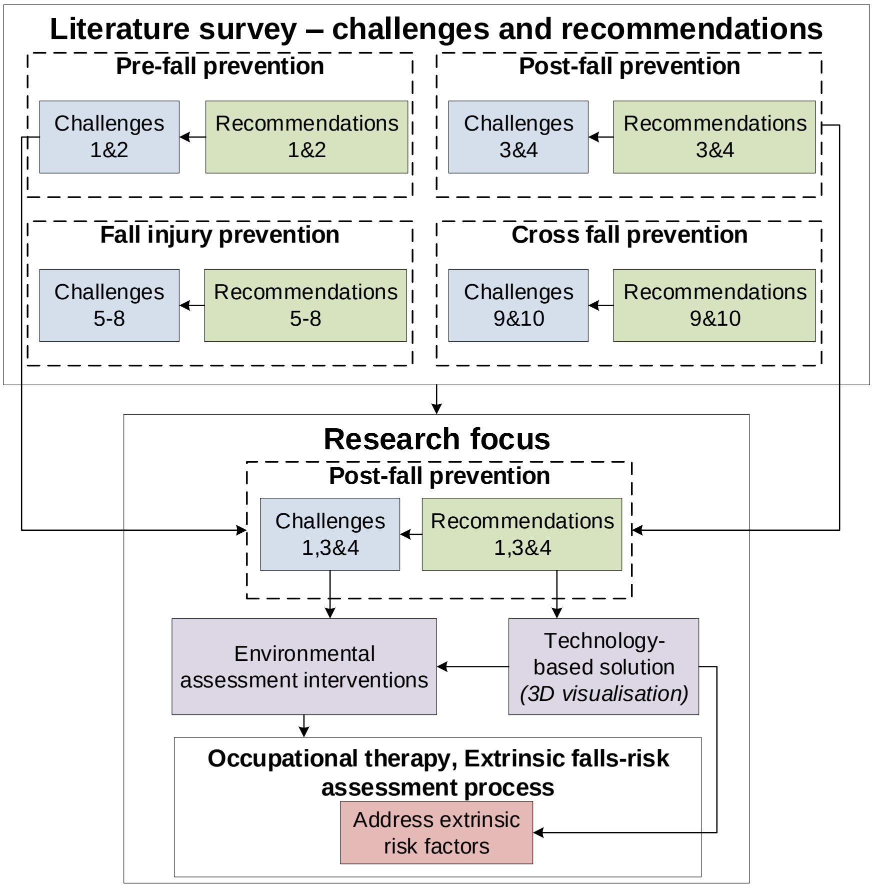


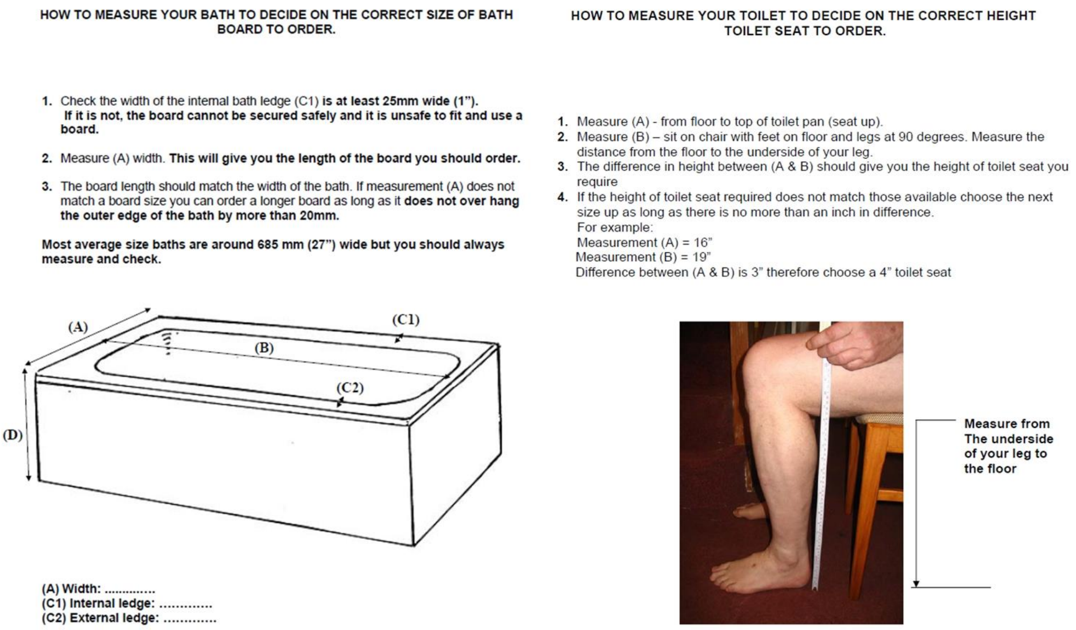
Figure 4-1: Research focus from the challenges identified in the literature survey (Chapter 2).

This involves working closely with patients to assess intrinsic and extrinsic fall risk factors. Intrinsic fall risk factors focus on functional ability deficits presented by the patient and typically relate to balance and cognitive impairments. *Extrinsic fall risk factors* focus on risks that are apparent within the environment in which patients carry out occupations on a day-to-day basis, which include poor lighting, slippery surfaces, raised door thresholds, stairs and steps, clutter, and trip hazards [12]. Extrinsic fall risk factors also include improper use of assistive equipment (AE), or the absence of assistive equipment such as stair handrails, toilet raisers, bath boards, and bathroom grab rails where these would be deemed necessary.

4.1.2 EFAP, measurement, and falls prevention

The goal of the EFAP is to identify and reduce barriers that impact upon patients' ability to carry out the ADL and mitigate the overall risk of falling. This is typically achieved by recommending minor and major adaptations to the home environment to accommodate functional changes, assist with ageing-in-place, and reduce the patient's overall risk of falling [5]. During the EFAP, clinicians assess whether AE is needed to help maintain independent living and/or to overcome potential fall hazards. A crucial part of the process involves clinicians measuring the dimensions of home furniture and specific parts of the patient's body. These measurements are used to determine the nature and details of the adaptations that are necessary to reduce the overall risk of falling and to enable patients to successfully engage in their ADL. The recorded measurements are used to determine the specific sizes of AE prescribed for fitment within the patient's home environment. An appropriate fit between the equipment, an item of furniture, and/or the patient, is only possible if measurements are taken from the correct locations on a person or item and are measured and recorded accurately. Adaptations to the home typically include OTs prescribing the installation of AE such as chair raisers, grab rails on stairs, bath boards, toilet raisers, and bathroom grab rails to help with transfers when bathing [244]. Measurements are used to ascertain whether the height of furniture either facilitates or hinders functional independence. To recommend a chair raiser, for example, the OT measures the height of the patient's leg (popliteal height) and the height of the chair. The OT calculates the difference between those two measurements, which provides the height that the chair must be raised. The customisation of measurements plays an important role in ensuring the successful fit of the assistive equipment to the patient [245]. Clinicians may receive some training in relation to the provision of assistive equipment; however, there is currently no mechanism in place to ascertain whether they are prescribing safely.

Current EFAP practice involves utilising paper-based forms designed to guide the clinician through the process and ensure that measurements are taken and recorded accurately, along with any necessary patient-related data. These paper-based forms often provide additional measurement guidance in the form of 2D representations of home furniture and the patient. The key function of the 2D representations is to help the clinician to identify the precise points within 3D space that must be measured, on each respective item of furniture/patient and to make an unambiguous record of these measurements with a view to accurately calculating and prescribing AE that will facilitate ADL and mitigate the risk of falling [17]. Some existing EFAP paper-based forms are presented in Figure 4-2. The prescription and fitment of inappropriate AE results not only in a failure to provide necessary assistance where it is needed, but also has the potential of compounding the very falls risks that they were installed to mitigate. Despite the widespread provision of paper-based 2D visual guidance which aims to minimise inappropriate prescription and fitment, approximately 50% of AE prescribed by clinicians is reported to be abandoned by patients [54-56], in part as a consequence of 'poor fit' between the AE, the patient, and the furniture on which it is installed [57, 58].



HOW TO MEASURE YOUR BATH TO DECIDE ON THE CORRECT SIZE OF BATH BOARD TO ORDER.

1. Check the width of the internal bath ledge (C1) **is at least 25mm wide (1").** **If it is not, the board cannot be secured safely and it is unsafe to fit and use a board.**
2. Measure (A) width. **This will give you the length of the board you should order.**
3. The board length should match the width of the bath. If measurement (A) does not match a board size you can order a longer board as long as it **does not over hang the outer edge of the bath by more than 20mm.**

Most average size baths are around 685 mm (27") wide but you should always measure and check.

(A) Width: ....
(C1) Internal ledge: ....
(C2) External ledge: ....

HOW TO MEASURE YOUR TOILET TO DECIDE ON THE CORRECT HEIGHT TOILET SEAT TO ORDER.

1. Measure (A) - from floor to top of toilet pan (seat up).
2. Measure (B) – sit on chair with feet on floor and legs at 90 degrees. Measure the distance from the floor to the underside of your leg.
3. The difference in height between (A & B) should give you the height of toilet seat you require
4. If the height of toilet seat required does not match those available choose the next size up as long as there is no more than an inch in difference.
   For example:
   Measurement (A) = 16"
   Measurement (B) = 19"
   Difference between (A & B) is 3" therefore choose a 4" toilet seat

Figure 4-2: Paper-based measurement guidance currently used in practice [246, 247].

The impact of such practice is, therefore, significant and widespread, and includes a negative impact on patient health outcomes, accelerated functional decline, an overall increase in exposure to fall risks in the home, and, more generally, an unnecessary depletion of valuable health care resources [20].

4.1.3 Existing and future technologies for falls prevention

The key areas in which falls prevention research is undertaken correspond to four overarching categories/sub-domains: (1) Exercise interventions; (2) Fall risk assessments; (3) Education interventions; and (4) Home assessments/prescription of assistive technologies [248]. However, when exploring the technology-based applications that have been presented across the falls prevention research landscape, it appears that certain of these sub-domains have received significantly more attention than others. For example, there are numerous *exercise intervention* focused systems such as that of Mirelman et al. [128], who augment treadmill exercise training with virtual reality technology to improve functional ability and cognitive function. *Fall risk assessment* systems include those presented by Staranowicz et al. [143] and Weiss et al. [141] which use motion capture sensors to monitor gait in real-time and predict fall risks, providing early intervention where necessary. *Falls prevention education* is presented by Bell et al. [94], who combine a Nintendo Wii game console with falls prevention education to enhance patient awareness of the importance of reducing clutter, arranging furniture in the living area, positioning of the rugs, flooring types, lighting, and staircase and bathroom safety. However, with regard to the *home* *assessments/prescription of assistive technologies* sub-domain, there do not appear to be any applications that attempt to assist in this falls prevention activity. A recent survey of state of the art falls prevention technology supports this finding (in Chapter 2), concluding that there is an urgent need to develop new technology-based applications, and highlighting the potential of applying 3D visualisation technologies to this particular area of fall prevention practice [248].

4.1.4 3D Visualisation Technologies for Guiding the EFAP

The term 3D visualisation technologies refer to computer graphics software applications that capitalise upon natural aspects of human perception by the visual simulation of three spatial dimensions in 2D space, enabling the user to visualise, interact with, and control a given object within a 3D scope. Considering the benefits 3D visualisation technology provides, most of the efforts in improving visualisation in medicine are exploiting features benefits of 3D, which will be discussed subsequent parts that follow of this section. Before delving into the discussion of such efforts, however, it is crucial that a brief look at the history of medical imaging is explained before beginning the main topic of discussion. In the medical field, much effort has been made in developing medical imaging for internal and external examination of the body and diagnostic purposes. An X-ray, known as a widely established medical imaging test, is an invisible radiation wave that penetrates through the body to display the bones, joints and conditions that affects soft tissue (i.e. internal organs) [249]. This is a standard procedure that is used to produce 2D visual images of the inside of the body. Traditional X-ray scans, however, provides a 2D view of the body from one position, which results in detail of the other structures in the body being obscured. Computerised tomography (CT) scans (also referred to as CAT scans) involve performing a series of X-ray scans from different viewpoints, which was introduced to succeed the conventional X-ray imaging [250]. Furthermore, CT scans generate more detailed images of inside the body, i.e. internal organs and bones and blood vessels. These images are then processed in a way to build 3D images. This allows medical practitioners to manipulate the images in order to observe the structures within the body and the different layers from various viewing perspectives to gain a greater insight into the patient's body. Magnetic resonance imaging (MRI) is another type of medical imaging that uses magnetic fields and radio waves to produce images of the internal structures of the body [251]. An MRI scan is used to examine several parts of the body including the brain, spinal cord, bones and internal organs, to name a few. Ultrasound imaging uses sound waves to create an image of inside the body [252]. The echoes of the waves are processed which produces the image of inside the body. Ultrasound is used to monitor unborn babies and to help diagnose a condition. While X-rays, CT scans, MRIs and Ultrasound continue to be used to date by medical practitioners and provide considerable benefits to the medical field, these imaging modalities, however, display 2D images of internal organs and body parts that are in three dimensional, leaving practitioners with having to visually stitch those images as if it was observed in their natural form.

Over the years, there has been an increasing amount of literature on developing techniques to improve medical visualisation to simulate, i.e. human autonomy/interior of the body (organs and tissues) and the brain to inform interventions and clinical analysis. Several visualisation techniques have been developed to better reveal interior structures of the human body so as to diagnose and treat disease, treatment planning and using sophisticated imaging to identify possible abnormalities/anomalies through the use of 3D visualisation technologies [253, 254]. Furthermore, 3D visualisation technologies have shown to offer a more realistic and better means of conveying information, and the function of internal organs and tissue as part of a medical treatment than that of 2D visuals. For example, Jang et al. [255] and Izard et al. [256] proposed 3D virtual environment system for education in medicine, specifically for medical students to “study complex anatomical structures” in its realistic setting to allow direct manipulation of anatomical structures. Medical students are able to perform surgical procedures, i.e. assemble a skull using different bones in Izard et al. [256] within the virtual environment. Introducing this solution allows medical students and doctors to perform a simulated procedure without having to use a real body.

More specifically, the value of 3D visualisation technologies for the falls prevention research domain has already been demonstrated in a number of existing falls prevention research studies that focus on the areas of exercise intervention. Some examples include Uzor et al. [257, 258] and Doyle et al. [259] who aim to improve uptake and adherence to home-based falls prevention exercise programmes by replacing traditional paper-based 2D illustration exercises with equivalent interactive 3D visualisations of these programmes. One existing study explores the potential of exploiting 3D visualisation technologies to assist clinicians in identifying extrinsic fall hazards. Du et al. [60] developed a robotic system to automatically model patients’ home environments in 3D space. A 3D visualisation of the environment is constructed to assist clinicians in identifying the precise location and nature of extrinsic fall hazards. The use of 3D visualisations have also shown promise in being able to overcome the challenges of existing 2D clinical tools by improving the visual quality necessary to conceptualise visual cues as part of a particular treatment and assessment [72]. For example, Spyridonis et al. [260] and Boudreau et al. [261] found that enabling patients to report the type and precise location of back pain using a 3D visualisation of the human body was more accurate and intuitive than the traditional paper-based 2D model of the human body typically used in practice. Other studies have found similar benefits to using 3D visualisation to communicate other forms of pain to clinicians. For example, Jang et al. [262] enable patients to express and communicate their symptoms of pain by annotating specific regions on an on-screen 3D representation of the human body using free-hand drawing. De Heras Ciechomski et al. [263] propose a preoperative surgical 3D visualisation system for breast augmentation using 2D digital photographs of the patient's torso and reconstructing these into 3D models. This system helps clinicians to perform virtual clinical analysis without the patient being present and visualises the required measurements on the modelled body in order to facilitate accurate measurements for the treatment. Östlund et al. [264] proposed a synergetic web-based tool using 3D visualisation technology and video conferencing which provide instructions and demonstrate the correct handling of pharmaceutical products for patients who are seeking advice. Three-dimensional pharmaceutical products are presented to advice-seekers with audio communication, effectively a pedagogical tool, specifically providing information about the products side effects, storage place and a 3D model of the medical device that patients use to self-care e.g. asthma inhaler, pen injector for insulin and disposable syringe for hormones. In addition, Kim and Chung [265] and Jang et al. [255] use 3D models of the human body that is segmented into multiple layers of the human body which present the skeleton, muscle, and organs. Specific parts of the 3D human anatomy model are directly selected by users which provide medical information regarding diseases, symptoms, treatment and prevention that correspond to each selected part of the body. Three-dimensional visualisation technology in this study is used to provide healthcare education, specifically diseases that are related to certain parts of the human body.

The research literature to date indicates that the use of 3D visualisations have shown promise in providing opportunities to overcome the challenges of existing 2D clinical tools to sufficiently provide either clinical or patient users with the visual quality necessary to conceptualise visual cues as part of a particular treatment and assessment [72, 266]. In light of the equipment abandonment issues faced by the current EFAP, discussed previously, there is a need to explore the potential value of 3D visualisation applications developed specifically for use by clinicians that serve as an aid in the process of carrying out the key measurement tasks that form part of the EFAP.

Improving the visualisation of 2D measurement guidance in effort to tackle the equipment abandonment issues is the underlying basis of this research. Achieving this would also improve interpretation of the guidance from a clinical standpoint and presents the measurement guidance to patients and clinicians in a more intuitive way that was otherwise not present in the previous 2D form. According to the researcher's knowledge, designing this particular software artefact would be the first of its kind and that there are no available software artefacts, in the literature or on the commercial market that address this research problem. The taking of measurements could be automated as taking the measurements is likely to be subjected to human error. This issue, however, is outside the scope of tackling the main research problem.

Nevertheless, many visualisation technologies and techniques could be used to address the issue of measuring objects. The following looks at real-world patented technologies available on the market that could be applied to this problem, specifically for measuring objects in the scene. 3D scanning devices, of which many software applications have been developed to use, are used to construct virtual 3D models. Microsoft Kinect, is a 3D camera device developed by Microsoft [267], which has been applied in areas of medical and healthcare research, exploiting its capabilities of detecting motion and controlling virtual objects based on real-life movement for clinical intervention purposes [268]. A number of commercial mobile apps use this device to enable users to scan real-world objects by the user holding the device and rotating it around the object, which then constructs a 3D virtual object to scale of the real-life object. Structured sensor, developed by Occipital [269], is scanning sensor device specifically developed for 3D scanning objects in reality which is converted into virtual 3D objects to scale, which aim to match real-world dimensions. A laser is emitted onto the environment, which creates a lighting pattern. The sensor then collects the reflected light to generate the depth sensing data. The distance from the sensor to the target is also calculated through the use of sophisticated algorithms. An output stream of infrared is projected onto the target real-life object/environment, where image processing algorithms are used to construct the geometry and pattern of the target object in order to create 3D scene/model. Another patented 3D scanning device developed by Zuccarino and Rafii [270]. This detachable scanning sensor requires users move the sensor device around the target object, to construct a 3D model, similar to that of the structure sensor [269].

Using such technology is, however, outside the scope of this research as training would be needed, particularly for the older adult user cohort, to scan the environment proficiently in the most optimal way that does not affect the accuracy of measurements. This would also affect user experience, and acceptance of technology, particularly for older adult patients as the scanning actions of real-life objects would need to be standardised in a way that guarantees reliable collection of measurements based on the 3D models [271]. While these techniques could perhaps be used to measure different furniture in the home automatically, the scope of this research was to augment the 2D guidance tools to improve intuitiveness/interpretation by using the benefits of 3D visualisation (as demonstrated in the literature study examples above). The purpose of this research is also to standardise the heterogeneous measurement guidance techniques by using 3D visualisation technology as a means to better present realistic illustrations of clinical measurement guidance. Translating the measurement guidance in an environment that is significantly intuitive thus affording patients the means of data collection should be understood and explored, before automating manual aspects of the EFAP. The findings that, therefore, emerges from this research could perhaps be looked at as a precursor to investigating 3D scanning to automate recording measurements as future research (discussed in more detail in section 9.5).

4.1.5 Clinician perceptions and acceptance of technology

Designing usable tools and applications and functionality aligned with the needs of the user are as important as the innovation itself [272, 273]. Patients and practitioners are more likely to engage with and adopt new technologies in practice if they are usable and are perceived to be compatible with their needs [274, 275]. Therefore, when developing technology-based healthcare applications, it is crucial that clinicians' needs and perceptions are understood and incorporated into every stage of the design and development process [276]. User-centred design methods [272] and technology adoption theories, such as the technology acceptance model (TAM), provide a means of gaining valuable insights into the factors that must be considered to ensure users adopt, accept and use new technologies and that these are incorporated into the design of that technology [196]. Until recently, TAM has been used predominantly in a quantitative context; however, increasingly the high-level TAM constructs, such as perceived usefulness (PU) and perceived ease of use (PEOU), are informing deductive qualitative user-centred design research on the incremental design and development of technological health innovations [72].

Considering the equipment abandonment issues faced by the current EFAP, issues relating to inaccurate measurement of furniture, and the subsequent 'lack of fit' of AE to the environment and patient, there is a need explore the potential value of utilising 3D visualisation technologies to aid the process of carrying out key measurement tasks as part of the EFAP. It should be noted, however, that equipment abandonment does not only occur because of inaccurate measurement or poorly prescribed equipment. There are a range of complex personal reasons involved, including perceived poor fit between the equipment and lifestyle, lack of volition to engage with rehabilitative activities, or desire to retain an un-adapted home environment [277].

Given the heterogeneous measurement-taking techniques used by OTs across the NHS that impacts equipment fit to the patient and their environment primarily as a result of the limited dimensions of existing 2D paper-based forms, calls for an alternative solution for more accurate assessment to be developed. As discussed previously, the existing paper-based tools provide measurement guidance in the form of 2D representations of home furniture and the patient. The key function of the 2D representations is to help the clinician to identify the precise points within 3D space that must be measured, on each respective item of furniture/patient and to make an unambiguous record of these measurements with a view to accurately calculating and prescribing AE that will facilitate ADL and mitigate the risk of falling [17]. Notwithstanding their benefits, these tools, however, are likely to lead to misinterpretation of the measurement guidance as the object it aims to resemble is represented in a space/area with limited dimension, which could cause the designated areas to be missed, resulting in the recording of inaccurate measurements. Therefore, as seen from the literature example studies given in section 4.1.4, the benefits that 3D visualisation technology provides could help to resolve such issues with limited dimensionality.

Employing the 3D visualisation technology could augment the existing EFAP 2D paper-based forms by assisting OTs to sufficiently visualise 2D measurement guidance illustrations in a more interactive and perceivable manner, through a prototype that can be easily transported for reporting of assessments around the home. Furthermore, by enhancing visualisation of measurement guidance utilising 3D visualisation, absence of standardised guidance impacting the accuracy in measurements, heterogeneous measurement-taking techniques and insufficient visualisation of 2D paper-based tools could be addressed in the EFAP. Consequently, promoting standardisation for measurement-taking and support OTs to better interpret the guidance could lead to more accurate measurement-taking. 3D visualisation, therefore, has the potential to provide sufficient visualisation of measurement guidance by virtual representations of the key furniture items found in the home along with mechanisms to help OTs localise areas to consider measuring and record the measurements in a less error-prone way. This also provides the opportunity for OTs to better interpret what is to be collected as part of assessing patients in their home environment in an acceptable and standardised means that is currently absent in the existing 2D illustrations in the paper-based tools. Effective use of such solution has the potential of improving OTs taking accurate measurements so that suitable equipment is prescribed to patients, thus potentially reducing the abandonment rates, and implications to the healthcare and social care services and quality of life.

In order to explore the feasibility of mobile 3D visualisation technology as a means of addressing the visual limitations of 2D EFAP measurement guidance paper-based tools, the aims of this study respond to objective O3 outlined in Chapter 1, section 1.3, and are two-fold. First, *to develop and present a bespoke 3D mobile application prototype that provides EFAP measurement guidance to OTs via the use of 3D visualisation technologies*. Second, *to explore OTs perceptions of the prototype application, particularly with regard to its usability and the feasibility, challenges, and opportunities of its utilisation to support the EFAP in practice*. This chapter is structured as follows: Section 4.2 presents the details of an initial concept design phase deployed with OTs and provides a detailed walkthrough of the 3D mobile measurement guidance application. Section 4.3 presents the methods and the main study which was conducted with OTs to explore utilisation of the 3D mobile application within the EFAP in practice. Section 4.4 presents the results of the main study. Section 4.5 outlines and discusses the key findings and proposes future design considerations and implications for deployment of the application in practice. Conclusions are drawn, and details of future work are provided in section 4.6.

4.2 Initial conceptual design and application walkthrough

As a first step towards developing the Guidetomeasure-beta application, an initial user-centred conceptual design phase was undertaken to ensure that the design and functionality of the application was aligned to the needs of clinicians. Three interaction designers, five older adults and eight OTs currently utilising the 2D paper-based guidance to support the EFAP took part in this phase. Figure 4-3 presents the protocol of the initial conceptual design phase. A sample of existing *2D paper-based measurement guidance* leaflets were provided for participants to use as a point of reference during the *conceptual design phase*. OTs were asked to reflect upon their experiences of using paper-based measurement guidance leaflets as part of their role.

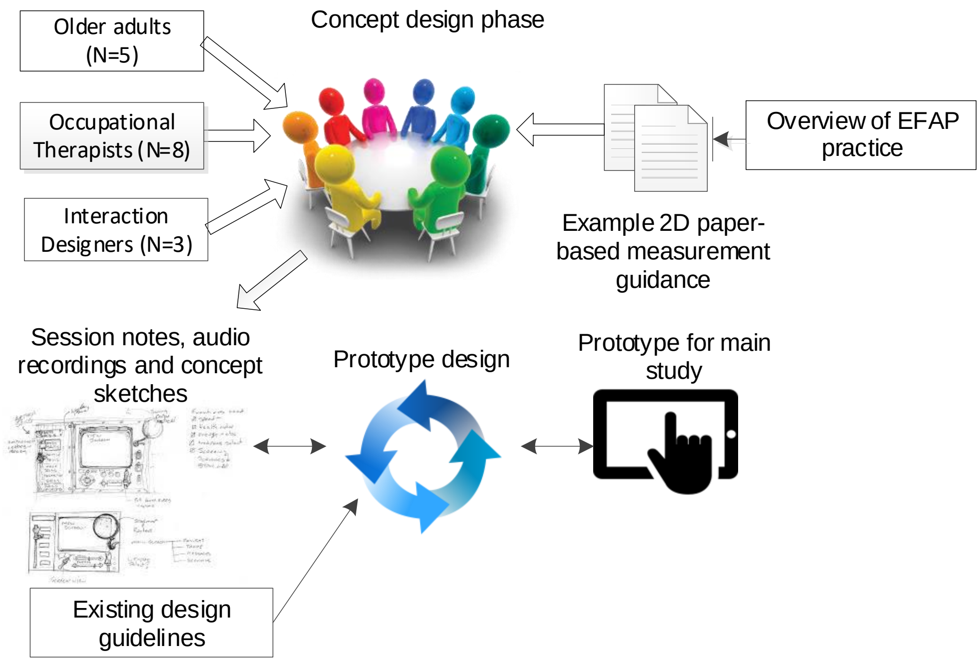


Figure 4-3: Overview of the protocol for the initial concept design phase.

They were also shown a low fidelity prototype application which demonstrated how 2D representations of the patient and furniture could be presented using 3D visualisation technology, deployed on a tablet, smart-phone, or laptop. Participants were asked to explore the idea of using a software application to assist in the EFAP and to suggest the key features and functionality that they believed would be necessary if it was to replace paper-based leaflets. Furthermore, alongside the interaction designers, participants were encouraged to develop annotated concept sketches of a potential application interface and associated requirements and functionality. Figure 4-4 provides an example conceptual design sketch produced during a participatory design session.

Once all participatory design sessions were completed, notes and recordings of the sessions and the annotated concept sketches were perused and used to inform the design and development of the Guidetomeasure-beta application. A total of 8 user requirements (UR1-UR8) were identified as a result of this concept design phase. Table 4-1 presents the key design requirements that emerged from these sessions.

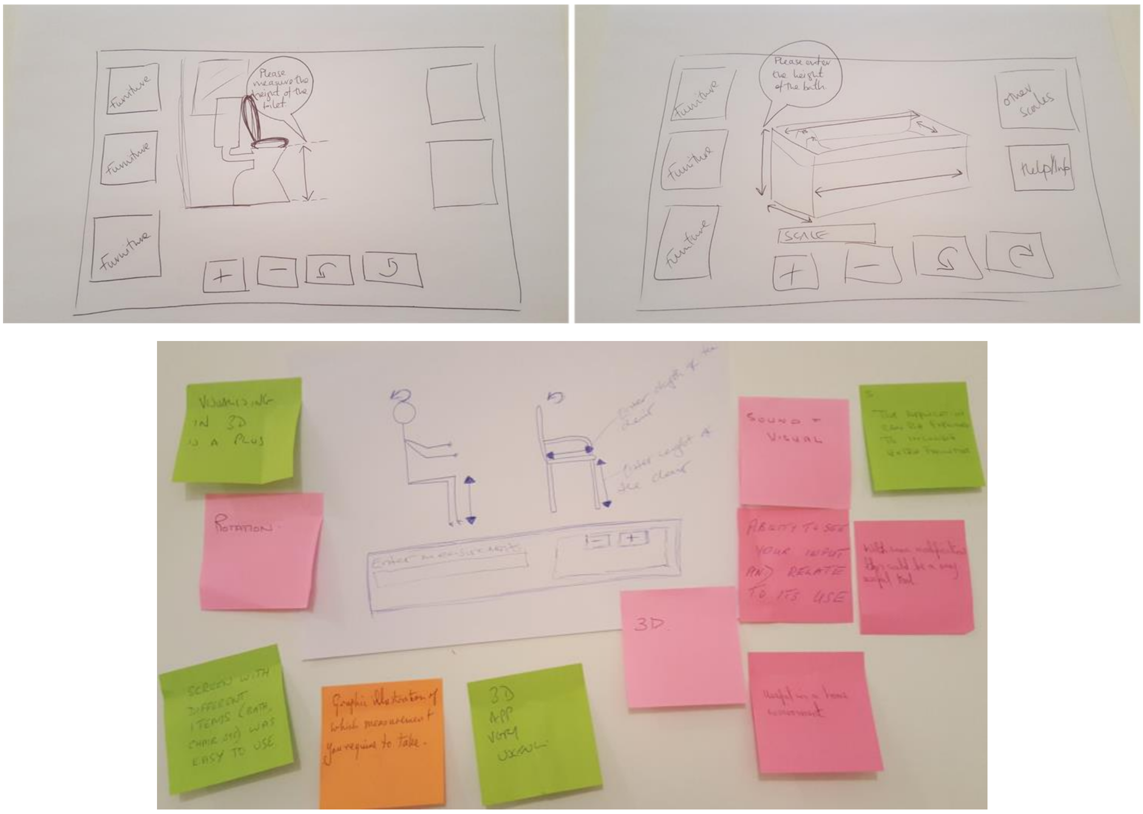


Figure 4-4: Concept sketches produced during the participatory design sessions with Occupational therapists and older adults.

Table 4-1: Participatory design meeting user requirements.

User and system requirements
UR1. Digitally record measurements on a 3D representation of the item
UR2. Clean and user friendly UI
UR3. Rotate and zoom the 3D furniture models
UR4. Provide arrow prompts to input measurements
UR5. Generate assessment reports
UR6. Merge assessments and prescriptions with patient records
UR7. Implement on range of mobile platforms
UR8. Provide audio cues that instruct/guide users to measure effectively

4.2.1 The Guidetomeasure-beta application: System Walkthrough

The Guidetomeasure-beta application used in this study has been developed taking into account the user requirements that emerged from initial conceptual design phase and in accordance with the 3D visualisation guidelines found in the literature [278, 279]. Clinical users are one of the primary users of the proposed app. The system architecture and an application walkthrough are presented in this section.

4.2.1.1 System architecture

The deployment platform chosen for Guidetomeasure-beta is the Android operating system (OS). This is an open source platform freely available for commercial and personal use. The application may be deployed on a range of devices, including mobile phones and tablets that are running an up-to-date version of Android OS. To support other required platform migrations in the future, the prototype was developed using a Unity3D game engine that allows multiplatform deployment, including Android, IOS and Windows *(UR7)*. The system architecture is presented in Figure 4-5.

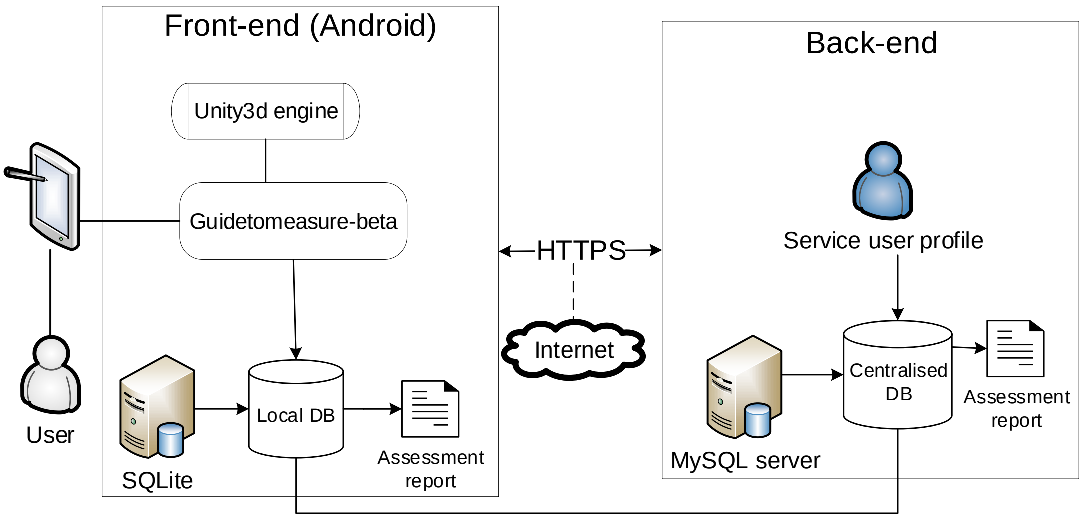


Figure 4-5: Guidetomeasure-beta system architecture.

The key input mechanism/user interface used for the application is the standard touchscreen interface provided by mobile Android devices. Users input measurements via the standard Android virtual touchscreen keyboard. Measurement data is stored temporarily in a *local database* (DB) on the device in order to account for situations with limited wireless and/or mobile network connection. The stored data is then transmitted by hypertext transfer protocol (HTTPS) to a *centralised MySQL DB,* which is in an encrypted format and accessible only to authorised clinical users. Initially, the clinician sets up a *service user profile* before conducting their home assessments. All measurements are saved to a local DB and mirrored across to a centralised DB. The data collected includes details of the service users' functional ability, personal and furniture item measurements, their ability to transfer to and from furniture, as well as lying-to-stand transitions *(UR6)*. Clinicians also have the option of generating an *assessment report (UR5)*.

4.2.1.2 Application walkthrough

The Guidetomeasure-beta application integrates all the user requirements identified in the conceptual design sessions. A crucial feature of Guidetomeasure-beta is the visualisation of the measurement guidance, based on the paper-based leaflets currently in use [10, 280-283]. The prototype application did not include a facility to assist in taking measurements of the patient, but rather primarily focused on furniture measurement. The application displays 3D models of the five items most commonly measured as part of the EFAP (bed, bath, toilet, chair and stairs) and are also known to be most frequently associated with falls in the home environment [284]. Measurement guidance for each respective item is accessed via the main menu shown in Figure 4-6 (UR2).

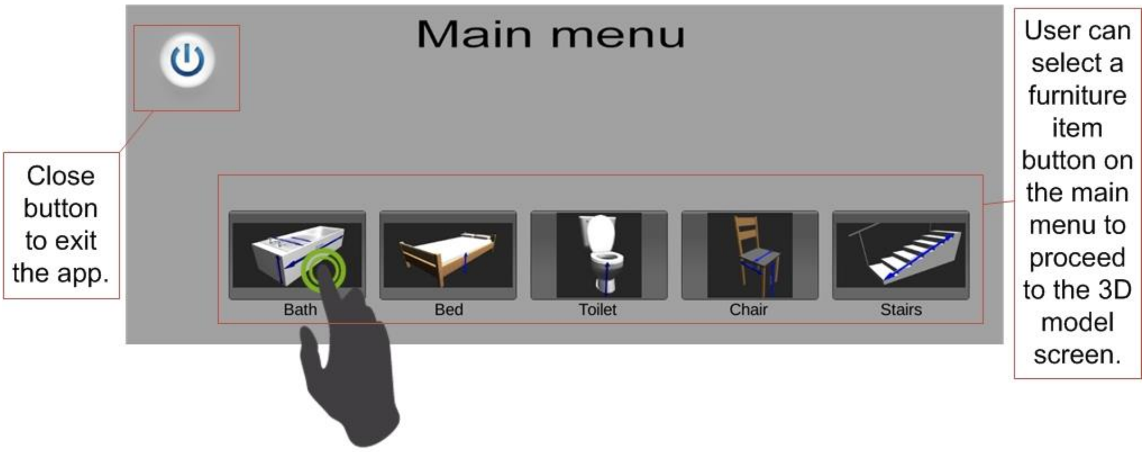


Figure 4-6: Guidetomeasure-beta application's main menu.

After selecting an item of furniture from the main menu, a representative 3D model of the chosen item is presented to the user, along with arrows that are superimposed onto the item which serve as prompts to indicate the discreet points on the furniture items that need to be measured (UR4). An example of the bath scene is presented in Figure 4-7. The measurement guidance is presented using two prompt features: 3D arrows (as mentioned above) and audio instructions, which guide the user to provide the necessary measurements (UR8).

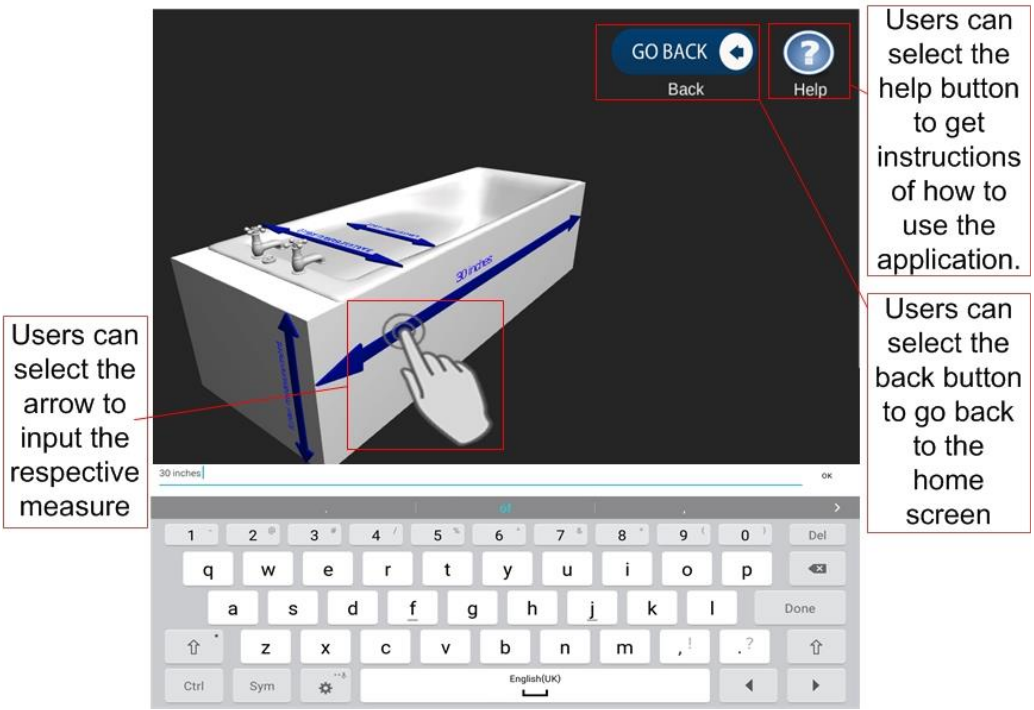


Figure 4-7: Bath measurement guidance interface.

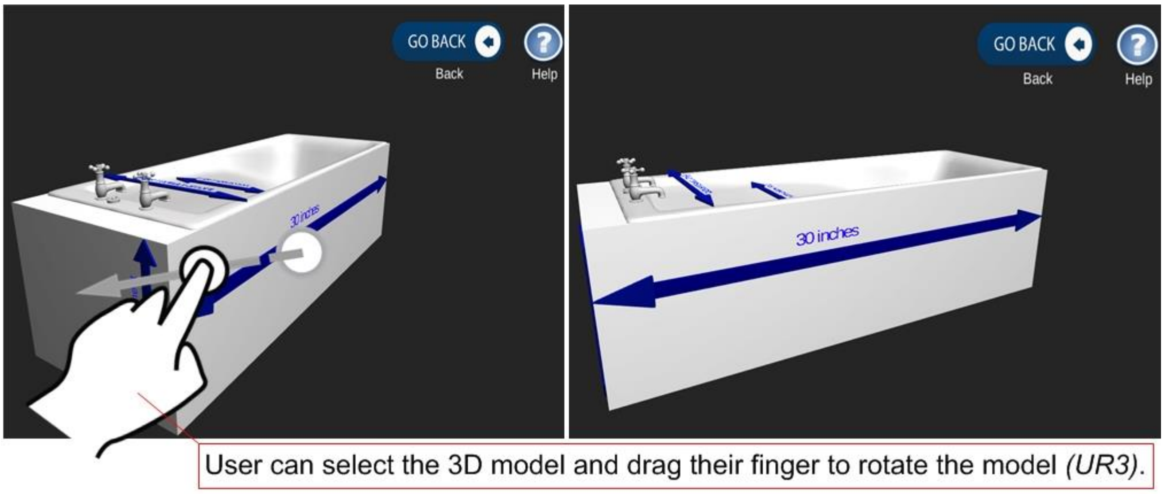


Figure 4-8: Rotation feature before rotation (left) and after rotation (right).

Users can rotate the 3D furniture models to view discreet areas of interest in detail. To do so, the figure swipe gesture input was employed, which enabled rotation of the models (UR3). Figure 4-8 presents an example of rotating one of the models clockwise by swiping horizontally to the left. Another key component of the design is the zoom-in and zoom-out feature, which changes the viewpoint and perspective and provides for a more detailed look at the 3D furniture models. The ‘pinch gesture’ is used to achieve this *(UR3)*. An example of this function is presented in Figure 4-9.

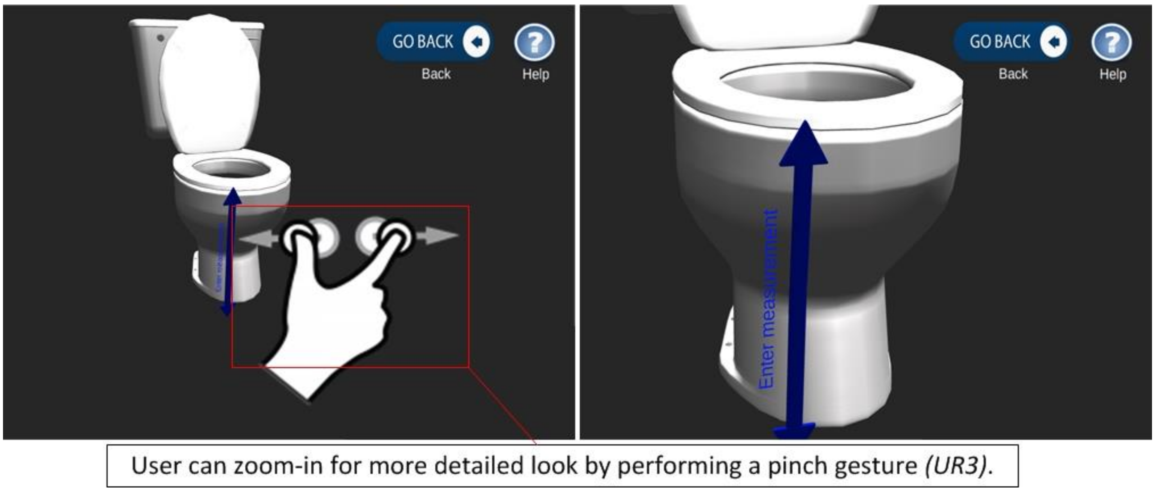


Figure 4-9: Zoom in/out to facilitate better clinical guidance.

The application enables users to input home furniture measurements via the use of the arrow prompts augmented with sound instructions *(UR1)*. The application is flexible in relation to the interface used and the visualisation capability and audio cue options provided to clinicians are also optional for users who have grasped the use of the application and no longer require audio assistance.

4.3 Methods

This section provides details of the data collection and analysis methods used to explore the perceptions of OTs regarding the use of the Guidetomeasure-beta application within the EFAP in practice. Figure 4-10 presents an overview of the study design.

4.3.1 Participants

A purposive sampling strategy was used for this study, which involved a total of 10 OTs. Participants were recruited via a range of sources, including online OT groups on social media networking websites (e.g. Facebook and LinkedIn), and by approaching local social service departments, NHS trusts, and specialist fall services. Candidates were initially sent an email invitation to take part in the study, with a £10 voucher offered as an incentive. The inclusion criteria were that participants were required to be practicing OTs, had relevant clinical experience of carrying out home visit assessments, prescribed assistive equipment, and had familiarity with using a smart-phone, tablet, or desktop computer. The sample size of 10 participants is in excess of the five-user assumption typically considered as a reliable guideline for carrying out usability and interaction design studies [285].

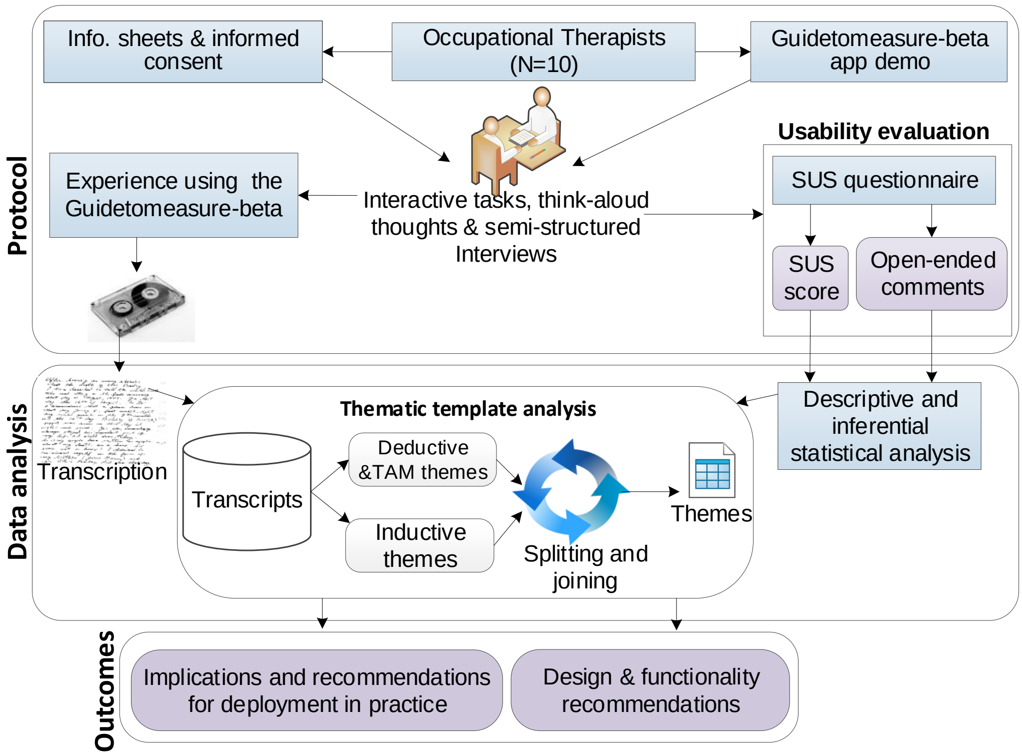


Figure 4-10: Overview study design.

All participants were female, which, to a large extent, reflects the female-dominated OT profession [286]. Table 4-2 presents a summary of participant profiles.

Table 4-2: Summary of participant profiles.

Part. ID	Gender	Years Exp.	Specialty
P1	F	>31	Adults of all ages
P2	F	>10	Social services
P3	F	>5	Surgical rehab.
P4	F	>5	Neurology therapy
P5	F	>20	Rehabilitation
P6	F	>10	Neurology
P7	F	>1	Neurology
P8	F	>2	Neurology
P9	F	>5	Re-ablement
P10	F	>15	Social services

4.3.2 Protocol and instrumentation

Participant sessions were conducted on a one-to-one basis and were approximately 90 minutes in duration. *Informed consent* was obtained at the start of each session. Initially, participants were given a brief demonstration of the Guidetomeasure-beta application and were shown how to use the key functions of the application, record measurements, and generate assessment reports. Participants were then asked to use the application and were given written instructions outlining a series of interactive tasks to be carried out. Concurrently, the think-aloud technique was used to capture participant thoughts and preferences in real-time whilst interacting with a software application [287]. This involved encouraging participants to share their thoughts about the Guidetomeasure-beta application whilst interacting with it. Prompts such as “what are you thinking?” and “what are you doing now?” we used if extended periods of silence were observed. The *interactive task* involved measuring home furniture items. Table 4-3 presents the key steps involved in interacting with the Guidetomeasure-beta application.

Table 4-3: Written instructions for the interactive task.

Instruction sheet for participants
Start the application
Select a home furniture from the main menu screen
Rotate 3D model left or right and up or down
Zoom in and out using the pinch touch gesture
Click on arrows to activate the audio prompt
Measure the 5 home furniture items
Enter measurements using the virtual popup keyboard
Click on the main menu button (move on to the next furniture item)

On completion of the interactive task, participants were asked to complete a *System Usability Scale (SUS) questionnaire* [288], which was used to gain insight into the usability of the prototype application. The SUS is comprised of 10 statements which users rate on a 5-point Likert-type scale ranging from 1 (‘strongly disagree’) to 5 (‘strongly agree’). After completion of the SUS instrument, each participant was asked to discuss the score they attributed to each SUS item. *Semi-structured interviews* were subsequently carried out with each participant at the end of the interactive sessions, which lasted approximately 20-25 minutes (mean=22.4 minutes) each. Participants were encouraged to reflect upon the experience of using the application, the functionality they found useful, challenging or required improvement and to discuss the feasibility, challenges, and opportunities of using a Guidetomeasure-beta application as an assistive tool in practice. The interview questions were designed to enable participants to provide their feedback and experiences through open-ended discussion in order to investigate the EFAP in more depth and the potential ways that the application may be successfully integrated; in addition to identifying their particular needs for better visualisation of guidance. All interviews were recorded and transcribed verbatim.

4.3.3 Data analysis

Statistical analysis of SUS responses was carried out using IBM SPSS v 20.0.0. Initially, the approach presented by Bangor et al. [289] was used to analyse and interpret the SUS scores. This involved calculating a SUS score from the completed questionnaires and generating a value on a 100-point scale which could then be mapped to descriptive adjectives (Worst Imaginable, Poor, OK, Good, Excellent, Best Imaginable), an acceptability range (Acceptable, Marginal, Not Acceptable), and a school grading scale (i.e. 90-100 = A, 80-89 = B etc.). These baseline ranges and gradings are derived from a sample of over 3000 software applications, which provide the comparative baseline [289]. Furthermore, Lewis and Sauro [290] propose that SUS is composed of a two-factor structure in which two sub-scales - namely Usability (SUS items S1, S2, S3, S5, S6, S7, S8, S9) and Learnability (SUS items S4, S10) - underpin the SUS instrument. Additional statistical analysis was performed using one-sample *t*-test to establish whether there were significant differences between the respective mean SUS scores and the mid-point value of three (of the five-point Likert-type scale responses) for each individual SUS item and for the Usability and Learnability constructs.

Transcripts of audio recordings of the interactive task sessions and semi-structured interviews were subjected to thematic template analysis. This is a qualitative analysis method used for searching and identifying themes that occur within textual datasets [291]. Using this method enabled patterns in the dataset to be identified and categorised. Analysis of the semi-structured interview data was both inductive, as the development of the themes was data-driven, and deductive, beginning with pre-defined (*a priori*) themes that are theory-driven and linked to the analytical interest of researcher(s) [235]. The first stage involved creating a template which used the pre-defined codes specified by the Technology Acceptance Model (TAM). Hence, analysis considered the participants' perceptions of the Guidetomeasure-beta application in the context of the two high-level TAM themes; Perceived Usefulness (PU) and Perceived Ease of Use (PEOU), and themes that emerged in addition to these. The entire dataset was then read, and comments were assigned iteratively through several stages of splicing, linking, deleting, and reassigning sub-themes within each pre-determined high-level theme.

4.4 Results

This section presents the results of the analysis of the SUS, think-aloud, and semi-structured interview data.

4.4.1 SUS evaluation

The overall SUS score for the Guidetomeasure-beta application was 85 (85 out of 100) ($SD = 5.6$), which, according to the evaluation criteria for SUS [289], indicates that the application delivers 'excellent' (Descriptive adjective), 'acceptable' (Acceptability range), and 'Grade B' (School grading scale) levels of usability. An analysis of SUS Usability and Learnability revealed that both constructs achieved mean scores significantly above the neutral mid-point value of 3.00, of 4.56 ($p = 0.000$) and 4.85 ($p = 0.000$) respectively. This indicates that users were positive about the Usability and Learnability of the application. The Cronbach measure of consistency for both constructs was above the threshold of acceptable reliability of 0.6 for small sample studies [292]; however, items S1, S5 and S8 were removed to reach the consistency threshold. The result of individual SUS items, compared against the mid-point, is presented in Table 4-4.

Table 4-4: Mean SUS score and Mid-point comparison.

SUS item	Mid-point	Guidetomeasure-beta	Gap score	Df	t-value	*P*-value (2-tail)
S1: Use Guidetomeasure-beta frequently.	3.00	3.20 ±1.14	0.20	9	0.55	0.591
S2:Unnecessarily complex.[a]	3.00	4.60 ± 0.52	1.60	9	9.80	0.000*
S3: Easy to use.	3.00	4.60 ± 0.52	1.60	9	9.80	0.000*
S4: Support of a technical person[a]	3.00	4.80 ± 0.42	1.80	9	13.50	0.000*
S5: The various functions were well integrated.	3.00	3.30 ± 0.95	0.30	9	1.00	0.343
S6: Too much inconsistency.[a]	3.00	4.00 ± 0.94	1.00	9	3.35	0.008*
S7: Learn to use Guidetomeasure-beta very quickly.	3.00	4.60 ± 0.52	1.60	9	9.80	0.000*
S8: Cumbersome to use.[a]	3.00	4.30 ± 0.95	1.30	9	4.33	0.002*
S9: Confident using Guidetomeasure-beta.	3.00	4.60 ± 0.70	1.60	9	7.24	0.000*
S10: Learn a lot of things before using Guidetomeasure-beta[a]	3.00	4.90 ± 0.32	1.90	9	19.00	0.000*

[a] Responses of negative items were reversed to align with positive items
*Indicates statitisically significant <= 0.05 confidence level

All mean scores were above the mid-point, indicating that, overall, participants tended to be positive about the 3D application. In statistical terms, eight of the ten SUS items (S2-S4, S6-S10) were significantly higher than the mid-point benchmark. Although items S1 and S5 were above the mid-point benchmark there was no significant difference between the means and mid-point.

Item S1 asked participants to report how frequently they would like to use the application. While the mean score was higher than the mid-point benchmark, the difference was not significant (mean = 3.20, p = 0.591). There were mixed opinions about using the application frequently. Some OTs expressed an interest in its regular use provided that they had access to a tablet computer. Others suggested that the application required additional functionality before it could be fully incorporated into daily OT work activity, such as assisting in the task of recommending items of assistive equipment.

> *"... if it's around, I would use it, purely because you know I've not got scraps of paper…and also provided that we have a tablet, which we haven't got." (P5)*

> *"As the application stands...I don't think I would use it. If it was providing…a more visual impression to somebody in 3D…so I'm showing them a virtual drawing of what the rail is going to look like beside their bath…then possibly yes." (P1)*

Results for S2 revealed that participants were positive about the application and tended to disagree that it was unnecessarily complex (mean = 4.60, p = 0.000). The application's purpose appeared to be clear to participants; however, one participant working with patients with complex needs felt that additional functionality - such as a note-taking facility - would be a useful addition.

> *"It's not complex, what it's lacking is the complexity. So as an OT, I'm looking into so many little details, so for example, I'm working in neurological ward at the moment, I need to consider so many abilities, disabilities of the patient, risks, that one, two, three measurements per furniture might not cover...I would have to write extra notes about that piece of equipment and extra take measurements because this wouldn't give me enough information later on." (P6)*

Responses to S3, relating to the application's ease-of-use, were significantly higher than the mid-point (mean = 4.60, p = 0.000). Participants noted that the written instructions and audio cues provided by the application were basic but effective, and that, overall, it was easy to use. Some expressed concerns about the alignment of measurement arrows for the chair item, which they felt provided ambiguous guidance.

> *"Some of them I was doubting. What do you want me to measure, the width of the chair with the arms...or just the seat…it was somewhere in between, the arrow, so that wasn't very clear, but otherwise using it...that's very easy." (P5)*

For S4, participants tended to disagree that there was a need for a technical person to be able to use the application (mean = 4.80, p = 0.000). One participant commented that it could even be used without a demonstration (P9). However, there was a feeling that technical support should be available if the application malfunctioned.

> *"No, I'm OK with technology, so, and that was fairly easy…but I think a normal person would be able to manage." (P9)*

> *"If it went wrong you…you'd like to know there was somebody on the end of the phone." (P6)*

Mean scores for S5 were only marginally above the mid-point (mean = 3.30, p = 0.343). Explanatory comments relating to this statement revealed that whilst the application provided the necessary measurement guidance, it needed additional functionality such as the enabling the recording of additional information to supplement/contextualise the recorded measurements.

> *"Yes, you've got the measurements for certain things but…I'd still need to have paper to write down all the additional information ...it would be good to have it in one place." (P4)*

Participants tended to disagree with (S6), the statement that there was too much inconsistency in the application (mean = 4.00, $p = 0.008$). However, some participants did suggest that the application would benefit from additional features, such as the ability to create bespoke measurement arrows.

Participants strongly agreed with S7, that people could learn to use the application very quickly (mean = 4.60, $p = 0.000$). However, one participant noted that some older adults might struggle if they were not familiar with touch-screen devices.

> *"... if you were asking...somebody older, it's not true of all older generation but just some people who aren't familiar with that type of technology might struggle a bit more with it." (P4)*

Participants tended to disagree with S8; that is, the notion of the application being cumbersome to use (mean = 4.30, $p = 0.002$). The application interface tended to be perceived as simple in design with intuitive features and clear measurement instructions.

> *"I think it's quite simple in design. It's quite clear what object you're measuring...and easy to learn, easy to remember how to use it." (P8)*

Participants tended to agree with statement S9; that they were confident about using the application (mean = 4.60, $p = 0.000$). The ability to change measurement values (as opposed to 'cross-out' paper-based values) was a factor that helped participants to have confidence when using the application.

The results for S10 indicates that users disagreed with the notion of having to learn a lot of things prior to using the application (mean = 4.90, $p = 0.000$). In particular, participants commented that the application was user-friendly; however, some emphasised that a basic understanding of touch-screen technology was a prerequisite for using the application.

> *"If they've got kind of a basic understanding of technology, are able to use it, then yeah, it's very user-friendly." (P4)*

4.4.2 Semi-structured interview results

Four high-level themes and numerous sub-themes were identified as a result of the thematic analysis of the think-aloud interactive task data and semi-structured interview data. These are: (1) perceived usefulness; (2) perceived ease of use; (3) application use; and (4) application functionality. Figure 4-11 presents a thematic mind map of the key themes and sub-themes.

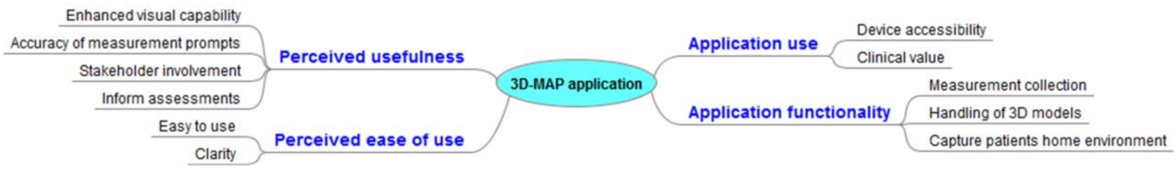


Figure 4-11: Thematic mind map of key themes and associated sub-themes.

Perceived usefulness

Participants reported that they were satisfied with the *enhanced visual capability* of the 3D application, compared with the equivalent 2D diagrams presented in paper-based measurement guidance leaflets. In particular, they highlighted that the 3D models seemed to offer a more realistic representation of the item they were measuring and aided them to better comprehend the precise measurement locations. Some participants believed that the visual clarity of the 3D visualisations could also help to improve patient's understanding of measurements taken and how the process translated to fitment of assistive equipment in the home. However, the application in its current form does not show how assistive equipment fits onto items of home furniture; or, indeed, how these fit within the context of the home environment. This is a function which some participants felt would enhance its usefulness.

> *"..it was useful looking at a 3D model, rather than just you know a flat model…as an OT you're kind of used to doing it flat but…if service users are (going to look at it) it's good to see it in 3D, it's more easy to understand" (P5)*

> *"…so they can have a look and then look at the 3D dimensions, it might give people a better idea." (P9)*

Some participants were of the opinion that, whilst the look and feel of the 3D models were a significant improvement, the *accuracy of measurement prompts* was lacking in some respects, which could affect how the measurement guidance is interpreted and impact negatively on the reliability of the data collected.

> *"… Some of the arrows were not working when pressed and I think it could have done with more aligning…you know, showing you exactly where you measure from." (P4)*

Participants felt that the use of the application would support enhanced and wider-ranging *stakeholder involvement* in the EFAP. For example, it was considered that the application could be used by patients' family members or carers, who may be able to take furniture measurements on behalf of the service user. The application was also seen as having potential educational value for OT students to practice and familiarise themselves with measurement tasks.

> *"I would use it to give it to family members to measure things." (P7)*

> *"As the application is now, probably it would be useful for OT students, you know just like for practice, to get used to measuring and recording measurements" (P6)*

It was also suggested that, whilst the application may not necessarily make the act of carrying out measurements any easier, it would have value helping to *inform assessments*, i.e. provide more effective prompts to ensure the relevant dimensions of items are measured and collected in accordance with existing guidelines.

> *"It could serve as a prompt. I don't know if it would make measurements...any easier, but I think it would help." (P7)*

Perceived ease of use

Overall, participants felt that the 3D application was *easy to use*. However, one participant believed that the rotation of the 3D models was awkward, especially to get the model back to its original starting position. Consequently, it was suggested that a feature to reset the 3D model position was incorporated.

> *"Yeah, fairly easy, just the rotation was a little tricky to kind of get it back to normal view. Maybe if you had a button to reset it back to what it was when you first moved it." (P5)*

Participants noted that the *clarity*, look and feel of the application, and the instructions it provided were clear. In particular, the icons on the main menu clearly indicated what each section included (participant P4).

> *"I think the simplicity...all you do is add a number basically (a measurement) and the visuals are very clear." (P4)*

Application use

Benefits of using the application compared to paper-based approaches were also highlighted. Some participants expressed their intention to use the application but stressed the need for *access* to a tablet if they were to be able to use it in practice.

> *"I thought it was easy to use and not more complicated certainly than a pad or a form that you would otherwise fill in by hand. So yeah, the simplicity of it I think is making it user-friendly. I would use it…is this only available on a tablet because we don't have access to these" (P9)*

It was also suggested that using the Guidetomeasure-beta application in practice could be of *clinical value* to collaborate with other clinicians and service users. More specifically, it was felt that the application would be useful for handing over a case to another OT. Value was also seen in integrating recorded measurements with other information such as assessment notes about service users, which would save time and effort.

> *"I think if it incorporated more of the whole report thing, so you weren't kind of having to go from paper to tablet, then definitely, it would be even better" (P7)*

> *"Sometimes, like if I want to order rails for instance, I'll take a picture, go back, e-mail it to myself and then go on to paint and draw a rail on top of the picture and then send it to the equipment company. So...if I could just screen shot that rail on the bathroom, then that would make my life easier!" (P8)*

Application functionality

Participants felt that using the Guidetomeasure-beta application would provide clinical value and were enthusiastic with respect to *measurement collection*, which, with the help of the application, could be done in a more standardised and systematic fashion. Some additional application features were suggested, particularly with regard to enabling better control and *handling of the 3D models* within the application. Some participants expressed a need to include a function to photographically *capture patients' home environment*, particularly the item being measured, so that there was a pictorial record as a point of reference alongside the annotated 3D model of the furniture item. It was felt that having photographic records of the item - ideally in its context within the home - would help shed light on issues that may later feed into the decision-making of selecting assistive equipment.

> *"If there could be a photo, capturing more information, possibly that might be useful more than me asking them or writing and drawing on a piece of paper." (P6)*

4.5 Discussion

This study presented a mobile application which uses 3D visualisation technology, designed to guide and assist OTs in the taking and recording of measurements as part of the extrinsic fall-risk assessment process. A total of 10 OTs used the Guidetomeasure-beta application to engage in a measurement task of home furniture known to be associated with falls and routinely measured as part of the EFAP. The analysis of the quantitative SUS data revealed that the sample attributed a score of 85/100 to its Usability, indicating that the application may be described as 'excellent', delivering 'acceptable', 'Grade B', levels of usability overall. In terms of the two SUS sub-scales, OTs also tended to strongly agree with statements related to the Usability and Learnability of the application. The SUS results highlighted a general consensus that the application was easy to use and that learning to use it was also straightforward. These are promising results, and it is likely that the early conceptual design phase and participatory design sessions conducted with a separate sample of OTs, played an important role in ensuring that the Guidetomeasure-beta application was fit for purpose and able to generate a range of comments about the overall concept of using 3D visualisation technologies during the main trial, as opposed to being related to fundamental usability issues only. Analysis of the individual SUS items and associated open-ended comments, along with think-aloud and semi-structured interview data, provided detailed study outcomes on the perceived feasibility, usability, challenges, and opportunities of the application being deployed in practice. Table 4-5 presents a summary of the key study outcomes and categorises these in terms of implications for deployment in practice and design and functionality recommendations. Each of these outcomes are mapped to their respective sources, i.e. individual SUS items (S1-S10) and/or the high-level inductive and deductive themes that emerged from the analysis of the semi-structured interviews (PU; PEOU; AU; AF).

In terms of *implications and recommendations for deployment in practice,* OTs reported that they felt that the application could be used in practice without the need for technical support, assuming that there was no malfunction (S4). The interface was perceived as being clear (S2, S8), consistent (S6), and easy to use (S3), and requiring minimal levels of effort to learn how to utilise key features and functionality (S7). Interestingly, it was suggested that even 'a normal person would be able to manage with the app' (S4) implying that there may be scope for non-OT engagement with application, such as by service users, care givers, or other healthcare professionals. It was also submitted that the use of such an application could help to enhance collaborative practice (AU) in a team of clinicians; for example, when handing over referrals or to enable patients to take measurements of their own, which in turn could be used to inform shared decision-making related to assistive equipment prescription. The notion of empowering patients to take their own measurements has become an important emerging area of interest in the field of occupational therapy and within the EFAP, particularly given increasing constraints on healthcare sector budgets [293]. This finding, in particular, supports the personalisation agenda which advocates the delivery of home-based

Table 4-5: Study outcomes, implications and recommendations.

Areas of focus	Study outcomes	Source
Implications and recommendations for deployment in practice	Clear and usable application without the need for technical expertise/support	S2- S4,S6-S8
	Valuable tool to facilitate collaborative practice and inter-professional handover	AU
	Enhanced visual quality of home furniture measurement guidance	S1, PU
	Systematic, organized solution which instills confidence	S1, S9
	Standardised furniture measurement guidance, clear instructions	PU, PEOU, S3
	Explore use by alternative users including care givers and service users	S7, PU
	Include educational component regarding AE and measurement function	PU
	Access to tablets is necessary in order to use the 3D application	AU
Design & functionality recommendations	Provide improved guidance to make assistive equipment recommendations	S1
	Provide a facility to record notes & assessment data	S2,S5
	Clearer prompts to measure home furniture	S3 & PU
	Clear and more usable controls to rotate 3D models	PEOU
	Additional function to reset the 3D models to its original position	PEOU
	Capture images of the patients environment to provide context	AF, PU

healthcare services and the enablement of older patients to engage in self-assessment practice [294]. Whilst the personalisation agenda promises numerous health benefits to the patient, it is also seen as a strategy to reduce costs and lessen the burden on healthcare systems. Specifically, in this respect, it should be noted that OTs make up 2% of the health and social care sector, with 35% of adult care service referrals having to be handled by them [295]. Although further research is required to establish the extent to which this application is usable by other user types, its realisation would certainly compliment the evident need to move away from the view of the patient as a passive recipient of care, to models where they are responsible for carrying out important aspects of their own care [296]. The observation that the application provides a systematic, organised (S1, PU), and standardised (PU) solution that helps to instil confidence in the user, whilst recording accurate measurements is a positive implication for deployment in practice (S1, S9). The fact that measurements can be input and easily changed, if the initial entry was found to be inaccurate, was seen as a significant benefit over paper-based records. It was felt by most of the participants that the application provided clear prompts of where to measure, using the 3D arrows alongside audio instructions (PU, PEOU, and S3).

Furthermore, use within a health education setting (S7, PU) was suggested, particularly to educate trainee/junior OTs on the practice of measurement. These findings are in line with a recent review that explored the value of 3D visualisation technology for educational health interventions to inform and shape clinical practice in a simulated environment, prior to implementing interventions in practice [297]. This is a particularly important finding given that approximately 50% of assistive equipment prescribed is abandoned [54-56, 284] partly due to the 'poor fit' as a result of misinterpretation of guidance and absence of standardised measurement practice [19, 284]. Due to the heterogeneous practice of the EFAP across UK NHS trusts, and the lack of consensus in terms of practice [298], the 3D application was seen as having potential in improve and standardise the measurement process (PU). The present findings are also supported by a recent study which concluded that there is a need to standardised measurement guidance, particularly for the provision of assistive equipment [299]. Clinicians viewed the Guidetomeasure-beta application as a tool which improved the visual quality and detail/clarity of measurement guidance (S1, PU), constituting an alternative solution to the typical 2D diagrams currently in use across NHS trusts. This finding is consistent with those of past studies by Spyridonis et al. [260], which found that 3D visualisation technology improved the visual quality of 2D paper-based assessments currently in use, visualising and locating exact points on 3D models that are of clinical relevance and importance. Another study found that 3D visualisation enhanced visualisations of patients' movements, highlighting discreet areas to target for rehabilitation exercise programmes [300]. However, one key obstacle to an application such as Guidetomeasure-beta being adopted in practice is the availability of mobile touch-screen devices. Some participants commented that they did not have access to such devices, and, consequently, although the deployment of the application may be desirable, it is not feasible in practice until such technologies are provided. Although this issue is not related directly to the usability/functionality of the application, it still poses a problem to realising the benefits that such applications may be capable of [301].

A significant concern which continues to persist for clinicians is how to successfully integrate new technology in practice. While incorporating the needs and requirements of clinicians into the application was a key lesson learned, issues with using the application in practice (which would require a supporting infrastructure) and the impact of its adoption would need to be addressed and closely studied before its deployment in the field. This supported by previous findings, particularly as the maintenance and deployment of any new technology typically requires changes to the health organisation, delivery of care, and collaboration between clinicians and patients [273, 302]. More broadly, this research is aligned with the UK government's encouragement for clinicians to adopt new technologies and develop associated strategies that respond to on-going challenges in healthcare delivery [69, 133]. Having technology that addresses issues with prescribing the right assistive equipment could have cost-saving implications for the health and social care system [20], providing that adequate training and support is available to stakeholders. Whilst implications that relate to deploying the application in practice have been noted in this study, the application as a component is interoperable; hence, giving some flexibility to clinicians from different health services to develop their own ad hoc solutions via the support of the application and move away from a ‘one-size-fits-all’ approach.

There were numerous *design and functionality recommendations* that emerged from this study, which indicate how the application may be further developed to accommodate the needs of OTs who intend to use the application in practice (and, in doing so, possibly further enhance the application’s functionality). For example, the measurement guidance provided by the current version of the application requires further extension to help prescribe appropriate assistive equipment for the item of furniture that has been measured (S1). Several suggestions were made regarding the need for a facility to record notes in conjunction with the assessment data collected, as the clinical decision-making process for prescribing equipment includes clinicians’ observations of patients carrying out day-to-day activities (S2, S5). Participants expressed the need for clearer visual prompts to measure home furniture items, as some of these appeared to be unclear and/or counterintuitive, which could impact the reliability of users interpreting the guidance for logging accurate measurements (S3, PU). This requirement is particularly important considering that the application was developed to enhance the visualisation of measurement guidance using 3D models and arrows to sufficiently locate end-to-end points on an arrow. Participants expressed that they had trouble rotating the 3D models. Consequently, it is concluded that the controls were counterintuitive and need further development, especially given that older patients may use this application (PEOU). Several further adaptations were suggested, in particular, to better handling for the 3D model by resetting its position, to help remedy the current counterintuitive rotation function (PEOU). There is a need to explore alternative controls that can be implemented to improve the current ones for manipulating the viewpoint/position of the 3D models and better support both patient and clinical users of the application. Furthermore, it should be noted that this prototype Guidetomeasure-beta application did not include a facility to assist in taking measurements of the patient, but rather focused on furniture measurement. Future work should include this additional function and explore how the application may be further developed to ensure an accurate fit between the patient and the prescribed equipment is achieved.

Enabling photographic capture of the patients’ home environment, particularly images of the home furniture items within their real-world context (AF) could provide important information that may be used when prescribing AE. Existing studies in the literature have explored the use of taking images of the patient’s home to provide a visual aid to support clinical decision-making/reasoning and serve as an adjunct to or substitute for the traditional home visit assessment [303]. Interestingly, some participants mentioned using their smart-phones to take photographs during home visits to help with their assessments and the decision-making process for recommendations. This particular feature has been reported in the literature as being a valuable technique within the provision of home visit assessments and AE to explore the feasibility of home modifications and to remotely inspect the home environment for extrinsic fall risk factors [303, 304]. As such, this shows the potential of a photographic feature may have value over and above the provision of detailed guidance for recording measurements.

4.5.1 Limitations

Despite the positive outcomes, this study has identified certain limitations and direction for future work which, therefore, need to be recognised. One limitation of this study is the number of participants which may be considered too small to make any generalisations about the utility of 3D visualisation technology in healthcare more generally. However, these outcomes could perhaps be generalised with regard to the effective use of 3D models, and the perceptions of OTs towards the adoption of such 3D models in visualising clinical guidance for healthcare assessments. Given the somewhat challenging endeavour of recruiting a large number of participants for this study, due, in large part, to the demands and work pressures widely known within healthcare, the sample size, however, exceeded the 5-user threshold essential to gain useful feedback in studies that involve participants interacting with software applications whilst thinking aloud [285]. Further, the principles guiding part of this study were congruent with the qualitative tradition, and as such, data collected in this study continued until the point of saturation [305].

Another limitation noted is that the numbers of male and female participants are not equally balanced, due, in large part, to the field of occupational therapy being a female dominated profession [286]. Despite such limitation, this study provided useful insights of clinicians' perceptions of utilising 3D visualisation technologies to support this area of practice within occupational therapy, as they have a great deal of experience across a number of clinical settings as well as supporting assisted living. Clinicians' were able to provide recommendations to improve on the design and functionality of the Guidetomeasure-beta app and highlight promising areas of its adoption and implementation, as they carry valuable experience of measuring furniture items and are aware of the existing limitations of guidance leaflets. Furthermore, while there were quantitative outcomes that measured the general usability of the Guidetomeasure-beta app, exploring the clinical utility of the application in terms of evaluating its effectiveness, efficiency and accuracy and reliability of recorded measurements against 2D guidance leaflets within a controlled environment could provide further insights, if this application is to sufficiently support clinicians within the EFAP. This line of enquiry should be considered in future, once the application has been further developed and incorporates the needs of OTs revealed in this study.

In relation to the TAM model, the deductive approach implemented in the analysis of qualitative datasets, via the two core TAM constructs, could be considered a limitation of this study. Adopting the thematic template approach in this study may have minimised the coverage of themes that would have emerged if a solely inductive approach was employed. In this respect, the approach enabled the analysis to be partly data driven, as well as focus in more detail on factors associated specifically with technology acceptance, which was in line with part of the aim of this study. It is noted, however, that other alternative candidate frameworks that are descendants of the TAM model, which cover a breadth of dimensions that explain usage intention and usage behaviour of technology, could perhaps be perused to further explore insights into the clinical utility of an improved version of the application [306]. Nevertheless, the TAM model provided a suitable framework in this study through which perceptions of clinicians relating to the adoption of the Guidetomeasure-beta app were interpreted and made sense of.

4.6 Conclusion

This study investigated OTs' perceptions regarding the feasibility, opportunities, and challenges of using the Guidetomeasure-beta application prototype as a measuring tool within the extrinsic fall-risk assessment process. OTs were positive about the application, in terms of its usability by them as part of EFAP practice, and, potentially, other stakeholders such as care givers, trainee OTs and patients. The study also showed that OTs considered that the Guidetomeasure-beta application has the potential to effectively augment existing 2D diagrams and deliver numerous benefits over these. For example, OTs believed that Guidetomeasure-beta enhanced the visual quality of measurement guidance via the use of browseable 3D models, more clearly articulated the discreet points of measurement, and introduced the opportunity for patients and clinicians to engage in greater collaborative practice, and possible easing of the handover process. One of the key challenges to deploying such an application, however, is the lack of availability of mobile touch-screen devices to practitioners. Further research is needed to establish whether such an application could feasibly be used by service users (motivation for study 2 in Chapter 5), family members, and care givers and to include the facility to assist in the measurement of the patient as well as the home environment. It is also necessary for more research to be conducted into the clinical utility of this application in terms of its efficiency, effectiveness, and the relative accuracy and reliability of measurements recorded by clinicians using the Guidetomeasure-beta application compared with 2D paper-based guidance leaflets (which is the motivation for carrying out the experimental studies reported in Chapter 7).

4.7 Chapter summary

This chapter reported the first study which designed a prototype of the research artefact with OTs and older adults and specifically explored OTs perceptions of the challenges and opportunities of using the Guidetomeasure-beta application within the EFAP. Along with some other outcomes, a set of user requirements from a clinician perspective was generated and used to redesign the app, which is later described in Chapter 6. Based on this research focus and an outcome of this present study, the next chapter (Chapter 5) therefore reports study 2 which explores the benefits and challenges using the app with older adult patients.

Chapter 5
Patient perceptions of supporting falls prevention self-assessments via mobile 3D visualisation technology

5.1 Background

To recap, the findings of the literature survey reported in Chapter 2 indicate that there is a lack of fall prevention technology systems proposed in the literature that target environmental assessment interventions to overcome extrinsic risk factors and provide a means to support patient-practitioner collaboration for more effective assessments of fall risks. Consequently, in order to address the challenges faced by existing fall prevention technology research, the EFAP fall prevention strategy in occupational therapy was, therefore, explored to augment it by employing mobile 3D visualisation technology via a novel mobile 3D prototype app (Guidetomeasure-beta) designed together with clinicians, patients and interaction designers in a number of participatory design workshops in the first part of the study 1 reported in Chapter 4. The main study (discussed in Chapter 4) investigated OTs views of the developed prototype application's usability and feasibility, and the challenges and opportunities of deploying it to facilitate the EFAP in practice. Whilst there were challenges highlighted in the study with regards to the application's adoption in practice, OTs were, however, considerably positive about the app, in terms of its usability by them as part of EFAP practice. They also felt that the application has potential to effectively augment existing 2D paper-based tools and deliver several benefits over these. It was proposed that further research is needed to establish whether such an application could feasibly be used by service users to assist in the measurement of self as well as the home environment, considering that future fall prevention systems would benefit more from addressing extrinsic risks by patients being able to self-assess their needs for assistive equipment in the absence of clinicians in the home (see section 4.1). This present study, therefore, explores the applications use in the EFAP from the perspective of older adults.

5.1.1 Extrinsic Fall-risk Assessment Provision and Patient-Led Self-Assessment

Current practices of the EFAP involve clinicians conducting home assessments which involves taking and recording measurements or may ask patients and their family members to do so [293]. Patients taking and recording their own measurements and carrying out self-assessment or family members/carer doing it on their behalf has already become part of practice in some NHS trusts in the United Kingdom [293], partly due to time and health care resource limitations, whilst involving patients in the assessment process. In the clinical literature, studies have shown that there is a correlation between patients' involvement in the selection of equipment and increased patient satisfaction, thus resulting in an increase of long-term use [18]. Given the issues of 'poor fit' that already arise as a result of trained OTs typically carrying out these tasks, it is likely that 'poor fit' will remain a significant issue, particularly if patients and carers are being given the responsibility of carrying out these skilled tasks [22].

As discussed in Chapter 4, the use of standardised 2D paper-based measurement guidance is becoming increasingly prominent in light of the important role that accurate measurements have on optimal AE prescription, approximately 50% of AE that is prescribed is abandoned by patients [18]. A chief reason for equipment abandonment is largely a result of 'poor fit' between the equipment and the person using it [18, 19], resulting in significant consequences and exposure to fall risks in the home environment (subsection 4.1.2 provides a more detailed discussion on the consequences). Although there is a shift towards patients taking on such skilled tasks, there are, however, research evidence where clinicians call into question the accuracy of the measurements taken by patients and their carer or family member [307]. Research in the literature have underscored the need for providing patients with a means to taking measurements independently and accurately, as a way of promoting their involvement in the EFAP and indeed ensuring the appropriate fit of equipment to them and their home environment [293]. If patients, family members, and carers are able to carry out the EFAP effectively, there is a need to be supported via the provision of appropriate information, training, and new and innovative tools that provide clear and effective guidance, support, and facilitate the necessary gathering of reliable and accurate information. Until recently, little is known with regards to the tools that patients use to facilitate taking and recording accurate measurements as a part of self-assessing for equipment to ensure successful or correct fit of equipment [22], particularly given the patients desire to being involved in self-assessing for equipment.

Attempts have been made in developing measurement guidance to inform patients measurement-taking in the EFAP. A recent evidence-based 2D paper-based measurement guidance tool has been developed and published which was designed to improve and standardise the quality of paper-based guidance and improve the accuracy of AE self-assessment measurements recorded by patients and practitioners [308]. Similar to other 2D paper-based forms used in the EFAP, it is used to assist in the assessment process, with a view to ensuring the correct measurements are recorded, and necessary associated assessment data is collected. These forms include measurement guidance which is presented in the form of 2D illustrations of information that must be collected from key items of home furniture, fittings and the patient. The paper-based 2D illustrations are typically annotated with measurement arrows that serve as prompts to indicate the precise points in 3D space that must be accurately identified and measured in order to gather the necessary data to formulate an assessment; the data is subsequently used to prescribe the necessary home adaptations and assistive equipment [17]. Simulating the width, height, and depth dimensions of furniture items in 2D causes issues with visualisation and could be augmented with a more interactive environment that allows manipulation of models for more precise interpretation and thus accurate collection of measurements. Moreover, given the high levels of equipment abandonment and issues of poor fit that remain, despite the provision of detailed paper-based measurement guidance, there is a need to explore whether new and innovative technology-based tools can provide clearer and more effective assessment guidance, support, and facilitate more accurate and reliable recording information. There is, however, a need to explore the potential value of 3D visualisation applications developed specifically for use by older patients that augments the limited visualisation capabilities with the exiting 2D paper-based forms and serve as an aid in the process of carrying out the key measurement tasks that form part of the EFAP.

As illustrated from the literature example studies provided in subsection 4.1.4, the feature benefits of 3D visualisation help to augment 2D illustrations, by providing depth perception in areas to be measured that are not in view in paper-based form. This can provide clearer and more effective assessment guidance, support, and facilitate more accurate and reliable recording information. Utilising 3D visualisation technology could assist patients with understanding the measurement guidance, specifically localising crucial areas to measure and provide measurement recordings onto a 3D model rather than 2D diagrams. Using 2D diagrams/pictures of home furniture illustrating where user must take measurements makes it difficult to perceive an area on an item that is best illustrated with depth perception, especially for this particular user cohort. 3D models provide those natural depth dues of the home furniture, which allows patients to accurate record the measurements.

As also seen in the literature example studies (in section x), the 3D models were particularly beneficial as they could be observed by users from different view perspectives. Manipulation of the models (i.e. rotation and zoom in/out functionalities) allow patients to navigate their way around the home furniture for a more detailed look for what needs to be measured. Providing this depth perception could better reveal the end-to-end points of a dimension on a furniture item, which is a feature benefit that is hypothesised to facilitate patients with taking measurements in the EFAP. Making the proposed technology available on a device that would allow patients to mobilise around the home environment to gather assessment data could support them a great deal in this particular endeavour. As stated in section 4.1.4, this research focuses specifically on presenting an enhanced visualisation of measurement guidance via the use of 3D visualisation technology to view information that needs to be collected in a more intuitive way. The taking of measurements could be automated using 3D scanning technology (i.e. structured sensor). However, using this technology in replacement of Guidetomeasure-beta would not eradicate the problem of misinterpretation of guidance for prescribing equipment. Also, using such technology would significantly affect user experience and acceptance technology, particularly if patient users would be required to scan furniture items in the patient's home.

As discussed previously which equally applies, the effective design of health technologies that are usable and deliver functionality aligned with the needs and preferences of the patient is as important as the innovation itself [272], since this is likely to realise higher levels of engagement and adoption of a given technological innovation [309-311]. Consequently, it is vital that patient experiences and perceptions are sought and explored if new tools and technologies are to be viable, accepted, and usable in clinical practice [312]. Guidetomeasure-beta prototype and reporting of its design, involving both user cohorts, is formally introduced in section 4.2. A technology acceptance theory previously employed (in Chapter 4) is similarly applied in this present study as a way of gaining valuable insights into patient user needs and perceptions of the proposed technology and explore how they can be factored into the design of that technology. This follows the increasing use of such theories to obtain the perceptions of patient users to inform the iterative design and development of proposed technological innovations within a health care context.

The aim of this study was *to investigate the perceptions of community dwelling older adults regarding the feasibility, benefits, and challenges of using a 3D visualisation technology application to facilitate carrying out EFAP self-assessment tasks in practice*. Further, this study aims to respond to objective O4 outlined in section 1.3. This chapter is structured as follows: Section 5.2 presents the main study along with the methods used to explore the experiences and views of community-dwelling older adults after using the 3D visualisation application for carrying out EFAP measurement tasks. Section 5.3 describes the results of the main study. Section 5.4 presents a discussion of the findings and implications and recommendations for use of the 3D visualisation application in practice. Conclusions are then drawn, along with details of future research directions in Section 5.5.

5.2 Methods

5.2.1 Overview

This section provides details of the data collection and analysis methods used to explore the perceptions of community-dwelling older adults regarding the use of the Guidetomeasure-beta application as a self-assessment tool within EFAP in practice. Figure 5-1 presents an overview of the study design, methods, and research instruments employed to produce study outcomes and recommendations for practice.

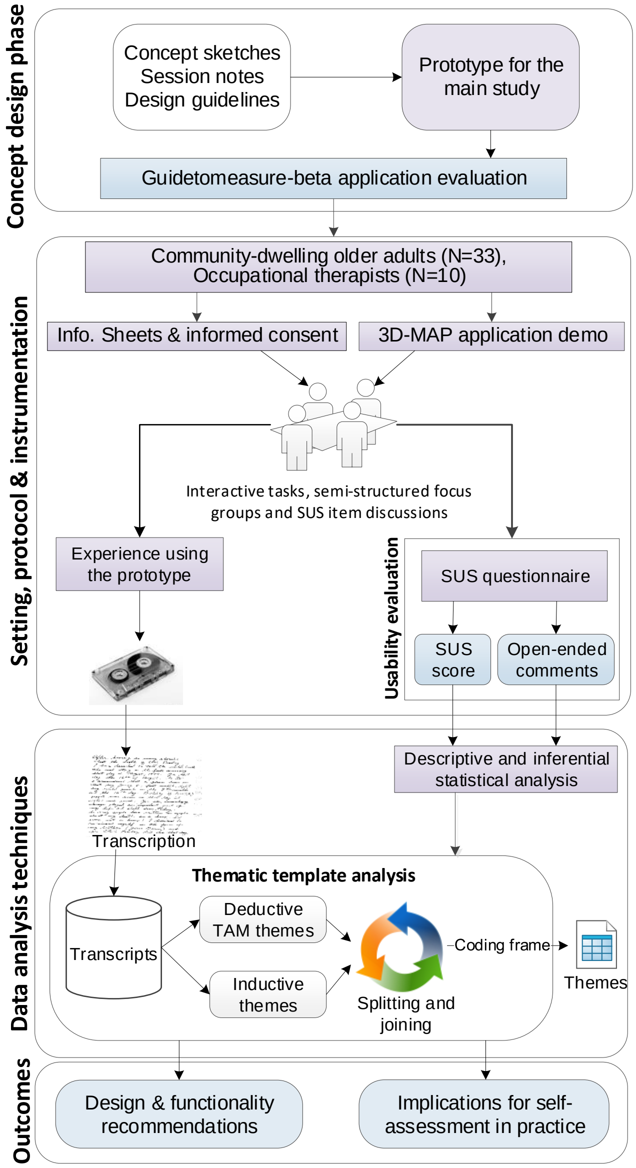


Figure 5-1: Overview of the session, methods, and process.

5.2.2 Participants

A purposive sampling strategy was used for recruitment of participants for this study, for which a total of 33 community-dwelling older adults were recruited. This was in line with a post hoc power analysis that was performed, which indicated that a similar sample size of 33 participants was sufficient (power=0.80) to detect a large effect (0.5) with alpha set at 0.05, 2-tailed. Participants were recruited through a number of different sources. In the first instance, managers of leisure centres that run exercise classes for 50+ groups were contacted as gatekeepers to disseminate invitations to older adults. A total of 18 participants were recruited through the “active 50’s” group at Brunel University and 15 participants through the “active lifestyles” group in the area of South West London. A financial incentive of a £10 voucher was offered in acknowledgement of participants who agreed to take part. The inclusion criteria for selection were that participants were over the age of 50 years, familiar with or had basic skills of using technology (e.g., the use of desktop computers, laptops, mobile phones), and considered themselves as active and healthy. Each participant reported their familiarity with touchscreen technology used within their personal and in some cases professional lives. Twenty-three of the participants were female (70%, 23/33) and 10 (30%, 10/33) were male; (23 females; 10 males, mean age=71.2 years, range=56-89, standard deviation=8.3). The majority of participants were retired or semiretired with the exception of 2 who were in full-time employment. This sample had no prior exposure to using self-assessment tools for the EFAP, however, 5 participants reported to have second-hand experience of family members having their home adapted due to ageing changes. Table 5-1 provides the demographics and summary of participant profiles for this study.

Table 5-1: Summary of participant profiles.

Part. ID	Gender	Age in years; mean (SD), range	Occupation	Group number
#F1-#F8	2 F[a], M[b], 5 F	66.2 (7.7), 52-75	6-retired, aircrew, flight manager, administration	1
#F9-#F14	M, 2 F, 3 M	75.2 (7.9), 65-86	Retired	2
#F15-#F18	M, F, M, F	71.0 (3.7), 66-75	Retired	3
#F19-#F27	M, F, M, 2 F, M, 3 F	70.6 (9.6), 54-89	Retired	4
#F28-#F33	6 F	76.2 (6.4), 68-87	Retired	5

[a]F: female.
[b]M: male.

5.2.3 Protocol and Instrumentation

Participant sessions were conducted on a one-to-one basis for the main interaction task, followed by a series of focus group sessions to discuss participant experiences of using the Guidetomeasure-beta application. The total duration of each session was approximately 90 minutes. Each session consisted of five key stages: (1) issue information sheet, question and answer, and complete consent form (individual); (2) provide a demonstration of the Guidetomeasure-beta application and answer questions (individual); (3) carry out the interactive task using the Guidetomeasure-beta application (individual); (4) administer system usability scale (SUS) questionnaire and retrospective think-aloud discussion (individual); and (5) follow-up focus group discussions about individual SUS items and perceptions and experiences of using the application (group).

An information sheet was given to participants on arrival before taking part in the session; this provided a background, aim of the study, and listed tasks that participants were expected to perform during the session. The content was worked through with each participant. They were continuously given the opportunity to ask questions to resolve any misunderstandings or queries. Informed consent was obtained by asking participants to complete a consent form, which explained their ethical rights to withdraw from the study at any time without having to provide any reason. Participants were given a brief demonstration of the Guidetomeasure-beta application, which included showcasing key features of the application, inputting measurements, and generating assessment reports. At this point, further information was provided regarding the application and participants were allowed to practice using it, while being individually supervised by a facilitator who answered any questions as they arose. The participants were allowed to provide their thoughts and feedback on their first impression of the application during the demonstration. Subsequently, participants were then set up with the application on their Android tablet and were asked to use the application, and were given written instructions outlining a series of tasks to perform using the application.

For the interactive task, participants were asked to use the application and to manipulate the viewpoints or position of the 3D furniture models to obtain the necessary depth of clinical guidance to measure the 5 home furniture items. Participants were encouraged to verbalize their thoughts immediately after interacting with the application, while adopting a retrospective think-aloud approach (otherwise known as think-after [313]) immediately after interacting with the application [314]. This provided insights into the usability of the application, thus resulting in additional qualitative data. The think-aloud approach is a well-established technique used for gathering thoughts of users while they are interacting with a software application. The technique is particularly useful to gain insights and understand the reasoning behind participants' preferences and thoughts. It is most commonly used in usability testing studies and has been employed to study older adults' interactions with user interfaces (UIs) and ways in which they structure their tasks when using the interface [315]. Variants of the technique such as concurrent think-aloud has limitations when being used with this user cohort, particularly those who exhibit cognitive impairments, find unfamiliar interfaces challenging to use, and employing the technique can hinder the completion of the task [315, 316]. With this in mind, retrospective think-aloud was, therefore, adopted to get participants to explain their behaviour after completing the tasks [313]. Users were reassured that there was no urgency in completing the task and were encouraged to take as long as they felt necessary to verbalise their thoughts while interacting with the application. Think-aloud prompts such as "what did you think at this moment?" and "what were you thinking?" were used after completing the task and whenever there were long periods of silence [317]. Furthermore, participants were encouraged to use the application to stimulate think-after thoughts.

Participants were asked to complete a SUS questionnaire [288] on completion of the interaction task, which was used to evaluate the general usability of the Guidetomeasure-beta prototype. SUS is a 10-item questionnaire instrument that asks users to rate a system against a list of items on a 5-point Likert scale from 1= 'strongly disagree' to 5= 'strongly agree.' The word 'cumbersome' in SUS item 8: "I found the system to be very cumbersome to use" was replaced with 'awkward' to increase comprehension as suggested by Bangor et al [318]. Each SUS item was further modified by replacing 'system' with 'Guidetomeasure-beta application' to assist users in scoring the application accurately. Such changes to SUS are standard practice and have no impact on the questionnaire's validity or reliability [290]. The SUS produces a score that represents a quantitative measure of the general usability of a system (for this study Guidetomeasure-beta application).

After completion of the SUS instrument, participants were asked to discuss the score they attributed to each respective SUS item. Focus groups were conducted in a semi-structured format with participants who were asked to discuss their experience of using the application with respect to each individual SUS statement, and then more generally about their perceptions of the opportunities and challenges of the Guidetomeasure-beta prototype as a self-assessment tool in practice. In total, five focus groups were undertaken and the number of participants in each group varied (*N*=8, 6, 4, 9, and 6, respectively). The number of focus groups and sample of participants in each group is in line with the minimum four focus group rule and the recommended 4-12 participant threshold [319] that is considered to be suitable numbers for conducing focus groups within a health care context [320]. Written notes were being taken by moderators to supplement the analysis of later discussions held at the end of the sessions.

5.2.4 Data Analysis

IBM SPSS statistical software package version 20.0.0 was used to analyse the SUS responses collected for this study. The quantitative data collected in this study was subjected to descriptive and inferential statistical analysis. To better understand and interpret the SUS scores, the adjective [289] and curved grading scales [321, 322] were used to analyse and interpret the SUS scores. This involved calculating a SUS score from the completed questionnaires and generating a value on a 100-point rating scale, which may then be mapped to descriptive adjectives (best imaginable, excellent, good, OK, poor, and worst imaginable), an acceptability range (acceptable, marginal-high, marginal-low, and not acceptable), and a curved grading sale (F=absolutely unsatisfactory to A+=absolutely satisfactory). *These baseline ranges and grading are derived from* a sample of over 3000 software applications that provide the comparative baseline [289]. Until recently practitioners viewed SUS as uni-dimensional until Lewis and Sauro [290] concurrently with Borsci et al [323] proposed SUS is composed of a two-factor structure in which 2 subscales, namely, usability (SUS items S1, S2, S3, S5, S6, S7, S8, and S9) and learnability (SUS items S4 and S10) underpin the SUS instrument. Additional statistical analysis was performed using one-sample *t*-test to establish whether there were significant differences between the respective mean SUS scores and the midpoint value of three (of the 5-point Likert type scale responses) for each individual SUS item and for the usability and learnability constructs.

Audio recordings of SUS item discussions, retrospective think-aloud sessions, and associated focus groups were transcribed verbatim into text format. Thematic analysis is a qualitative analysis method used for searching and identifying themes that occur within textual datasets [291]. Using this method enabled patterns in the dataset to be identified and categorized. Analysis of the semi-structured interview data was both inductive as the development of the themes were data driven and deductive, beginning with predefined (a priori) themes that are theory driven and linked to the analytical interest of researchers [235]. The first stage involved creating a template that used the predefined codes specified by the TAM. Hence, analysis considered the participant perceptions of the Guidetomeasure-beta application in the context of the two high-level TAM themes: PU and PEOU, and themes that emerged in addition to these. Carrying out the analysis in this way conforms to what is considered to be a contextual constructivist approach to thematic analysis [324]. The entire dataset was then read, and comments were assigned to the two predetermined TAM themes and other high-level themes that emerged, moving similar texts into one place and rereading segments to ensure that connections were justified. The dataset was then examined iteratively through several stages of splicing, linking, deleting, and reassigning subthemes within each predetermined high-level theme. Subthemes in the context of individual participants' accounts were considered, as well as examining the data across participants. Subthemes were included because of their relevance to the research question and not necessarily because of their prevalence across the data set, as is acceptable in qualitative research.

5.3 Results

This section presents the results of an initial usability evaluation of the Guidetomeasure-beta prototype and the associated follow-up focus groups.

5.3.1 System Usability Scale (SUS) Evaluation Results

The overall SUS results for Guidetomeasure-beta revealed a mean score of 65.8 (SD 16.05) on a 100-point scale. According to the SUS scoring matrix [289] this indicates that the application delivers 'marginal-high' (acceptability range), 'good' (descriptive adjectives), and 'grade C' (curved grading scale) levels of usability. The results were analysed with regards to the SUS usability and learnability subscales [290, 323], which revealed scores that were significantly above the midpoint benchmark of 3.00: 4.02 (*P*=.004) and 4.27 (*P*=.001), respectively. This shows that participants were positive about the application's usability and learnability. The Cronbach measure of consistency for the 2 constructs (0.67 and 0.63, respectively) achieved scores above the threshold of acceptable reliability of 0.6 for studies with small sample size [292].

A Spearman rho correlation was performed to determine the correlation between age and SUS scores. There was no significant correlation between age and SUS score (r=−0.041), which indicated that the Guidetomeasure-beta was considered usable independent of age. The study, therefore, continued with a follow-up analysis of the individual SUS items against the midpoint of 3.00, to identify any usability issues that the users in the sample experienced during the interactive task. To conduct this analysis, the negative SUS items (S2, S4, S6, S8, and S10) were reversed so that scores above 3.00 indicated a positive response. Table 5-2 presents a breakdown of the results of this analysis, accompanied by the full SUS item open-ended responses that participants provided.

Mean scores for all 10 SUS items, in absolute terms, were above the neutral midpoint of 3.00, which indicates that participants tended to be positive about the Guidetomeasure-beta application in terms of the SUS items. Furthermore, in terms of statistical significance, mean responses to all 10 SUS items were significantly higher than the midpoint benchmark. The results of the statistical comparison of the SUS scores and midpoint are now considered alongside the open-ended responses provided for each respective SUS item.

Responses to item S1 indicated that participants tended to agree with the statement that they would like to use the Guidetomeasure-beta application frequently (mean=3.42, *P*=.03). However, when analysing the open-ended responses to this item, it was apparent that some participants noted that they did not anticipate taking home measurements would be a task that they would have to carry out frequently. One participant disagreed with the notion of frequently using the application, as they reported having arm mobility issues that made using the handheld tablet device difficult.

> *"Well, hopefully, we wouldn't have to use it frequently, if we don't need too many things. This is just mainly for ordering things to help us round the home isn't it?" (F14)*

> *"I wouldn't use the 3D app frequently because, well it's hard to hold...but it's easy to use." (F22)*

Table 5-2: Mean system usability scale (SUS) score and midpoint comparison.

SUS[a] item	Midpoint	Guidetomeasure-beta[b], mean (SD)	Gap score	Df[c]	*t* test values	*P* value (2-tail)
S1: I think that I would like to use this Guidetomeasure-beta application frequently.	3.00	3.42 (1.062)	0.42	32	2.30	.03[d]
S2: I found the Guidetomeasure-beta application unnecessarily complex.[e]	3.00	4.09 (0.879)	1.09	32	7.13	<.001[d]
S3: I thought the Guidetomeasure-beta application was easy to use.	3.00	3.88 (1.083)	0.88	32	4.66	<.001[d]
S4: I think that I would need the support of a technical person to be able to use this Guidetomeasure-beta application.[e]	3.00	3.91 (1.234)	0.91	32	4.23	<.001[d]
S5: I found the various functions in this Guidetomeasure-beta application were well integrated.	3.00	3.94 (0.933)	0.94	32	5.78	<.001[d]
S6: I thought there was too much inconsistency in this Guidetomeasure-beta application.[e]	3.00	4.19 (0.873)	1.19	32	7.62	<.001[d]
S7: I would imagine that most people would learn to use this Guidetomeasure-beta application very quickly.	3.00	3.94 (1.435)	0.94	32	3.76	.001[d]
S8: I found the Guidetomeasure-beta application very awkward to use.[e]	3.00	4.26 (0.682)	1.26	32	10.28	<.001[d]
S9: I felt very confident using the Guidetomeasure-beta app.	3.00	3.82 (1.211)	0.82	32	3.88	<.001[d]
S10: I needed to learn a lot of things before I could get going with this Guidetomeasure-beta application.[e]	3.00	4.39 (0.747)	1.39	32	10.71	<.001[d]

[a]SUS: system usability scale.
[b]Guidetomeasure-beta: 3D measurement aid prototype.
[c]Df: degrees of freedom.
[d]Indicates statistically significant ≥.05 confidence level.
[e]Responses of negative items were reversed to align with positive items, higher scores indicate positive responses.

Participants tended to disagree with S2, that is, that they found the application unnecessarily complex (mean=4.09, *P*<.001). Participants did, however, highlight difficulties with rotating the 3D furniture models but felt that the other functionality of the application offered an easier way to record measurements compared with paper-based counterparts, as it did not require writing and that some of the other measurement arrows clearly showed exact areas to measure on furniture items.

> *"Although I do find that rotation a bit of a pain...It's not complex, you don't have to do the writing and it gives you the arrows, it's showing you where you have to measure across." (F3)*

Participants tended to agree that the application is easy to use (mean=3.88, *P*<.001). There were, however, usability issues expressed particularly relating to items that had multiple measurement entry arrows and in relation to rotating the 3D models using the touch gesture. One participant noted that the difficulties encountered were not associated with using the application or understanding the instructions given by it but rather, with the physical task of taking the actual measurements.

> *"I think it needs some more development, but I would be happy to use it. I think the concept is really good...things like the toilet, when you've only got one measurement; you can get the link on that very quickly and easy. It's when you've got multiple measurements to do the screen doesn't seem...sensitive to what you need." (F3)*

> *"It's better than it would be because you've got clear arrows and everything to show you where you've got to measure. My problem is, if like me and a couple of other people, who live on their own and have, and are elderly, it's hard to measure, it really is hard to measure." (F7)*

Responses to S4 indicated that participants did not feel that a technical person was needed to help them use the application (mean=3.91, *P*<.001). Nevertheless, some participants noted that they felt other user groups may require such assistance, depending upon factors such as age, functional abilities, and previous exposure to technology.

> *"...it depends on age and whether you are, you know, you have like tablets. And it depends what your history is with you know with computer stuff." (F2)*

> *It depends very much on the individual person using it, but for me, no...it gives a bit of explanation for what you need. If you were using it with other patients it's going to be a very wide range of abilities." (F21)*

There was a tendency to agree that the various functions of the application were well integrated (mean=3.94, *P*<.001). Some participants, however, commented that they had difficulty determining the measurement status of some items, that is, whether a measurement had already been entered or was still required.

> *" It was integrated but I was hitting the screen avidly trying to get a measurement and it was already there but we couldn't see it you know that sort of thing...a little measurement box." (F9)*

For S6, participants tended to disagree that there was too much inconsistency in the application (mean=4.19, *P*<.001). Nevertheless, some participants felt that the positioning of some of the measurement guidance arrows (particularly for the chair) could be further optimized and, in some cases, reported that the functionality appeared to be unresponsive.

> *"It's the responsiveness. It's just that some of the arrows weren't responsive all the time." (F11)*

> *" ...the only one I would say I was a bit confused about was the chair...it's sort of measuring the depth of it, you know where the chair is but the arrow was underneath it." (F9)*

Participants tended to agree with S7 that most people could learn to use the application very quickly (mean=4.19, *P*=.001). One participant, however, considered that a step-by-step wizard type interface would be a useful design feature to reduce the amount of learning necessary to be able to use the interface and ensure that all measurements were collected as needed.

> *"I think if they were taken through it bit by bit, like...a little icon to touch that says move to the next bit once you've answered the first bit." (F18)*

Responses to S8 tended to disagreed that the application was awkward to use (mean=4.26, P<.001). Some participants commented that the 3D models were easier to use and comprehend than their 2D counterparts. One participant reported issues with rotating the 3D models and suggested that on-screen rotation buttons may help this task.

> *"It's certainly better than having a picture." (F6)*

> *"I had it back to front or upside down (the 3D-model). If it had...a little button with the arrows going four ways...you could turn your 3D thing round better than trying to do it with your fingers." (F30)*

Participants tended to agree with S9, that they felt confident using the application (mean=3.82, P<.001). However, one participant noted that their confidence could have been related to having used this with the study facilitator present, which would not be the case if it were used, as intended, independently within the home setting.

> *"Well, because we've got someone with us, probably if we were doing it on our own, we'd be a little bit, ooh did I do that right, that sort of thing." (F23)*

The results for S10 show that participants tended to disagree that they had to learn a lot of things before they could start using the application (mean=4.39, P<.001) although the application demonstration provided at the start of the session was noted as being useful by one participant (F5).

5.3.2 Semi-structured Focus Group Discussion Results

Four high-level themes emerged as a result of the inductive and deductive thematic template analysis carried out on the data collected from the focus group discussion sessions. These themes were: (1) PU, (2) PEOU, (3) application use (AU), and (4) self-assessment (SA). An overview of the high-level themes and associated subthemes are presented in Figure 5-2.

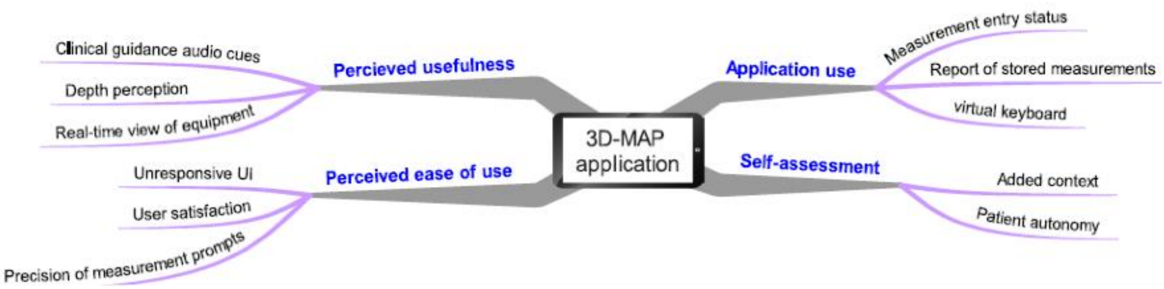


Figure 5-2: Thematic mind map of core themes and associated sub-themes.

Perceived Usefulness

Participants felt that the *clinical guidance audio cues* functionality was useful and made the Guidetomeasure-beta application easier to use. They commented that the audio cues provided useful instructions on how to take measurements and complemented the measurement arrows. However, some participants suggested that the Guidetomeasure-beta would have been even more straightforward to use if there were more audio cues to assist in the use of the application. Other participants also noted that the measurement arrows overlaid onto the 3D models were a useful aid in identifying the precise points that needed to be measured.

> *"If there was the voice command throughout it would have been easier." (F8)*

Participants commented that the 3D models offered realistic representations of real-life items that were to be measured. They suggested that the 3D models afforded improved *depth perception* of the discreet points that should be measured for the task and improved the visual quality of the measurement guidance, compared with the paper-based equivalents. Other participants were enthusiastic about the capabilities that 3D visualisation provides with respect to the clarity of the illustrations and differences between inner and outer length measurement arrows.

> *"You need to have a diagram like this to show you the depth of the object...and the arrow showing you what you meant by the depth." (F5)*

> *"Providing that 3D view so you know you can see where to measure...makes it more clear and distinguish whether to measure the inside length or the outside length." (F32)*

As an additional feature to enhance the usefulness of the application, there was discussion about adding some sort of augmented reality feature to the application that could deliver a *real-time view of assistive equipment* in place within the home. Participants felt that such a feature could help them to better understand what home adaptations (and items of assistive equipment) may look like when fitted and indeed what their function may be.

> *"...whether you could input in the measurements of the room and where you ask to put something and then superimpose to see whether it would go and which best position for it in that particular space that you want to put it in." (F6)*

Perceived Ease of Use

Numerous issues were identified in relation to the usability of the application by this user cohort. Participants reported on the application's *unresponsive UI*, particularly the difficulties that they experienced with some of the measurement arrows not responding to touch gestures. For example, clicking to insert measurement information for 3D models that contained multiple measurement arrows triggered a slow response by the application. Similarly, sluggish response times were noted when attempting to rotate 3D models that had multiple superimposed measurement arrows.

> *"...the arrows for the measurements weren't always responsive. Some of them were fine, but the ones with say 4 you couldn't input all of them. But the voice was very useful..." (F3)*

In general, however, participants reported that they enjoyed using the application; to the extent that they expressed their interest of using it again within a home setting. Some participants elaborated on this point, suggesting that the application showed potential for use in practice, enabling patients to feel more involved in decisions and activities related to the provision of assistive equipment.

> *"Actually I loved it. Because I've never measured anything before and put it in. so I'm not familiar with this measurement. So I loved it...I'll go home and practice. I'll get my iPad out." (F7)*

> *"I think it shows great potential for use in the field...and the patient would feel more involved. That is a good thing." (F9)*

One particular 3D model was regarded as being problematic in terms of providing ambiguous measurement guidance, that is, the 3D model of the chair. The measurement arrows for the chair and toilet were highlighted as a need for more precision if it is to have a much-desired effect in terms of users accurately interpreting the measurement guidance based on the use of *precise visual prompts*.

> *"The chair, was I thought...more difficult, the width of the chair is it to the outer arms or it's more likely that the seat position is...It's that degree of precision." (F26)*

Application Use

Participants were positive about using this application in practice and were enthusiastic about using it as a guide to taking measurements within the home setting. However, in terms of current interface design features functionality, participants suggested some adaptations that they felt would improve the user interaction experience, and hence, the potential of using it in practice. *Measurement entry status* was identified as a feature that required improvement. Participants noted the importance of more clearly signposting when a measurement has been input successfully, for example, in addition to the current feature that superimposes the measurement onto the arrow once it has been input, it was suggested that a clear change in colour of the input arrow would help to signify the measurement had been provided. An option to generate a *report of stored measurements* was also put forward as a valuable additional feature. It was foreseen that the benefits of such a feature included the service user being able to review all the measurements that had been provided but also the potential to enhance the level of dialogue between service users, clinicians, and assistive equipment providers after the measurements had been taken.

> *"...the capacity to be able to save your measurements and refer to them you know once you've sat down with the practitioner or whatever so ok that's what you've measured...and to be able to refer...back and look at it again and say are you sure you got the measurement right." (F30)*

Although participants reported being satisfied with the process of inputting measurements via the full Android *virtual keyboard*, some issues were raised about the type and size of the virtual keyboard. The launch of the full Android keyboard obstructed the view of the 3D model screen and consequently, suggested having a small numeric keyboard to enter measurements values was proposed. It was suggested that if a unit of measurement could be selected prior to inputting the values (i.e., centimetres, millimetres, or inches) the full keyboard would no longer be necessary and could be replaced by a simple numeric keyboard.

> *"There's a problem we've got here. When you have a touch screen or you touch the arrow you want and if you know you're only going to put inches in or something like that, then you wouldn't need to have a full keyboard...if you do you just need to have a small sort of standard dialer type touchscreen rather than the big one. But that's how it suddenly occurred to me you know that the limitation of the device is probably causing some confusion there because it covers the screen when it comes up you see." (F7)*

Self-Assessment

The notion of *patient autonomy* was raised as a direct consequence of utilizing the Guidetomeasure-beta application. The process of enabling users to carry out self-assessment for the subsequent prescription and fitment equipment was seen as an opportunity to reduce the typical waiting time necessary for a clinician or technician to carry out the home assessment process and for the necessary items of equipment to be installed more rapidly. Indeed, the view shared by the majority of the participants was that deploying such an application in this way would be of benefit in this regard.

> *"It's the fact that you can do this yourself and you're not waiting for somebody to say, ooh we can't come until four weeks' time to do the measurements for you, isn't it (group agreement)." (F11)*

> *"Having this (the Guidetomeasure-beta application), you know, could help get equipment for the bed...stairs...handrails and obviously the chair...all the things that sort of promote independent living." (F28)*

Whereas participants were generally enthusiastic with respect to the concept of the 3D visualisation approach to better interpret measurement guidance for the purpose of accurately gathering measurements, opportunities to extend the application's functionality were also suggested. For example, recording or mapping the dimensions of the room and the other items therein were seen as a way of carrying out more in-depth falls risk assessments and hence may have added benefits in order to prevent extrinsic fall risks. Participants believed that the *added context* in which the furniture item is placed should be considered in conjunction with taking measurements of furniture items.

> *"Rather than individual items, measuring height width and other things, if you had a bedroom...that would have been easier to see (all of the risks). Because then you could assess where your bed is and where your other furniture is...then you could think ways of other preventing falls." (F31)*

> *"You're measuring this and you're measuring that. Surely you should measure the rooms...the places it's got to go in. I mean a bath is fine so you measure that. Shouldn't that be used in conjunction with something to do with room measurements?" (F30)*

5.4 Discussion

This study presented a novel mobile application that uses 3D visualisation technology, designed to guide and assist older adult service users in the taking and recording of measurements as part of the extrinsic fall-risk assessment process. A total of 33 older adults used the Guidetomeasure-beta application to engage in a measurement task of items of home furniture that are known to be associated with falls and are routinely measured as part of the EFAP. Based on the analysis of the quantitative SUS, data revealed that the sample of older adult participants attributed a score of 65.8/100 for its usability, which indicated that the application may be described as having ‘marginal-high’ (acceptability range), ‘good’ (descriptive adjectives), and ‘grade C’ (curved grading scale) levels of usability.

In terms of the two SUS subscales, participants also tended to agree with statements relating to the usability and learnability of the application. The SUS results, therefore, indicate that there was agreement that the application was easy to use and that learning to use the application was also straightforward for this user cohort. However, despite some promising results and the outcome that the older adults who took part in this study were enthusiastic about the prospect of using the application within the home setting to carry out self-assessments, the findings indicate that there are improvements to be made to the application. Implementing the improvements may contribute to the successful adoption of such an application by the older adult cohort in practice. There was no significant correlation between age and SUS scores. However, this could perhaps be a consequence of the older adults in this sample being more familiar with using tablets or mobile phones, which may have mitigated any significant age-related effects. This also may explain why age was not found to be a factor involved in how users perceived the usability of the application.

Table 5-3: Study outcomes.

Areas of focus	Study outcomes	Source
Implications for self-assessment in practice	Confident using the application without assistance or supervision	S4, S9, S10
	Still some service user concerns about measuring furniture items independently	S3
	Valuable tool for self-assessment, patient involvement, and patient empowerment	SA, S1, PU[a]
	Sharing furniture measurements with clinicians	AU[b]
	Reduced time and resources overhead	SA[c]
	Provides an improved ability to visualise and understand measurement guidance	S8, PU
	Useful multimodal interaction features for clear measurement guidance	PU
	Indicate exact areas to be measured on furniture items	PU
Design and functionality recommendations	Provide usage instructions and short demo of key features	S4
	Develop improved 3D rotation function to improve visualisation guidance	S4, PU, S3, S8
	Precise and unambiguous measurement arrow prompts for multiple measurements	S6, PEOU[d]
	Brighter visual interface	AU
	Provide context of the furniture items	SA
	Visualise equipment installations in real-time in context of the home	PU
	Provide smaller-sized numeric keyboard for measurement entry	AU

[a]PU: perceived usefulness.
[b]AU: application use.
[c]SA: self-assessment.
[d]PEOU: perceived ease of use.

Analysis of the individual SUS items and associated open-ended comments, along with think-aloud and semi-structured focus group data provided detailed study outcomes relating to the perceived feasibility, usability, challenges, and opportunities of the application being deployed in practice. Table 5-3 presents a summary of the key study outcomes and categorises these in terms of the implications for deployment in practice and design and functionality considerations. Each outcome is mapped to its respective source, that is, the individual SUS item (S1-S10), and the high-level theme that emerged from the analysis of the semi-structured focus groups: PU, PEOU, AU, and SA.

In terms of the *implications for self-assessment in practice*, older adults reported that they felt comfortable using the application without any assistance or supervision (S3, S9, and S10). One participant reported to a feeling of apprehension with regards to the physical task of taking measurements on their own, in part due to advanced ageing factors (S3). However, a recent update of the health care act stipulates that "capacity must be assumed" for those responsible for carrying out ADL around the home and that patients must take ownership of their own care within reason, if they are capable of doing so [325]. Therefore, despite the development of applications such as Guidetomeasure-beta, designed specifically to provide enhanced levels of guidance and support (compared with traditional paper-based equivalents), there still appears to be some demand for more personalized support for some user types. The application was seen as a useful tool to promote independent living and to empower older adults to take ownership and be involved with parts of the EFAP (SA, S1, and PU). Some participants viewed the recording of measurements as being a valuable feature to have in order to send to clinicians as part of the equipment provision process, which could enable patients to take part in crucial aspects such as taking measurements of their home furniture (AU). This has potentially significant positive implications on the outcomes of current practice, particularly given that older adults who are empowered to participate in technology-assisted interventions are more likely to contribute to decisions made pertinent to them personally [326] which, in turn, could improve overall patient satisfaction, quality of life, and, ultimately, the level of engagement with assistive equipment [327]. There is also a potential time-saving advantage associated with this technology-assisted self-assessment approach, which means that patients can go ahead with assessments without having to wait for a clinician to conduct a home visit.

Waiting times were also seen as another component in adopting the Guidetomeasure-beta application to facilitate self-assessment (SA). This is particularly advantageous given the growing demands on clinicians' time, coupled with the increasing strain on publicly available health care resources [133]. Notably, participants remarked that they saw benefits of using 3D visualisation, which they believe provides improvement in the depth perception required to improve the way in which the guidance is perceived (S8, PU). The application was perceived as a useful solution as compared with the existing 2D paper-based self-assessment tools. It provided a rich set of multimodal interaction features (i.e. both visual and audio) to help interpret the measurement guidance and enable the recording of accurate furniture measurement (PU). Previous studies have shown that the combination of visual aids and audio features are both useful and effective in enhancing older users experience while interacting with software applications, particularly for those who have lower health literacy [328, 329]. This is a promising and important outcome given that 50% of assistive equipment is abandoned by patients, partly due to inaccurate measurements being collected using the current 2D paper-based guidance [18]. Older adults viewed the application as a promising and practical tool, which they felt, enhanced the visualisation of measurement guidance and helped to more accurately indicate the precise areas on furniture items that must be measured for the purpose of self-assessment (PU).

Several *design and functionality recommendations* emerged from this study, providing insights into how the application prototype could be further developed to align it with the needs of older adults if it is to be successfully suited to and adopted in practice by the intended user group. It was suggested that some users may require more detailed usage instructions and a short application demonstration (S4). This is in line with existing research focused on overcoming barriers to technology use and adoption by older adult users, which suggests that challenges often stem from lack of confidence as a consequence of being unfamiliar with some mobile technologies [330]. Other studies have found ways to assist older adults in addressing the lack of confidence is through adequate training, demonstrations, and providing built-in assisted features, which heightened competence and confidence levels when using technology [331]. Participants expressed experiencing difficulties while rotating some of the 3D models and found that the rotation controls were occasionally difficult to manage when they manipulated the perspective view of the 3D models (S4, PU, S3, and S8). This aspect of the functionality therefore requires further development, as it impacts the interpretation of measurement guidance.

Participants commented on the need for clearer and unambiguous visual prompts to measure furniture items, as some prompts (particularly for the chair that has multiple inputs) seemed less clear and could compromise the reliability of older users effectively perceiving the guidance for accurate measurement entry (S6, PEOU). This requirement is particularly crucial given that the application was developed to enhance the visual quality of measurement guidance via the use of annotated 3D models to sufficiently locate end-to-end points on the measurement arrows. It was also commented upon that the interface needed brighter visuals as it impacts on one’s confidence and attitude while using the application (AU). Moreover, the current design of the arrows appeared to require more effort than expected to input measurements, which seems to impact participants’ level of confidence in using the application independently without support. Indeed, a body of research concerning the design and development of interfaces suited for older adults suggest a set of design guidelines for this particular older user cohort and infers that many usability issues can be addressed by adhering to those guidelines, whereas also assessing the effectiveness and efficiency of system functionality [315, 332].

Other participants felt that measurements of the context in which the furniture item is located should be equally considered as gathering the dimensions of home furniture (SA). As an extension to this idea, one participant suggested a potential feature to visualise assistive equipment installations in real-time in the home before prescriptions are given (PU). Providing visual sense by overlaying virtual objects onto the real-world environment (in camera view), thus augmenting older users' imagined changes to their home environment before it is physically adapted by EFAP, can decrease cognitive load, promote continuous engagement in health care interventions, and improve health outcomes [333]. Interestingly, there is evidence from a study investigating the application and effects of augmented reality in exercise interventions for fall prevention, which found an improvement on falls efficacy, gait, and balance [334]. Superimposing 3D models of assistive equipment within the home was viewed as having potential to increase the reality effects and participation during the intervention, giving patients the capability to visualise imagined changes to their home environment before it is physically adapted within the extrinsic fall-risk assessment process. Participants expressed the need for smaller numeric keyboard style interface for measurement entry, as the full sized alphanumeric keyboard obscured the 3D model screen, which in turn could impact the integrity of the input and users forgetting what measurements they are inputting (AU). Previous research has shown older adults' preference for onscreen numeric-style keyboards [335] and suggests that data entry should be kept to a minimum. The type of keyboard interface chosen should be relative to the amount of data entry activities performed by older adults [336]. There is also further evidence of onscreen numeric keyboard as the preferred interface for accurately recording numerical values and reducing the number of input errors in a health care setting [337, 338].

5.4.1 Limitations

Older adults recruited for this study were sourced primarily from active ageing exercise groups and hence, the sample in this study is likely to have been susceptible to selection bias. Furthermore, participants reported to be healthy, active, and familiar with the use of desktop computers, laptops, and mobile phones and also had some level of familiarity with touchscreen technology. Whereas this represents a skewed sample, it enabled the study to focus on evaluating the application and its functionality as opposed to the focus of perceptions being limited to basic usability issues that may arise from not having a basic understanding of the platform on which the application was deployed. Nevertheless, it is important to note that this sample may not be representative of the typical groups of older adults that OTs frequently engage with, and therefore should be taken into consideration when interpreting the results. The typical older adult patient profile is changing, as younger and more technologically aware generations make the transition into the older adult category, so the typical level of familiarity with ICT of this cohort will increase over time. Therefore, although the sample in this study is biased, such participants were recruited with the motivation of gaining insights from a sample, that may to some extent, better represent the more technologically aware older adult user group of the future.

In relation to the TAM model, the deductive approach implemented in the analysis of qualitative datasets, via the two core TAM constructs, could be considered a limitation of this study. Adopting the thematic template approach in this study may have minimized the coverage of themes that would have emerged if a solely inductive approach was employed. Having said this, the approach enabled the analysis to be partly data driven, as well as focus in more detail on factors associated specifically with technology acceptance, which was in line with part of the aim of this study. Furthermore, it should be noted that no formal spot checks were carried out to ensure that participants adhered closely to the directions and guidance provided by the application. There is, therefore, a possibility that the lack of adherence observed when patients utilize paper-based guidance could similarly be a challenge to the tablet-based version of the guidance and something that should be taken into account when considering the results.

5.5 Conclusion

This study investigated the experiences and views of 33 community-dwelling older adults who engaged in an interaction task with a custom-built Guidetomeasure-beta application developed as a tool to engage in self-assessment tasks and assist them in taking and recording measurements as part of the EFAP. The usability of the Guidetomeasure-beta application was evaluated via the statistical analysis of participant responses to the SUS instrument. Perceptions regarding the feasibility, benefits, and challenges of using this application in practice were evaluated via the thematic analysis of individual interview and focus group discussions that were held after participants carrying out an interaction task. Based on the results, several implications for deployment of this application in practice were identified. Furthermore, numerous design and functionality recommendations were identified, which exemplify the interaction challenges that this cohort experienced with this 3D visualisation technology.

Overall, community dwelling older adults believed that the application delivered an improved visualisation of the measurement guidance provided by traditional 2D paper-based guidance leaflets. The multimodal nature of the measurement guidance was also noted as a valuable benefit to deploying guidance via the mobile application. Furthermore, older adults were confident using the application without assistance and saw several benefits to deploying such an application in practice. Some of these included a perceived value in assisting with the self-assessment process, but also as a tool that could encourage patients to engage more fully in the delivery of their own care and collaboration with clinicians and associated decision making about their care. Further research is needed to establish whether such an application may be feasibly used by occupational therapists, family members, and regular care givers. It is also necessary to carry out further research to establish the clinical utility of this application in terms of the efficiency, effectiveness, and the relative accuracy and reliability of measurements that are recorded by older adults using the Guidetomeasure-beta application compared with 2D paper-based guidance leaflets. Furthermore, future research is needed to consider the use of an experimental design to empirically test the application against its 2D counterpart, to enhance and provide further insights into the findings presented here.

5.6 Chapter summary

This chapter described study 2 with older adult patients exploring their perceptions of the perceived benefits and drawbacks of the first prototype of the artefact (Guidetomeasure-beta application) and how it could be used in practice. A usability evaluation of the prototype was also conducted which uncovered some interesting outcomes of how the prototype could be further adapted. Similar to the previous chapter, this chapter resulted in a set of user requirements used to modify the prototype further. The next chapter describes the redesign and implementation process of the research artefact and descriptions of its technical architecture, specifically designed to facilitate users through the EFAP.

Chapter 6
Guidetomeasure: A mobile 3D measurement guidance tool for clinician and patient-led assessments and assistive equipment prescription

6.1 Introduction

The findings from the exploratory studies (Chapters 4 and 5) were included in the research artefact to refine this and provide functionality that enables accurate and reliable recording of measurements and equipment prescriptions, while at the same time, incorporating additional patient and clinician UI-based specifications/preferences. The effectiveness, efficiency, and subjective satisfaction of the refined artefact are evaluated in a set of user-based trials in Chapter 7. It is, however, necessary to provide a detailed technical walkthrough of the refined artefact before its evaluation. The aim of this chapter, therefore, is to demonstrate the design and implementation process of the refined artefact solution as an output of the research. This refinement was conducted over two iterations in the third step of the DSR cycle.

This chapter is structured as follows: Section 6.2 describes the redesign of the research artefact taking into account the user requirements and specifications collected. Section 6.3 presents the refined underlying system architecture and gives a brief discussion of the process which helped form the revised architecture. Through presenting the system architecture, Section 6.4 provides the design and implementation of the measurement guidance module accompanied by a side-by-side comparison of the app and 2D guidance booklet and a walkthrough of the module and associated functionalities. Section 6.5 provides the design and implementation process of the equipment recommendation module and a walkthrough of how it is used. Section 6.6 gives details of the external-facing unified API which is built into the backend of the app and describes how it connects to systems within the falls pathway. In section 6.7, the chapter closes with a summary of the content discussed therein.

6.2 Refining the Guidetomeasure-beta prototype

The final version of the artefact has been refined to take into account: (1) the need to better reflect practice and wider clinician and patient preferences; and (2) a more finely-tuned app which contains better quality 3D models and arrow prompts to enable better location of landmarks in and around furniture items and indication of measurements recorded. This is different from the previous version of the artefact, which did not display the arrow prompts clearly enough for the users. Following the evaluation of the Guidetomeasure-beta prototype, several usability issues and deficiencies in the interface was uncovered with the additional feedback provided by clinicians and patients alike. Of these emerged, a set of user requirements was formulated to implement in the next version of the app.

6.2.1 User requirement and specification

To understand the user requirements for adapting the Guidetomeasure-beta prototype, this section involves fleshing out each requirement, including the context in which the users interacted with the app. Interaction designers and clinicians were consulted throughout the design and development process, to ensure that the prototype is aligned with and relevant to the user requirements and augments the routine practices of the EFAP and self-EFAP. To ensure that the implementation of the user requirements was achieved, the MoSCoW [339] technique was used to compile and organise a more comprehensive list of requirements. These requirements are presented in Table 6-1, which are mapped to the user type from which they derived.

Table 6-1: User requirements and specification for the Guidetomeasure 3D app.

User requirements	User type
Provide improved guidance to make assistive equipment recommendations	OT
Provide a facility to record notes and assessment data	
Clearer prompts to measure home furniture	
Clear and more usable controls to rotate 3D models	
Additional function to reset the 3D models to its original position	
Capture images of the patients' environment to provide context	
Adaptable to be shaped by and to shape practice	
Clinicians adding their own ad hoc solutions	
Provide usage instructions and short demo of key features	Patient
Develop improved 3D rotation function to improve visualisation guidance	
Precise and unambiguous measurement arrow prompts for multiple measurements	
Brighter visual interface	
Provide context of the furniture items	
Visualise equipment installations in real-time in context of the home	
Provide smaller-sized numeric keyboard for measurement entry	

There are two sets of requirements linked to two user cohorts: *OT* and *Patient*. For the former, some requirements related to the management of home assessments, along with suggested improvements to the core app functionalities to better interpret the measurement guidance and record more accurate measurements for equipment recommendations. In respect of the latter, most of the requirements highlighted improvements to the look and feel and core functionalities of the app, contributing to a better user experience whilst also enabling patient users to better interpret the measurement guidance in order to collect accurate measurements. Supplementing these requirements, a number of suggestions to improve the app functionalities were provided from discussions held with clinicians and interaction designers (the arrow prompts being a case in point). In the context of the app's intended purpose, OT users would potentially use it in their daily clinical practice in cases where the patients themselves are unable to perform their own assessments and equipment prescription. Patient users would directly record their furniture measurements and assessments using the app and that data would then be stored remotely to be used by OTs to prescribe equipment to patients.

Analysis of the requirements is as crucial as its collection to ensure that they are clear, unambiguous, verifiable, and solution-driven to the specific problems they are intended to solve. To explore this further, the requirements were formulated (i.e. providing the context of use) as user scenarios by employing the behaviour driven development (BDD) technique. BDD is a human-readable natural language written in English that specifies the expected behaviour and outcome of a software application in a *given-when-then* style of framework (commonly referred to as Gherkin language) [340]. Using the BDD technique allowed the scenarios to be articulated into a format easily understood by clinicians and interaction designers during consultations. The BDD scenarios were used to execute acceptance tests, ensuring that the user requirements were specified explicitly, and that implementation of the requirements was met. Constructing requirements in the form of BDD scenarios breaks them down into sequential steps of how users interact with the app features so that multiple contexts of use can be considered during the design and development phases. The BDD scenarios were developed using Visual Studio code editor contained in *feature files*. For illustration purposes, there are a three BDD scenarios presented in Figure 6-1 as examples of the app features.

```
Feature: Clear and more usable controls to rotate 3D models
  I want to rotate the 3D models via an egocentric navigation
  So that I can gain a better visualisation of the guidance
  Scenario: rotate 3D models
    Given I want to view specific areas of interest on the model
    When I swipe the screen for an egocentric navigation or click on
    the controls to move the position of the model
    Then the 3D models should rotate accordingly
```

```
Feature: Better arrows for measurement entry
  As a patient or OT user
  I want to click on the arrow prompts
  So that I can record furniture measurements
  Scenario: Measurement entry
    Given that I visualise the measurement guidance via the arrows
    When I navigate to specific areas of interest
    Then the keyboard should launch
    And the entered measurement should be displayed on the arrow(s)
```

Figure 6-1: Two examples of BDD scenarios of the application teased out through consultations with clinicians and interaction designers. The following link is to the *.feature* file which contains the scenarios in the Guidetomeasure app repository on [341].

Providing the rest of the BDD scenarios developed is beyond the scope of this study. However, a URL link is given to the BDD scenarios within the Guidetomeasure 3D app repository on GitHub

[341]. As such, the app functionality caters for multiple-use cases related to the two-user cohorts of the app. The app provides the capability to the patient user to support the 3D visualisation of measurement guidance, thus facilitating the collection of furniture measurements and associated assessment data. It is intended that all the assessment data collected (either by clinician or patient users) is then stored in both the local and remote database for further clinical analysis. Stored data is accessible by clinicians as they are synchronised to a remote server and fed into the built-in equipment prescription algorithm that complements the clinical reasoning used for later analysis of equipment recommendations to patients. Figure 6-2 shows an overview of the use case of the application.

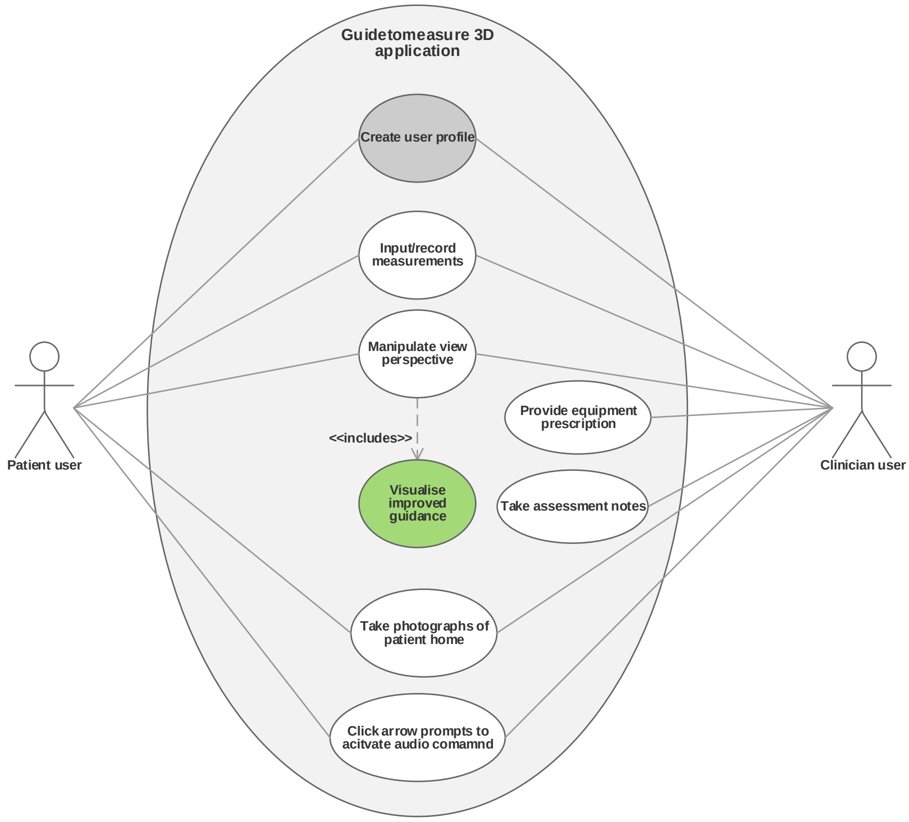


Figure 6-2: Use case diagram from the clinician and patient perspectives.

6.3 The revised system architecture

The redesign of the app architecture consists of the two core modules related to this research i.e. *3D measurement guidance* and *equipment recommendation* and other functionalities to integrate into the clinical pathway. To achieve this, the underlying architecture was refined and decoupled via the core functionalities of the app into a self-contained collection of microservices. This enabled each module to share the core functionalities through use of microservices. Each microservice is independent of the others and API-enabled, enabling them to work in combination to produce the module's functionality. A microservice exposes an API endpoint (triggering an event from the UI) which allows other services to consume requests it sends. Segmentation of core functionalities enabled integration directly into the existing clinical pathway. This also eradicates the 'single point of failure' that can result from a microservice, thus providing greater reliability by minimising dependencies. Each microservice is responsible for enabling users to complete a task within the EFAP. Figure 6-3 shows an onion layer of the architecture at an abstract level, separating the use case logic from the choice of technologies used in their delivery. This onion layer represents each of the microservices presented in Figure 6-4.

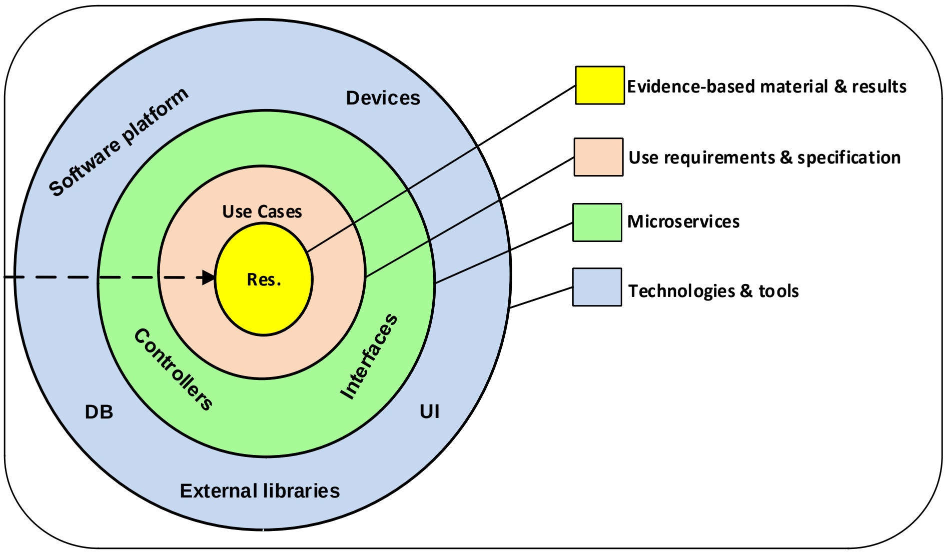


Figure 6-3: Onion layer-style architecture. This diagram illustrates the removal of dependencies, the onus on using certain technologies, and highlights the importance of translating use cases into microservices.

From the principles applied to the architecture, an overall system architecture is derived that consists of two main modules, namely *measurement guidance* and *recommendation*. The other components include the collection of microservices, rendering the 3D models and the scenes in which they are located, persistent storage, and integrated API. In light of the discussion and the user requirements derived from the previous stage of the research, Figure 6-4 shows the revised underlying system architecture of the Guidetomeasure app.

6.4 Measurement guidance module

This module provides users with an enhanced visualisation of the measurement guidance by displaying 3D models of the five furniture items (bed, bath, toilet, chair, and stairs), that are most commonly associated with extrinsic falls within the home environment and are therefore typically measured as part of the EFAP. *Rendering 3D models*: The *unity3D engine* is responsible for rendering the furniture scenes which contain objects such as the *avatar model*, *3D furniture models,* and *arrow prompts* of the application. Like the previous design stage, the prototype was further developed using the Unity3D, a game engine with cross platform capabilities developed by Unity technologies, which allows content to be developed and deployed on Android, IOS, desktop or the web. The other tool which was utilised in this research for the design of 3D furniture models was Blender. This is an open-source 3D authoring tool that allows 3D graphics/objects to be developed and integrated into any game engine e.g. Unity3D. It allows 3D objects to be imported and designed in accordance to the needs of the end-users. The version of the Blender used for this research is v2.76 [342].

Scenes: There are in total five furniture scenes: *bath, chair, stairs, toilet, bed* and an *'About You'* scene where users record their popliteal height dimensions. Each function and 3D model in the scene are *GameObjects* where the behaviour has been scripted using both JavaScript and C# programming languages. MonoDevelop, which is an open source IDE editor, was used to develop the behaviour via scripts for the gameobject. The *3D guidance models* located in each scene are used to facilitate users to record accurate *furniture measurements* and stored in local persistent storage.

Microservices: The application contains the core application functionality which has been decoupled into microservices and attached to the gameobjects in the furniture scene which are invoked by the UI component in the presentation layer. This adopts an essentially polymorphic principle of allowing scenes to use (overload and override) these services in the context in which they are used. *Model navigation functionality* contains two sub-functions. First, the 3D model rotation which uses the input touch library to detect users finger-swipe gesture on the screen to rotate the model along the x axis from its relative position. Second, the egocentric navigation is where the camera in the scene is rotated around the model itself along with the zoom-in/out function. *Takephoto* uses the android plugin to access the Android device's camera to take photos through the application. *Audio command* contains a corpus of pre-recorded measurement instructions in a .mp3 audio format to match each corresponding arrow prompt in the furniture scenes. *Notepad* is simply a UI gameobject which allows users to input their notes using the device's virtual keyboard and then stores the notes to the local database for reporting purposes. *Clicking mechanism* registers each of the arrow prompts as components which allow users to click on the arrows to activate the audio guides.

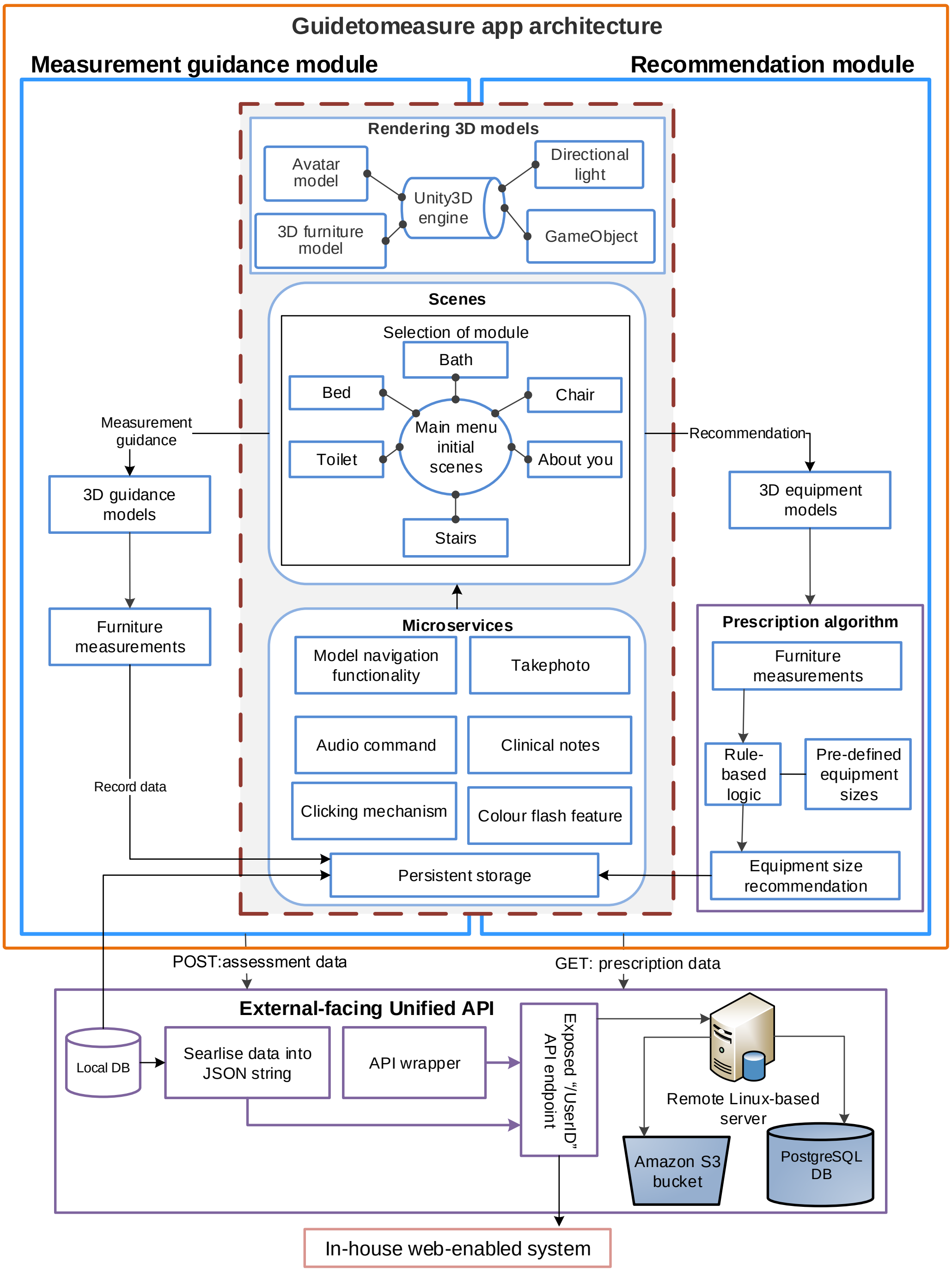


Figure 6-4: Guidetomeasure 3D app system architecture.

Colour flash feature is an animation developed using transitions and events to loop through colours in the RGB colour model. The service is attached to the arrow prompts and executed once the scene is initiated. *Persistent storage* is responsible for storing the measurements and the photographs taken on the device and then transmitting the data to a local repository and *local SQLite database.* Figure 6-5 shows the local and remote DB schema for the app.

6.4.1 Measurement guidance: module walkthrough

This section provides a walkthrough of the 3D measurement guidance module in the app, along with a side-by-side comparison of a 2D evidence-based booklet currently used to present the visual quality and improved feature enhancements. The first screen that users are presented with is the launch screen where they select the module they wish to use. Figure 6-6 shows the launch screen of the app. This asks users to select a module. As shown in the Figure below, when the user clicks on the module button 'Measurement guidance' it highlights the selection before taking the user to the main menu.

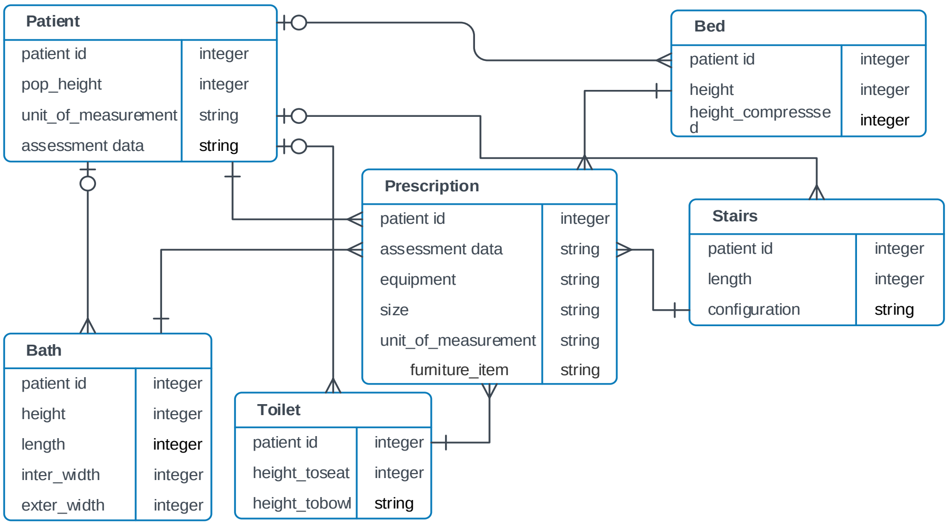


Figure 6-5: Local and Remote DB schema.

Figure 6-6: Launch screen (measurement guidance).

Upon selecting the module, users will then be able to proceed to the home screen of the application, as shown in Figure 6-7. This presents the five home furniture items and the 'About You' option where service users can record their popliteal height. Each furniture screen can be accessed by clicking on the buttons displayed on the home screen, as shown in Figure 6-7.

Once an option is selected, the application then displays a 3D furniture model scene. As discussed in previous chapters, presently 2D paper-based tools are typically used assessment methods. Notwithstanding their benefits and reported advantages, there are visual limitations to these which the Guidetomeasure 3D app addresses. Also, the textual descriptors on the paper-based tools are not easily captured how a user is expected to perform a measurement task in their current form.

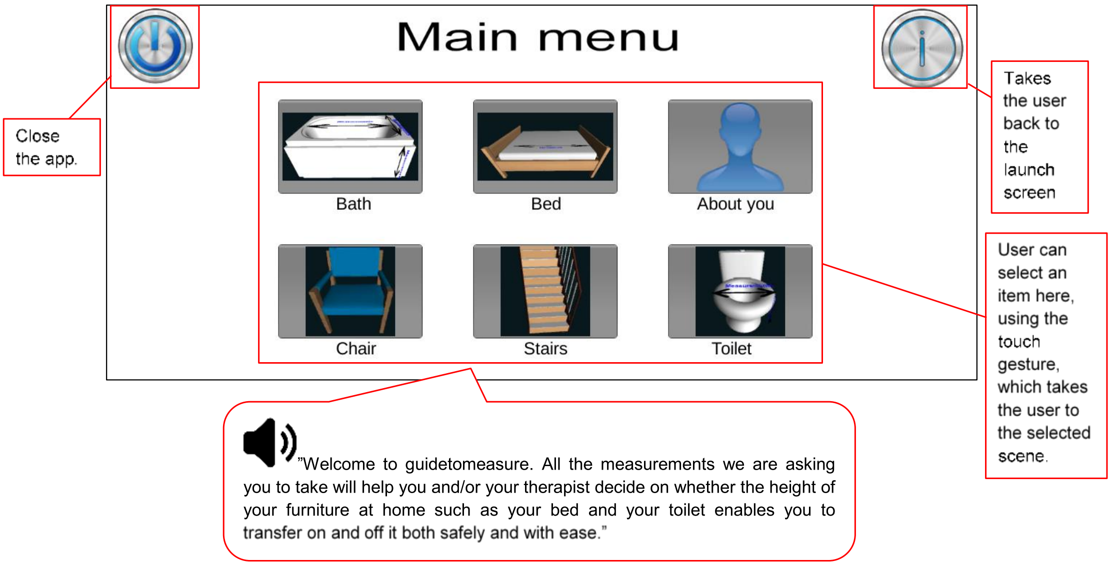


Figure 6-7: Guidetomeasure application main menu.

Figure 6-8-Figure 6-13 presents a side-by-side comparison of an evidence-based booklet and the Guidetomeasure application, where the notable differences between the two tools is the improved ability that the latter affords users in visualising crucial landmarks for measurement in 3-dimensions.

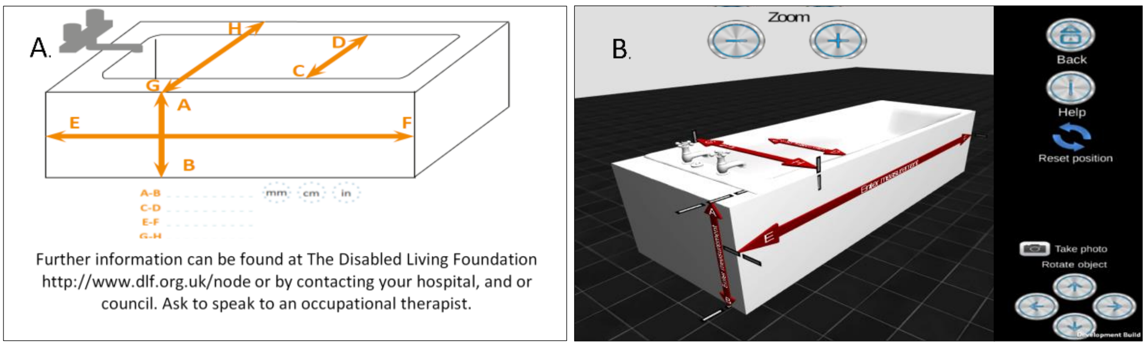


Figure 6-8: Bath guidance on the booklet (A) vs. the bath guidance provided by the application (B).

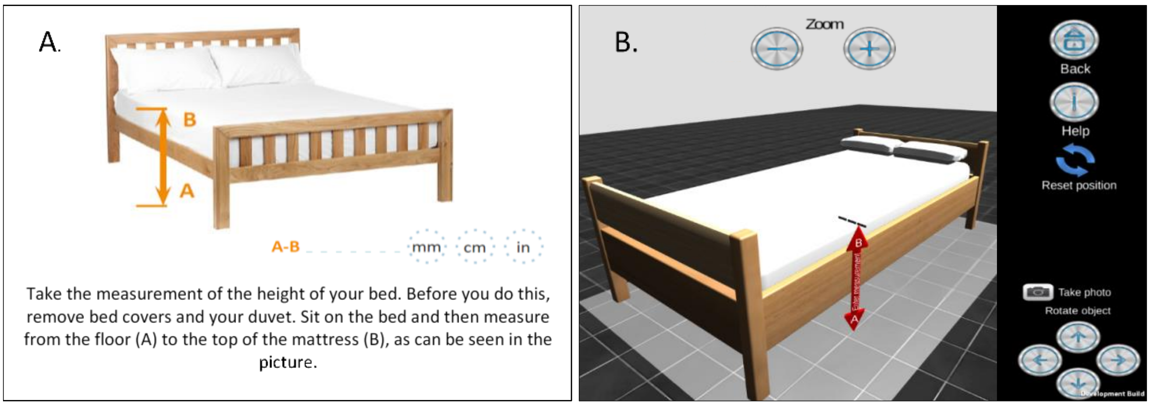


Figure 6-9: Bed guidance on the booklet (A) vs. the bed guidance provided by the application (B).

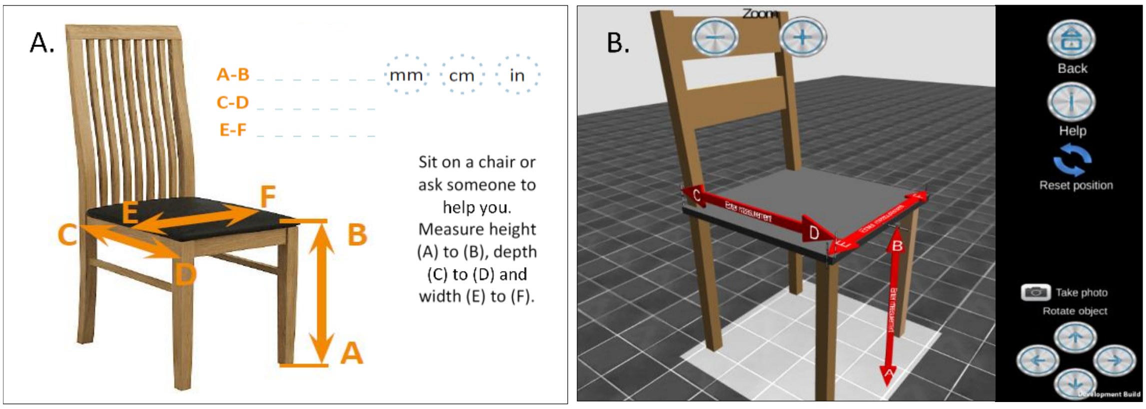


Figure 6-10: Chair guidance on the booklet (A) vs. the chair guidance provided by the application (B).

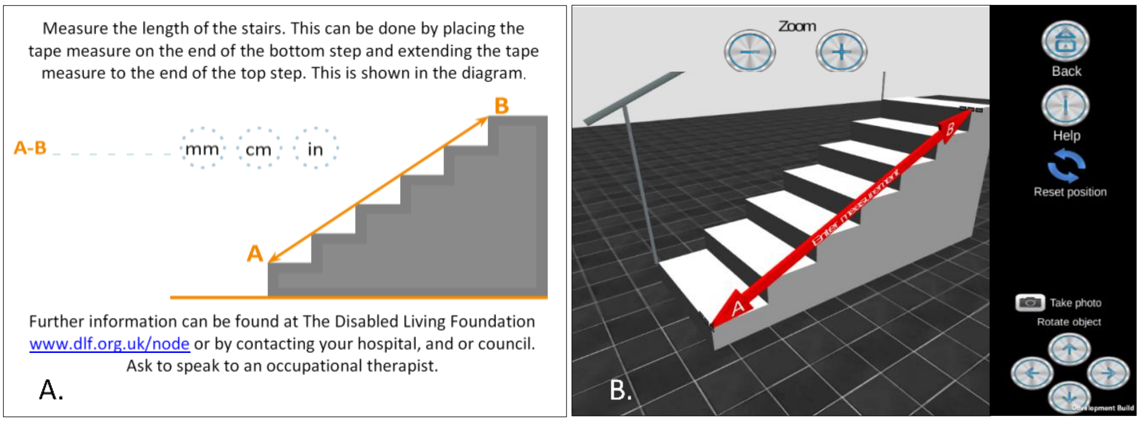


Figure 6-11: Stairs guidance on the booklet (A) vs. the stairs guidance provided by the application (B).

The 'About You' scene contains a virtual avatar - a 3D representation of an optimal physical position of the patient to allow users (e.g. patients or clinicians) to visualise how patients are required to be positioned (at a 90-degree angle when seated) to assist with high trunk flexion movements during furniture transfers.

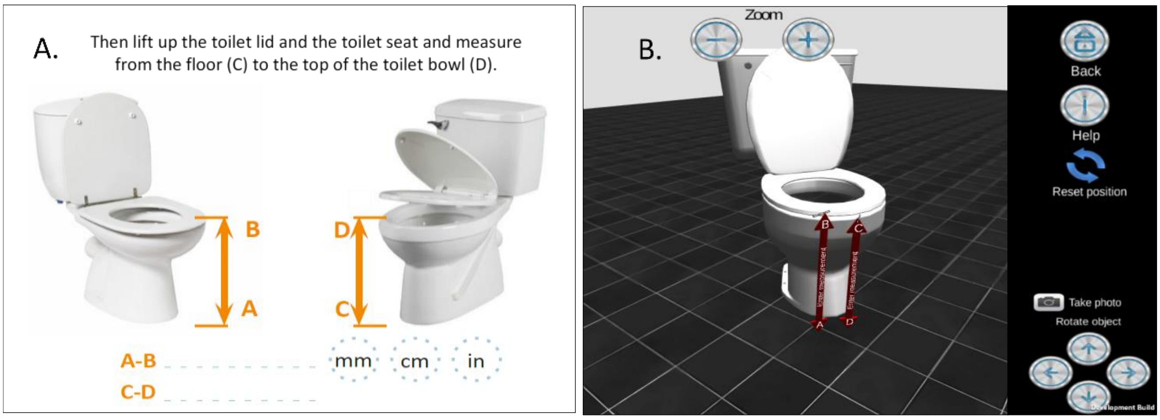


Figure 6-12: Toilet guidance on the booklet (A) vs. the toilet guidance provided by the application (B).

The avatar is used as a means of recording popliteal height measurement and providing correct sitting guidance to the users. It was designed after consultations with the OTs involved in the research. Users will be able to select the popliteal height arrow and input the measurement. The avatar also includes a pre-loaded animation which performs the sit-to-stand transfer [343, 344] where patient users can mimic the simulated movements to practice transfers on and off furniture items with safety and ease. Figure 6-13 shows a side-by-side comparison of the 2D avatar model in the booklet and a screenshot of the 3D avatar in the app.

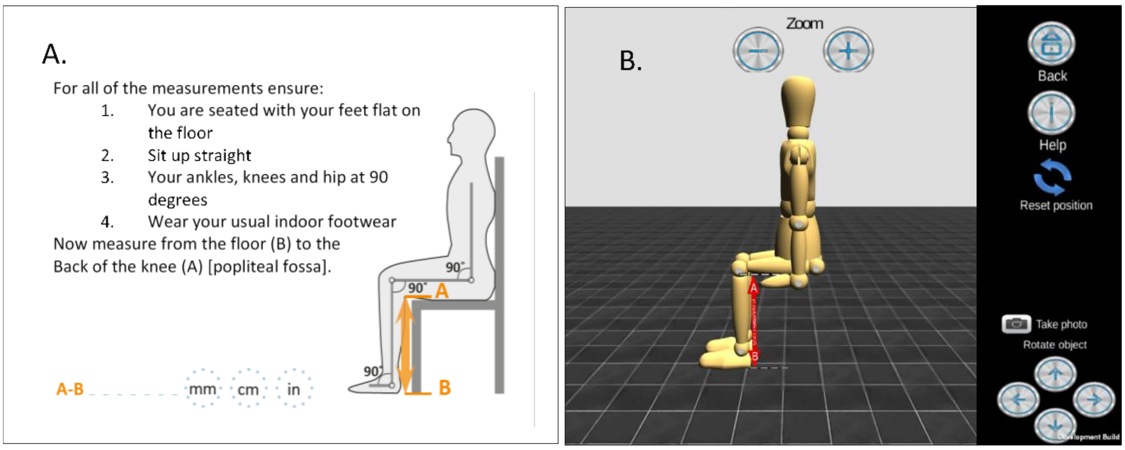


Figure 6-13: Popliteal height guidance on the booklet (A) vs. the popliteal height guidance provided by the application (B).

Once a furniture item button is selected from the main menu, the application then displays the 3D furniture model screen. In the scene, the user is presented with the 3D furniture model and arrow prompts i.e. toilet: *height from the floor to the bowl* and *from the floor to the top of the lid*, which visually indicates where the measurements should be taken. As stated previously, these arrow prompts were carefully positioned in clinically relevant areas after output from consultations with clinicians. Figure 6-14 shows a demonstration of recording the height (from the floor to the top of the lid) of the toilet via the use of a virtual numeric keyboard. The use of this style of keyboard was suggested previously as a means of avoiding the human errors that can be introduced when entering measurements.

Users can select the arrow prompt on the 3D model to activate the audio guide associated to the selected region on the furniture item. Moreover, based on previous work (in Chapters 4 and 5) and discussions with clinicians involved, the arrow prompts are embedded with flashing colour animation (multiple RGB colours with a few milliseconds transition between colours) to indicate to the user when a measurement has been recorded correctly. The arrow prompts contain an error handling mechanism to manage common user errors when inputting data via a virtual keyboard. Failing to manage user error (i.e. the recording of incorrect measurements) could cause inaccurate equipment prescriptions for patients. The app helps prevent this by the arrows continuing to flash until a measurement has been input accurately. Once a measurement is recorded the arrow prompts returns to its default colour red state. The virtual keyboard was changed to a numeric type in line with the requirements and healthcare studies which suggest that the keyboard interface and keying of numbers could be made easier by tailoring this to show the numbers typically used for the intended task [345]. This particular functionality was suggested as an improvement of the previous version of the app by clinicians and interaction designers.

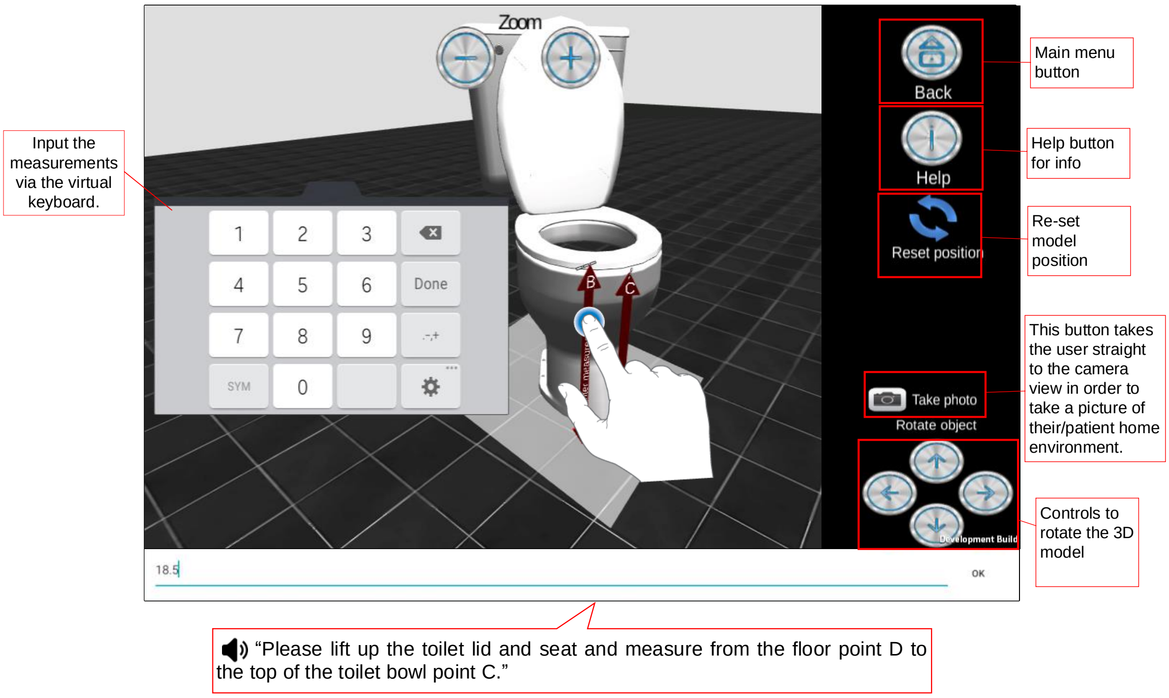


Figure 6-14: Example of recording measurements on the application.

Once the patient has entered their popliteal height, they are then presented with assessment questionnaire related to their demographics, activities of daily living, functional abilities to use equipment, and the furniture to which it is attached. The user is prompted to enter answers to the questions through the text fields, multiple choice items, and binary options (yes or no) answers.

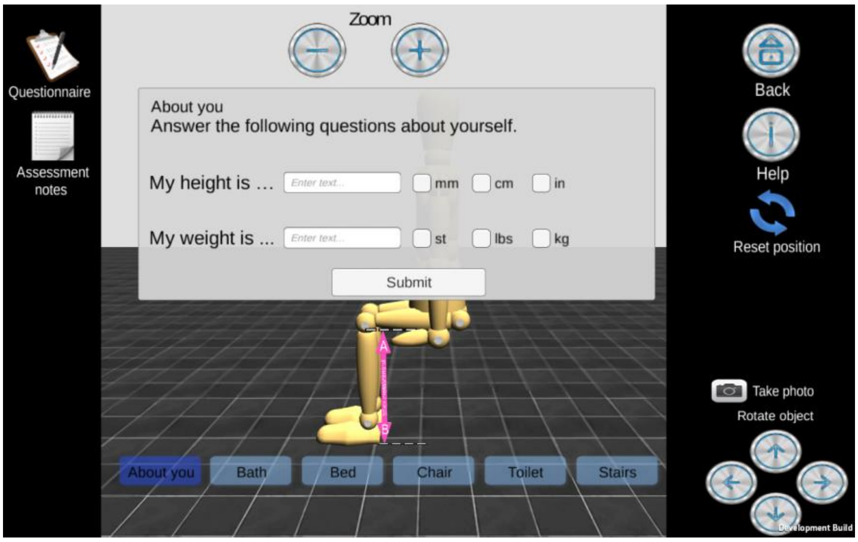


Figure 6-15: Assessment questionnaire on the 'About You' screen.

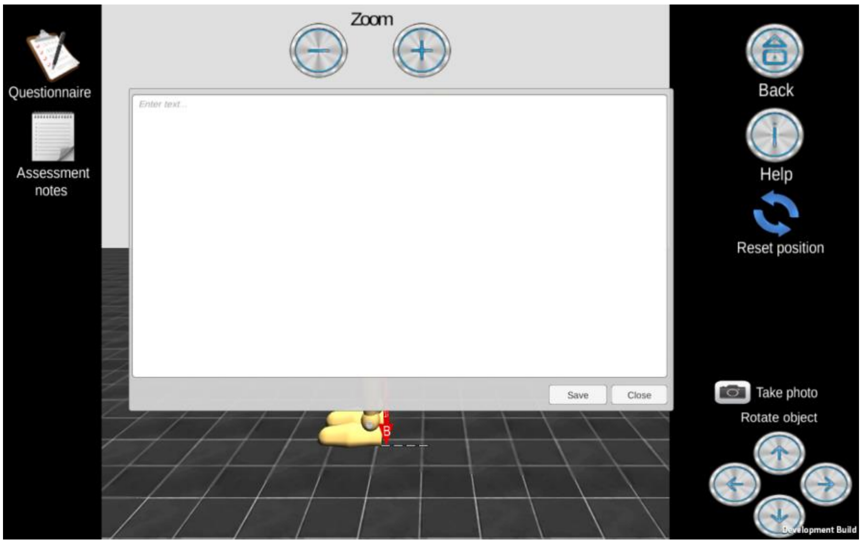


Figure 6-16: Note-taking facility for clinicians.

Figure 6-15 shows the assessment questionnaire window in the 'About You' scene. After the assessment data and notes have been entered (shown in Figure 6-16), the user can click on the Save button and the data is then stored in the local database and a textfile in the device storage. When the user selects a dimension to measure, the patient user can manipulate the view perspective of the 3D furniture models through means of the zoom in/out buttons (located at the top of the furniture screen) to the selected dimension of the furniture item. This functionality is implemented by a *camerahandler* script (developed in JavaScript) that essentially increments the field of view towards the target game object (with that being the 3D model). Note-taking facility for clinicians is presented in Figure 6-16. Figure 6-17 illustrates two options of zooming into the target (in this case the 3D chair guidance model) using the zoom buttons or 'pinch out' gesture (applying two fingers on the screen and gradually moving them apart) to a preferred level of detail for indication of the measurement area; this allows for a full 3D interaction (top screenshot Figure 6-17).

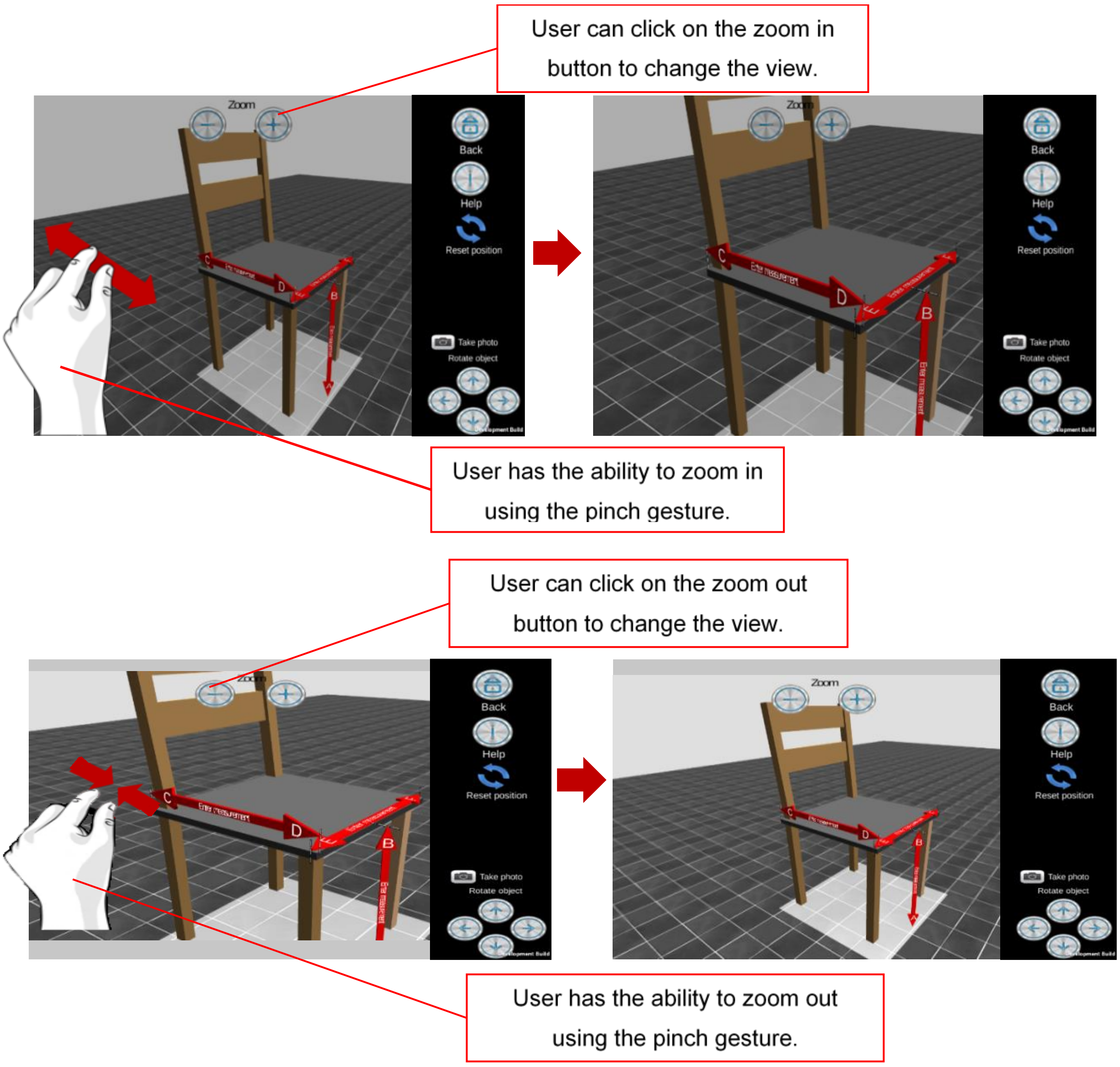


Figure 6-17: Zoom in/out of areas of dimensions to take of furniture items.

To zoom out, the user either employs the zoom button or places their two fingers on the screen and moving them closer together (bottom screenshot Figure 6-17). Alternatively, users can rotate the models via the use of the movement buttons (located at the bottom right-hand corner of the screen) or perform the swipe gesture which involves moving a finger across the touchscreen to orbit the view perspective of the 3D model as illustrated in Figure 6-17. Following user evaluation of the previous version of the app, an exocentric navigation technique was implemented to overcome issues encountered by users when directly rotating the 3D models in previous versions of the app. This technique replaced the earlier rotation functionality which proved to be difficult, as the touch-sensitive screen often interfered with measurement input. Before delving into the description of the exocentric technique used in this app, it is worth providing a definition of the common techniques used to manipulate 3D models in a virtual environment. There are two types of rotation navigation techniques: *egocentric* where the user directly interacts with virtual objects via the use of touch gestures, and *exocentric* where the user indirectly interacts with the virtual environment and objects in a third-person view [346]. As shown in Figure 6-18, the screen view orbits the 3D home furniture models using the touch drag gesture in the direction of the preferred viewing angle of the model.

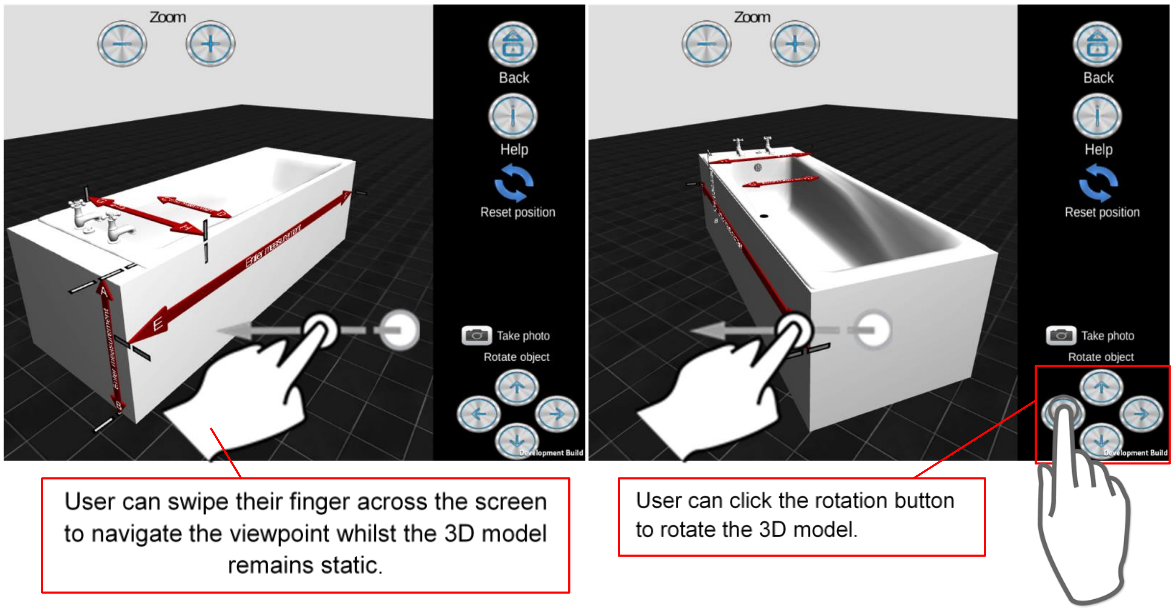


Figure 6-18: Exocentric navigation (using the drag touch gesture) and rotation button.

6.4.1.1 GET request API call and stored measurements in the local DB

To input measurements, the user selects an arrow which provides audio instructions (compiled following consultations with clinicians) on how to carry out a measurement and launches the virtual keyboard which allows its input. In accordance with earlier work, the arrow prompts were re-developed as a range of different coloured arrows, which flash continuously until the user clicks and enters the appropriate measurement. Recording measurements are also restricted for each arrow, as it encourages inputting correct measurements to be stored for such data to be valid for clinical use. The data is then stored in a local SQLite database file and mirrored to the centralised remote database.

It is noteworthy that the data stored are either screenshots, saved locally on the device, or numerical information, namely time, date, patient unique identifier and type of measurements. To gain access to service users' stored assessments, clinicians have the option of using a web browser or an API client to make a GET request to the endpoint linked to a service user. This is a significant improvement over the previous version of the app and the static prompts in the 2D paper-based tools. The service user assessments can also be viewed from the local and remote databases. Figure 6-19 presents an example of a client (e.g. Postman) that clinicians could use for a GET request to the service user profile which returns the measurements as a JSON string along with an HTTP status code: 200 Ok. This is a significant improvement over the previous version of the app and the static prompts in the 2D paper-based tools. The service user assessments can also be viewed from the local and remote databases.

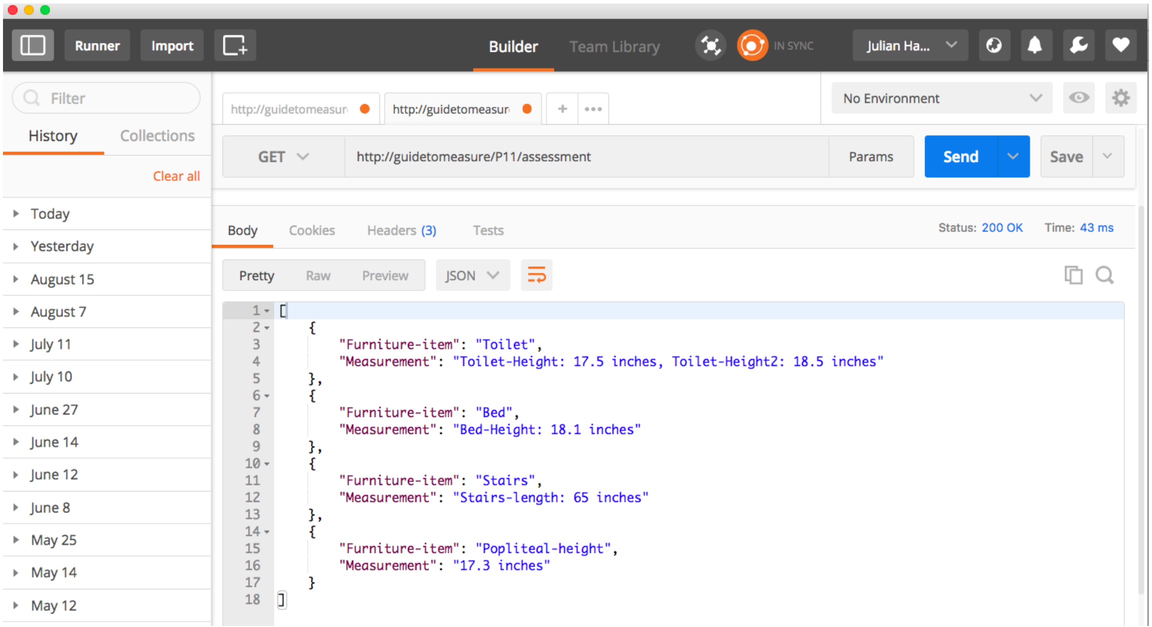


Figure 6-19: GET request of service user assessments using Postman (an API testing application).

Figure 6-20 shows a screenshot of the inserted service user assessment record in the local SQLite database by using a SQLiteViewer application (the top screenshot) and service user assessment record inserted into the remote DB (the top screenshot).

6.5 Recommendation module

The evaluation results derived from Chapters 4 and 5 indicated the need for additional functionality to facilitate the prescribing of equipment sizes based on the recorded measurements; thus a tool to support both assessment and prescription as part of the EFAP. The implementation decisions behind the recommendation module were effectively the same as those provided in the discussion of the measurement guidance module in the previous section 6.4. Nonetheless, the components in this module are set out in the following section and its evaluation discussed in detail in Chapter 8.

To implement the functionality required to provide equipment recommendations, a prescription algorithm was designed, with clinicians, which calculates the equipment sizes from the data collected by the patient. A more detailed description of the design of this algorithm is provided in section 8.2. Clinicians were consulted throughout the design and implementation process to ensure that the recommendation module was aligned with the newly developed algorithm and their specific needs. In keeping with best practice, the interaction designers involved in the previous stages were also involved in this stage. To facilitate the capture of user needs and requirements, clinicians were shown the development environment (i.e. Unity3D) used to develop the app.

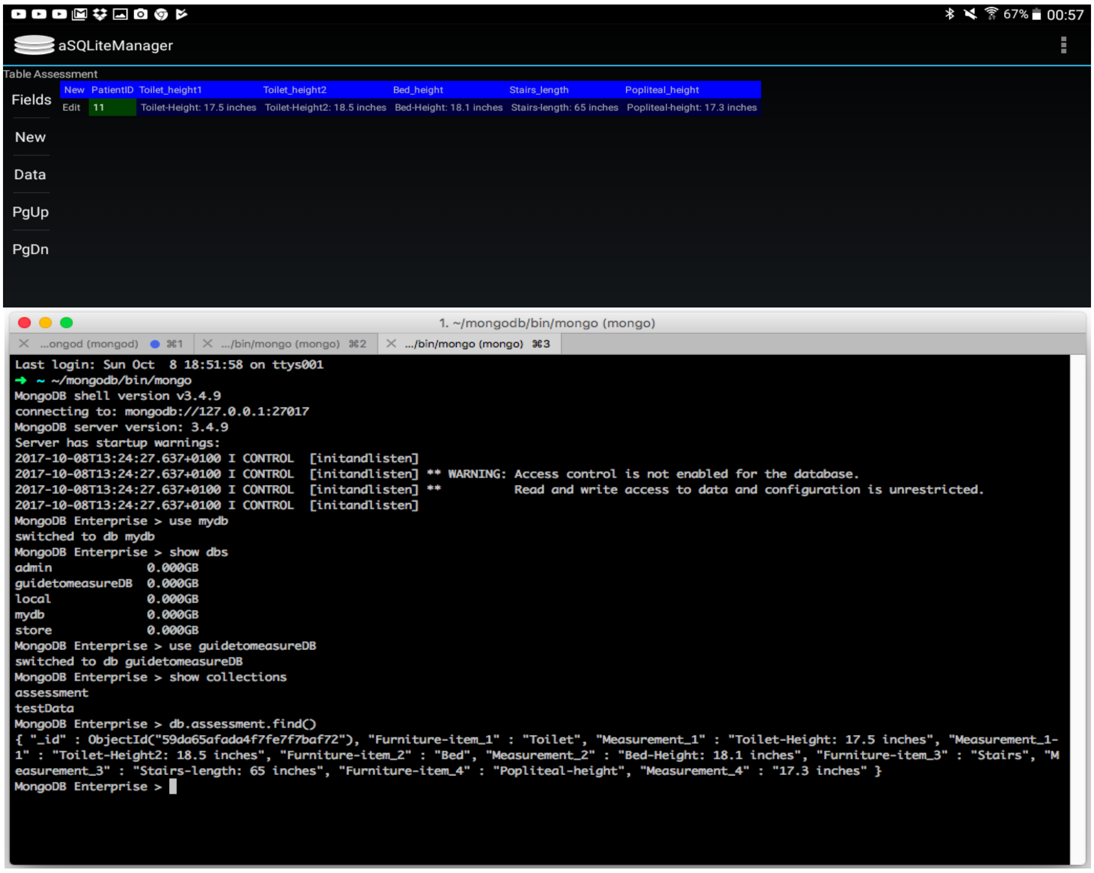


Figure 6-20: Local and Remote DBs for the measurement guidance module.

During the design discussions, participants provided suggestions on the design of the UIs to help stakeholders interpret the recommendations in a more intuitive and user-friendly way. Figure 6-21 presents a screenshot of the development environment used in discussions to help foster design solutions.

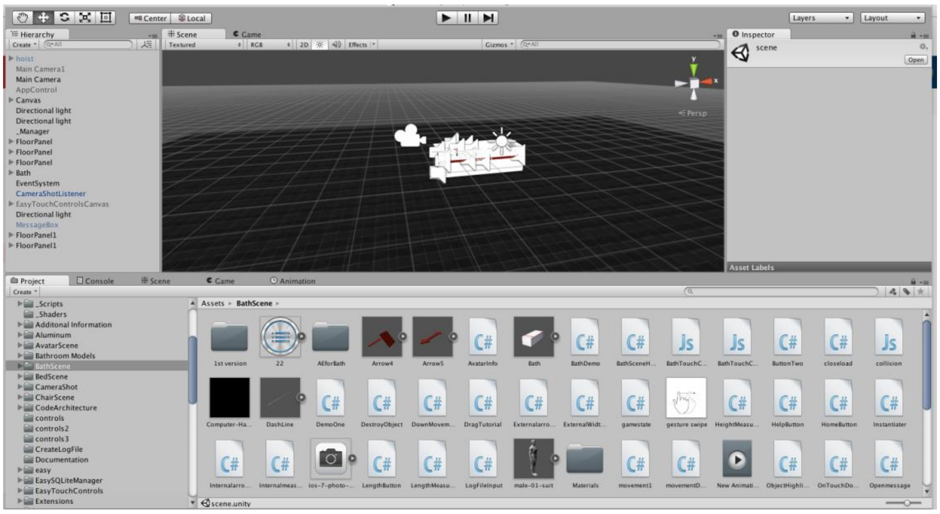


Figure 6-21: Unity 3D game engine environment. This tool was used to facilitate design discussions where changes were being made to the app whilst participants provided suggestions in real-time.

Rendering 3D models: The *unity3D engine* renders the furniture scenes which contain the objects such as the *avatar model*, *3D furniture models, assistive equipment models* and *arrow prompts* in the app. The *assistive equipment models* were implemented in the application based on an existing OT library which contained a sample of 3D assistive equipment models that was used in another research project [72, 196]. Some of the models, however, were refined for use in the app using the Blender v2.76 software [342].

Scenes: Like the measurement guidance module, there are five furniture scenes: *bath, chair, stairs, toilet, bed* and *'About You'* scene where users record their popliteal height dimensions. Once the user records the furniture measurements and selects an item of equipment from the left-hand panel, the *3D recommendation model* is then superimposed onto the 3D guidance model itself in the scene. A colour-flashing animation feature built-in into the arrow prompts was suggested as a useful mechanism to indicate whether a valid measurement was successfully recorded or not. A label of the equipment size is displayed on the 3D equipment model along with a popup window which also displays a description of the equipment and size recommendations – as suggested by clinicians during the design discussions.

The *microservices* are used in the 3D equipment scene as in the measurement guidance module. The user can zoom-in and zoom-out for depth-perception (to view areas of where equipment is installed within the home) and rotate the 3D models by touchscreen gestures using the *model navigation functionality* and *colour flashing feature* microservices inserted into the scenes. The *takephoto feature* allows users to take photos of equipment installed in the home environment. Also, the *audio command*, *notepad,* and *persistent storage* services are used in this module in a comparable way to how they are employed in the measurement guidance module.

Prescription algorithm: the furniture measurements are retrieved from persistent storage in a serialised JSON string and compared against pre-defined equipment sizes, defined as rule-based logic models for each equipment type. When pressed, the equipment buttons on the interface trigger a lookup dictionary function to calculate equipment size and make a GET request to the persistent storage microservice to obtain the measurements and response values from the assessment questionnaire. This generates more accurate equipment size recommendations. The recommendations are then serialised in a JSON string and cascaded to the output recommendation UI. The prescription algorithm is presented and discussed in more detail in Chapter 8. Figure 6-22 shows the recommendations retrieved from the local SQLite database. *Persistent storage* service stores the measurements and recommendations in local memory.

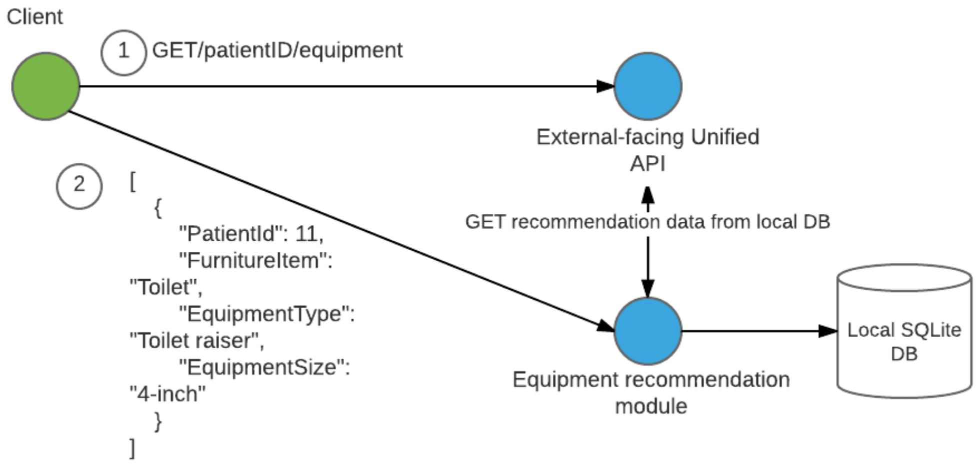


Figure 6-22: Demonstration of an API call to the prescription algorithm microservice.

6.5.1 Recommendation function: module walkthrough

As in the previous module, it is useful to provide an app walkthrough and describe how it was built and aligned with the collected user requirements. For this application module, clinicians can now prescribe equipment sizes based on the measurements and assessment data they have recorded. This could reduce the potentially error-prone task of manually calculating equipment sizes to prescribe to patients. Rendering the 3D equipment models into the scene could also provide a more realistic environment to best reflect the patient's prescription and indicate specific areas within the home where the patient would use the equipment. Figure 6-23 shows the launch screen of the app which allows the clinical user to select the recommendation module to prescribe equipment after home assessments with patients.

Figure 6-23: Launch screen (measurement guidance).

Once the user selects the recommendation module option they can then proceed using the home screen as shown in Figure 6-24.

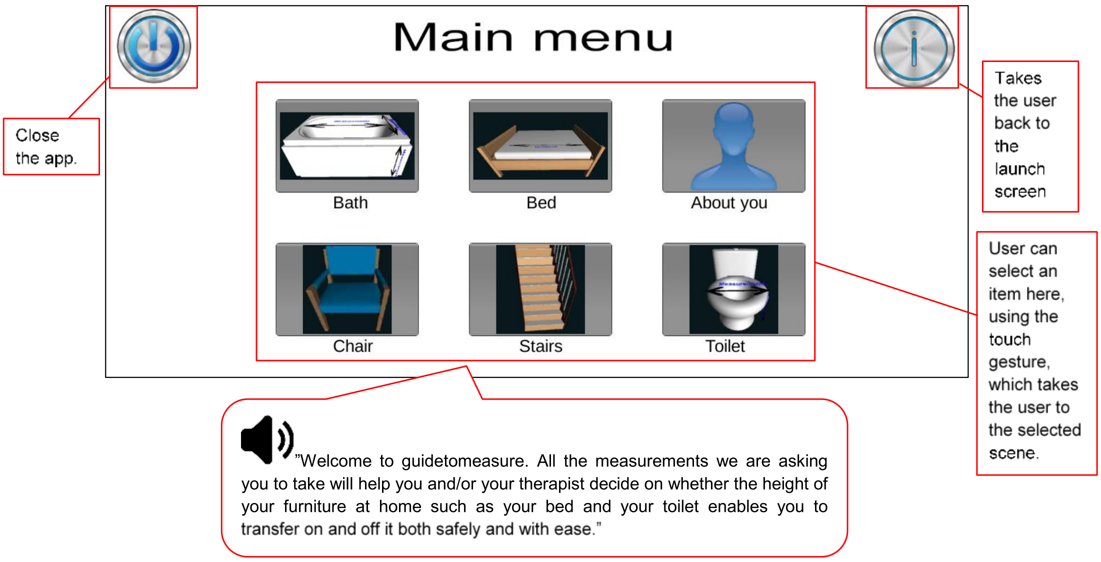


Figure 6-24: Guidetomeasure application main menu.

When this is launched it presents the five home furniture items and another option (*About You*) where the clinical user can enter more detailed assessment information with regards to the patient's functional abilities. This helps to build up a profile of the patient, contributing to the prescription received. By clicking a button on the home screen, the user can proceed to the 3D assessment model screen (for example, prescribing a bath board in the bath scene as shown in Figure 6-25).

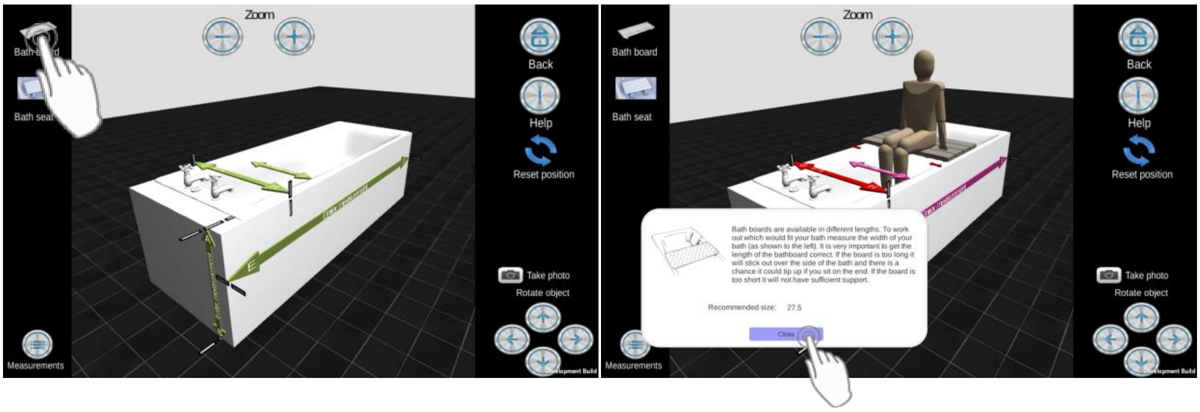


Figure 6-25: prescription of bath board – visualisation view of its context and use.

A UI panel, located on the left-hand side of the screen (as shown in Figure 6-25) contains a selection of minor assistive equipment prescribed to patients. In this screen, the user selects the equipment based on their initial judgement of the patient's needs. This initiates the prescription algorithm, calculates the equipment size, and outputs to the user both the results and a description of the equipment in a pop-up message box. While in the bath screen, the user can zoom-in and rotate by swiping their finger across the screen to manipulate the view perspective of the 3D equipment model. This enables them to gain the desired level of detail of the equipment fitted on to the furniture item. They can also view other measures (e.g. ensuring that the bath rim are 2 inches on either end of the bath board in order to be securely fixed as indicated by the arrow prompts) and see an illustration of equipment use (presented in Figure 6-26). By manipulating the view perspective (i.e. zooming in and rotating the screen view), the user can visualise the avatar superimposed, for example, on the bath board for additional guidance on the required sitting

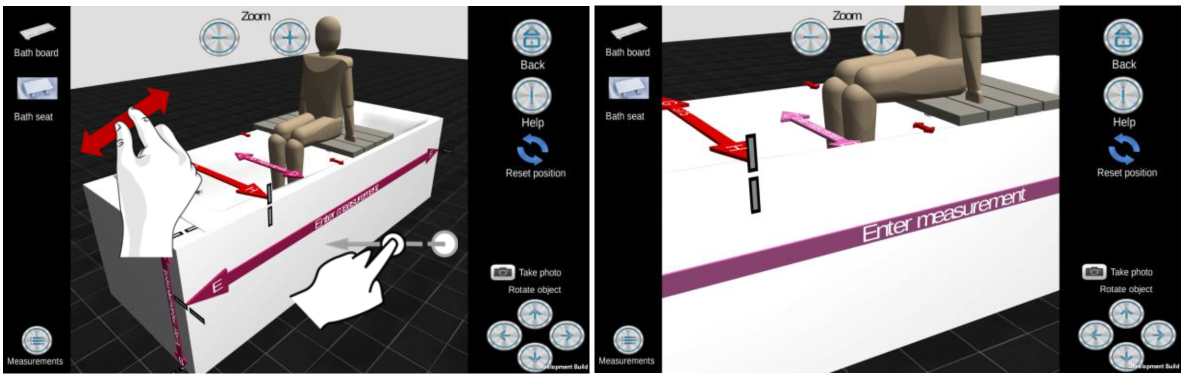


Figure 6-26: Manipulate the view perspective and zoom-in to view the fit of the equipment on the furniture item.

position of a prescribed bath board and help with transfers in and out of the bath. After viewing the equipment prescription, the notification is then presented to the user, showing relevant information about the equipment and provides the size to the user. The equipment recommendation's unit of measurement as inches is consistent with a number of equipment recommendation guidance [347]. Figure 6-27 presents the raised toilet equipment recommendation displayed in a popup message box to the user.

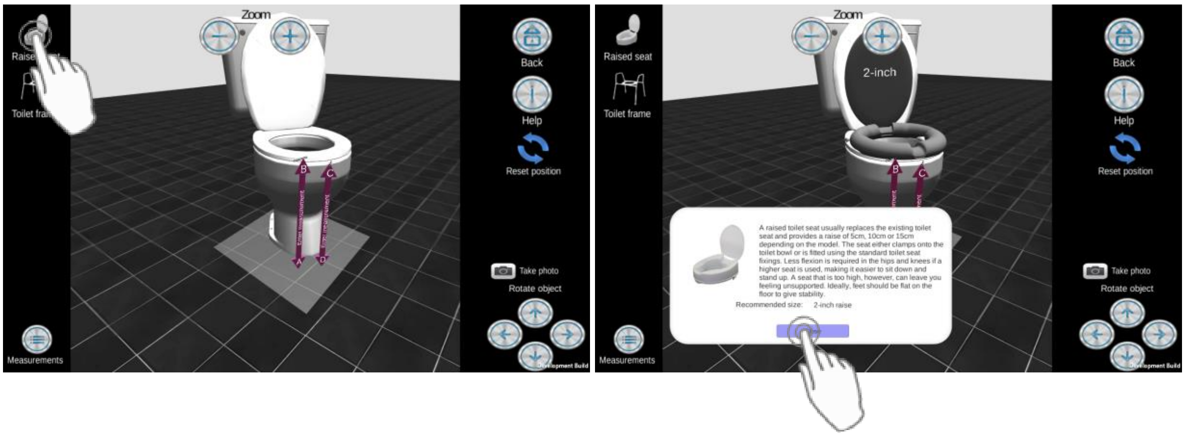


Figure 6-27: 3D toilet model interface, selecting a raised toilet seat as part of a prescription.

The prototype includes zoom-in/out buttons (located at the top of the prototype interface) for manipulating the perspective view of the 3D home furniture models to the preferred level of detail. Alternatively, users can rotate the models by the movement buttons (located at the bottom right hand corner of the screen) as shown in Figure 6-28.

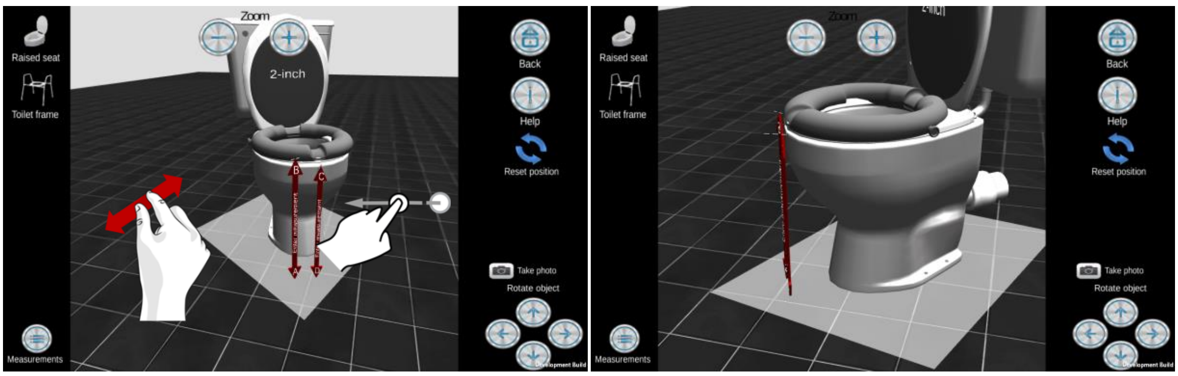


Figure 6-28: Raised toilet seat equipment.

6.5.1.1 GET request API call and stored recommendation in the local DB

The clinical user can request the prescription data produced by the app via the patientID API endpoint. Chapter 8 discusses a user trial study to evaluate the equipment recommendation module with a set of conceptually-modelled patient profiles, developed with clinicians, based on real-life cases.

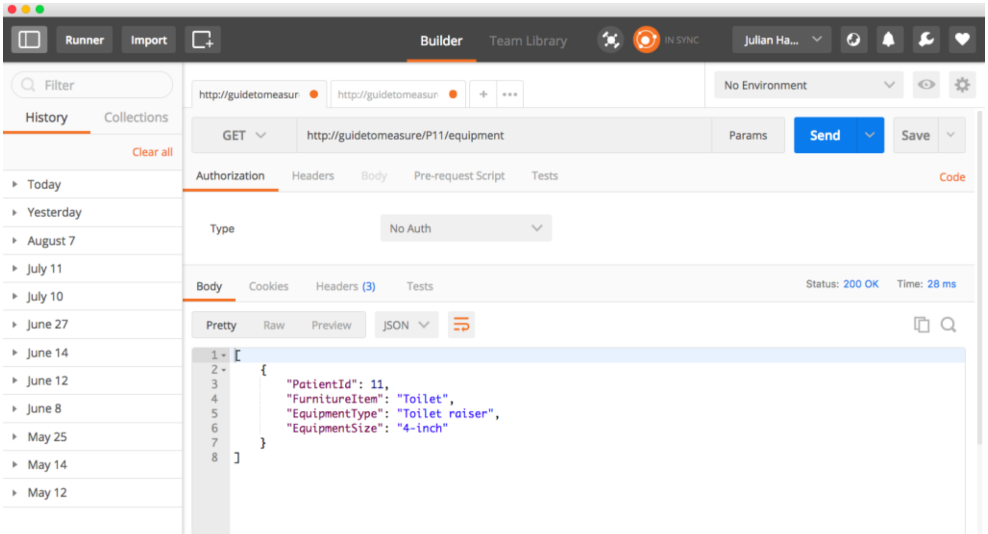


Figure 6-29: GET request for equipment prescription using Postman.

Figure 6-29 presents a screenshot of the GET request to the API which returns a JSON string object that contains the patient ID and associated equipment prescription based on the recorded measurements and assessment data. Like the measurement guidance module (in section 6.4) Figure 6-29, once the prescription data has been generated, it is then stored in both the local and remote databases by a POST request handled through the external-facing unified API (as shown in Figure 6-30).

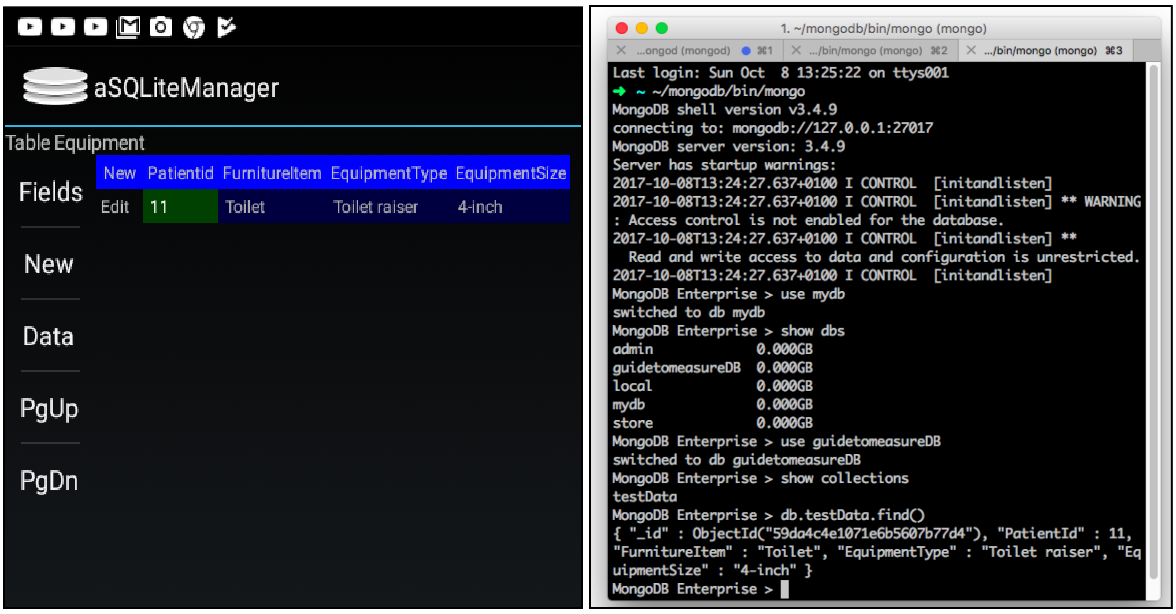


Figure 6-30: Local DB and Remote DB for the recommendation module.

6.6 External-Facing Unified API

The built-in API *exposes an API endpoint* to enable clinicians to retrieve patient assessments and self-directed equipment prescriptions. The naming of the endpoints is the service user ID concatenated onto the URL base address of the API (e.g. /UserID). These endpoints require special permissions to be accessed. Any client used to access the API must be secured using a digital security certificate. The measurement guidance module performs a *POST request* to the *API wrapper* with *serialised dataset in a JSON string* which is then consumed by a script which runs on the *remote Linux-based server* and stored to the *PostgreSQL database* or *Amazon S3 bucket* if any photographs were taken. The recommendations module stores the equipment recommendations directly to the local DB and a unit of logic within the persistent storage microservice then handles a GET request call made to the module by the API wrapper, which then feeds this dataset to the remote DB.

Given that an *in-house web-based system* used by clinicians in their practice supports API requests (or could be configured to do so), a GET request would be required to retrieve patient assessments and equipment prescriptions from the app. Recorded assessments and prescriptions are merged with the corresponding patient record, which is stored on a *PostgreSQL database* located on a remote *Linux-based server*. Any supporting photographs (aiding clinical reasoning) taken of the patients' home furniture is stored in the Amazon S3 bucket to be viewed by clinicians who have access via an API request call. There are two scripts located on the server which handle data that is stored to the remote DB and S3 bucket. A Docker image [348] is developed based on the Ubuntu image with Postgres DB and Amazon S3 client pre-installed to run the storage services and node.js to run the scripts which handle the API calls locally on the remote server (see the Docker file [349] and shell script [350] on Github). Using Docker allows for an environment which is consistent with any deployment environments that the storage services run on. A Docker Compose configuration file is created to launch the PostgresSQL DB and Amazon S3 bucket instance in two separate containers, running their corresponding node.js scripts (see the Docker Compose file [351] on Github).

6.7 Conclusion

This chapter presented the last two iterations that were carried out in accordance with the DSR approach and RAD used for the design and implementation of the research's artefact. Specifically, the user requirements, collected from previous studies and necessary to further improve the design, implementation, and underlying architecture of the application have been investigated. The refined system architecture of the app is then described. Subsequently, a description of the core microservices, individual components, and rationale of the implementation decisions provided for the two application modules have been described. A walkthrough of the two application modules has been similarly presented to understand their core functionalities before proceeding with a detailed evaluation with the user cohorts for which it is intended. In line with the evaluation metrics of the fourth step in the DSR cycle, and based on the ISO 9241-11 usability standard metrics, the app will be evaluated based on three usability measures, namely effectiveness, efficiency, and satisfaction.

6.8 Chapter summary

This chapter explained the process of refining the prototype based on the user requirements identified in study 1 and 2, and additional input from interaction designers and clinicians. A complete revamp of the overall system architecture was implemented to cope with the various use cases and the different environments/infrastructure in which the app would be deployed. It also described the two iterations of developing the measurement guidance and equipment recommendation modules within the app. The subsequent chapters (which reports user-based studies) will discuss the evaluation of the measurement guidance module and recommendation module with both clinicians and older adult patients and explores their satisfaction and attitudes towards adopting the app in the EFAP.

Chapter 7
Guidetomeasure: A mixed methods evaluation from older adult patient and clinician perspectives

7.1 Introduction

Until the work conducted in Chapters 4 and 5, little research emphasis has been placed on designing assessment-aid tools to enable older adults to become better stakeholders in the EFAP by allowing them to visualise and interpret measurement guidance more efficiently. Moreover, provides a means for which collaborate efforts are reached in resolving issues of the incorrect fitment of assistive equipment. Current 2D paper-based tools lacked natural depth cues to sufficiently visualise crucial areas in the home in a more perceivable way, as it provided static visuals. Consequently, 3D visualisation was, therefore, hypothesised as an alternative solution to address the limitations of existing 2D guidance tools. As a result, the challenges and opportunities of utilising 3D visualisation technology as a feasible and assistive tool for the EFAP were explored via a high-fidelity prototype co-designed with OTs and older adults. Employing 3D visualisation was seen as an attractive opportunity in which the visual quality of measurement guidance can be improved, whilst tackling the clinical input into shared decision making. A conclusion was reached, in both studies, regarding the need to evaluate the application for its capabilities, particularly its effectiveness to visualise specific areas of where users need to take measurements, effort/time expended on interpreting the guidance and to further explore a revised version of the prototype that accommodates the additional recommendation functionality.

Following the refinement of the Guidetomeasure-beta prototype, Chapter 6 formally presented the *Guidetomeasure application* and its associated system architecture as a further improvement to the 2D paper-based guidance tools currently in use. Given the increasing evidence of paper-based guidance tools used to inform the EFAP to ensure the correct measurements of the patient and themselves and associated assessment data is collected, creates opportunities in which the app, could be used by stakeholders in practice. The same 2D paper-based guidance tools is still being used as the main tool to assist in the EFAP, despite its drawbacks in accurately visualising measurement guidance via the use of 2D diagrams which lack the depth cues required to visualise measurement points on a furniture item or self in order to prescribe the necessary assistive equipment. A recent study funded by UK Occupational Therapy Research Foundation has developed and published an evidence-based 2D paper-based measurement guidance tool which provides as a means to improve the collection of accurate measurements of home furniture taken and recorded by patients and clinicians [352]. The booklet was proposed as a solution to address the equipment abandonment issues and developed via this five-stage user-centred study, represents the state of the art in 2D paper-based measurement guidance in the field of occupational therapy.

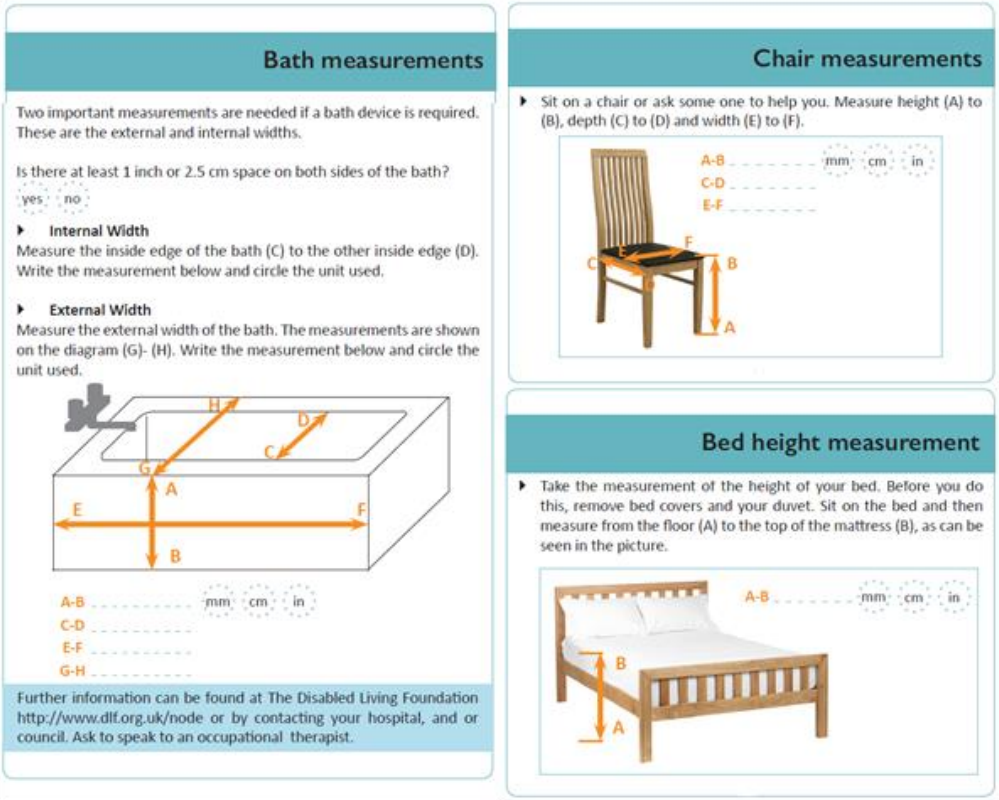


Figure 7-1: A disabled living foundation (DLF) measurement guidance tool used by clinicians in practice (e.g. toilet and bath measurement guidance) [352].

Figure 7-1 presents some example content from the 2D measurement guidance booklet. Exploratory studies of clinician and older adult perceptions of using 3D visualisation technologies for facilitating measurement tasks as part of the EFAP indicates positive attitudes towards their use in practice (reported in Chapters 4 and 5, respectively). According to the researcher's knowledge, no existing research, however, explores the clinical utility of the such technologies in terms of its effectiveness, efficiency, or indeed whether 3D visualisation of measurement guidance for equipment prescription enables the recording of more accurate and reliable measurements compared with the existing state of the art 2D paper-based currently in use. To conclude, it is anticipated that new technology-based tools is likely to play a key enabling role in future healthcare delivery and promote the shift towards the new patient-centred care paradigm to help realise patient self-care, self-assessment and self-management. If this is to be realised, it is pivotal to enable both patients and clinicians to accept and incorporate new technologies with a view to improving outcomes it is able to provide. Promoting technology-assisted health care is core to patient engagement, satisfaction, collaboration with clinicians and enabling patients to take ownership for their own care to enhance quality of life [353]. Above all, the falls prevention domain is no exception to this. Considering the clinicians and informal carers (i.e. family members) taking measurements on behalf of older adults, the increasing role of patients to carry out self-assessments for assistive equipment and the high level of equipment abandonment occurring as a result of using 2D paper-based measurement guidance, there is an urgent need to evaluate proposed technology-based solutions that support assessments required for equipment provision. More specifically, given the 3D visualisation technologies have achieved promising results in enabling patients to self-assess in other areas of healthcare reported in the literature coupled with the results in the previous studies, there is a need to further investigate the value of employing such technology in the EFAP context. The next subsection provides the aim of the present study in this chapter.

7.1.1 Aim

To address Objective O4 outlined in section 1.3, the aim of the two user cohort studies in this chapter is to evaluate the performance of the measurement guidance module compared with existing 2D paper-based measurement guidance tools that are currently used in practice with older adults and occupational therapists. This chapter explores the relative effectiveness and efficiency of the application, and perceptions of the application in terms of user satisfaction and attitudes towards adopting and using this new technology in practice. Specifically, the following research questions are addressed in two studies reported in this chapter:

- RQ1. Does the 3D Guidetomeasure application, on average, enable more accurate recording of measurements, compared with the paper-based measurement guidance booklet?
- RQ2. Does the 3D Guidetomeasure application enable more consistently accurate recording of measurements, compared with the paper-based measurement guidance booklet?
- RQ3. Does the 3D Guidetomeasure application enable measurements to be recorded more efficiently, compared with the paper-based measurement guidance booklet?
- RQ4. How satisfied, in terms of usability, are users of the 3D Guidetomeasure application, compared with the paper-based measurement guidance booklet?
- RQ5. What are service users' and OTs views of the 3D Guidetomeasure application, in terms of the perceived challenges, opportunities, and their intention to adopt and use this new technology in practice?

This chapter is structured as follows: Section 7.1 presents the main user-based studies along with the methods used to investigate the effectiveness of the Guidetomeasure app to accurately visualise measurement guidance and to explore user satisfaction, and to identify perceived challenges, opportunities and intention to use the app in practice. Section 7.2 and 7.3 presents the evaluation results of the OT study and older adult study, respectively, and their findings in the context of the five key research questions of the study (RQ1-RQ5). Section 7.4 discusses the limitations of both studies. Conclusions are drawn with details of both studies in Section 7.5.

7.1 Methods

This section provides details of the data collection and analysis protocol used to address the specific research questions of this chapter. Figure 7-2 provides an overview of the protocol.

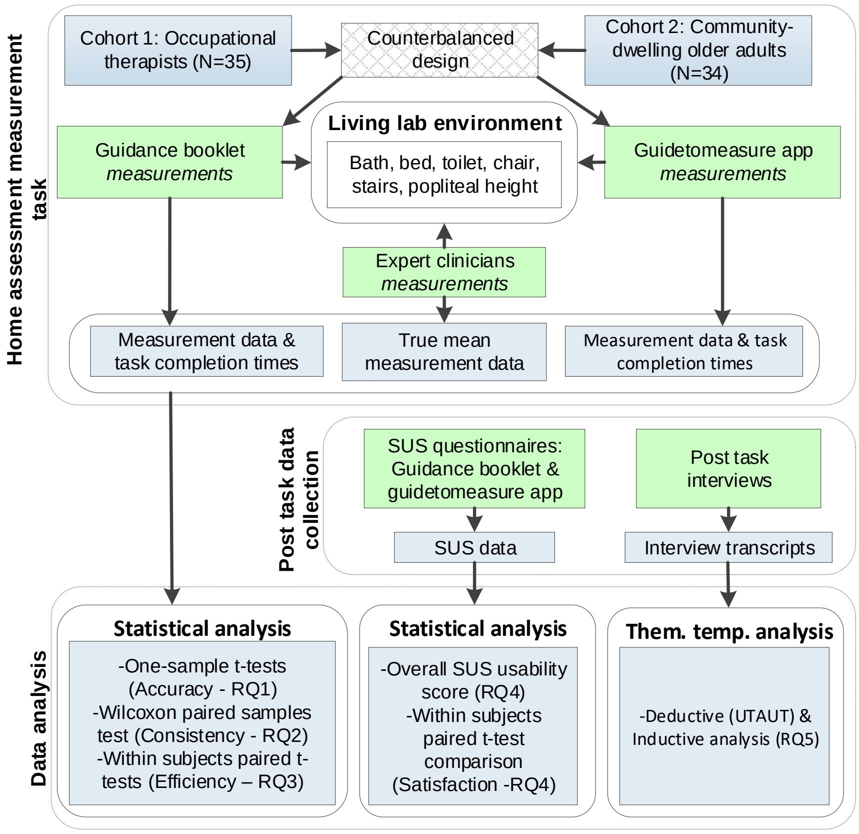


Figure 7-2: Overview of the user trial session, methods and process.

7.1.1 Participants

7.1.1.1 Occupational therapists (Cohort 1)

Thirty-five OT participants were recruited to via hospital and community-based occupational therapy services in the UK in an online search through the NHS service directories page. To recruit more participants, contact was made with 'gatekeepers' (such as clinical leads and heads of OT services) in the first instance in order to disseminate the invite to colleagues that work with older adults. OT teams working within the social care sector, as part of local authorities, were also identified by an online search. In addition, the invite was distributed through the College of Occupational Therapists (COT) on their website in the specialist sections and made available on the COT social networking pages (e.g. Facebook and LinkedIn); and also using snowballing technique to recruit from existing contacts. The number of participants required was estimated by carrying out an a priori power analysis using G* power 3.1 software, which to ensure a power of 0.80 with a medium effect size of 0.5 (dz) and for a 2-tailed hypothesis was calculated as N = 34 participants, of which 35 OT participants were recruited. The inclusion criteria were that participants: (1) had the relevant clinical experience of working with community-dwelling older adults within a hospital or other clinical setting (e.g. falls service and social care and health services) or in the community; (2) experience in the provision of assistive equipment and minor adaptions; (3) carried out home visit assessments; (4) used a range of technology; (5) were registered healthcare practitioners; and (6) were proficient English speakers. Participants' demographic details reveal that the majority of the participants were female *(93.9%, N = 31)*. This may be justified by the view that the occupational therapy field is identified as a female-dominated profession [286]. The mean score of clinicians' years of experience equated to 14.2. All clinicians reported experience working with community-dwelling older adults, specialising in a range of areas that fall within the community or hospital. Table 7-1 presents a summary of OT participant profiles for study 3.

Table 7-1: Summary of OT participant profiles.

Part. ID	Gender	Years of experience	Specialty
#P1	F	20	Community
#P2	F	6	Neuro
#P3	F	12	Local Authority/community work
#P4	F	10	Community
#P5	M	2.5	Older people
#P6	M	7	Adult social care, manual handling
#P7	F	17	Adult social care, assistive equipment
#P8	F	4	AT/telecare
#P9	F	15	Intermediate care
#P10	F	19	Community/Renal
#P11	F	21	ICT
#P12	F	7	Trauma Orthopaedics
#P13	F	35	Community/physical adults
#P14	F	24	Community
#P15	F	10	Social care, equipment and adaptations
#P16	F	20	Social care
#P17	F	14	Respiratory
#P18	F	1	Intermediate care
#P19	F	12	Neurosurgery, renal, stroke, CT
#P20	F	23	Physiotherapy
#P21	F	5	Intermediate care
#P22	F	14	Acute medicine
#P23	F	16	Community
#P24	F	27	Equipment, primary care
#P25	F	29	Primary care-Community
#P26	F	29	Community housing
#P27	F	6	Primary care(Community)
#P28	F	25	Community enablement/older people
#P29	F	11	Research
#P30	F	15	Intermediate care
#P31	F	13	Community
#P32	F	8	Community Nursing
#P33	F	6	Social care
#P34	F	4	Community enablement/older people
#P35	F	11	Community

7.1.1.2 Older adults (Cohort 2)

Thirty-four older adult participants were recruited to via adverts placed on the Disabled Living Foundation (DLF) and British Polio Fellowship (BPF) websites. A newsletter was also posted to members of these groups and Stoke on Trent Community Health Voice and the local carer group. The number of participants required was estimated using G* power 3.1 software, which to ensure a power of 0.80 with a medium effect size of 0.5 (dz) and for a 2-tailed hypothesis was calculated as N = 34 participants [354, 355]. The inclusion criteria were as follows: (1) aged 55 and over; (2) familiar with using smart-phones/tablets computers; (3) considered to be active with no restrictions that prohibit their ability to measure key items of home furniture; and (4) understand the English language. Nineteen participants were female, fifteen were male. The mean age of participants was 68.3 years (age range 55–86, *SD* 7.69). Twenty participants were retired, eleven employed and three did not specify their occupation. Table 7-2 presents a summary of participant profiles for this study.

Table 7-2: Summary of older adult participant profiles.

	Percent	Frequency
Gender		
Male	44.2	15
Female	47	16
Info not provided	8.8	3
Age		
50-60	26.5	9
61-70	29.5	10
71-80	14.8	5
81-90	9	3
Info not provided	20.8	7
Health condition		
Angina	3	1
Arthritis	9	3
Asthma	9	3
Cancer remission	3	1
Diabetes	6	2
Epilepsy	6	2
Heart disease	3	1
Hip replacement	3	1
Polio	6	2
Stroke	6	2
Info not provided	47	16
Occupation		
Retired	59	20
Employed	32.5	11
Info not provided	12	4
Notes: Participant ID = P1-P34 (*N*=34)		

7.1.2 Protocol and instrumentation: Applied to Cohort 1 and 2

A within subjects counterbalanced design was used to verify the accuracy and consistency of measurements recorded using the Guidetomeasure application (measurement guidance module) compared with the 2D paper-based booklet measurement guidance. It is worthy to note that a pilot study was carried out with 7 clinicians and 3 patients in the same setting in which the main studies was conducted. This trial run was to iron out any issues with the experimental design and to rectify any issues that arise from it and make changes accordingly. The study was conducted in a controlled

Living Lab space located in the Stoke on Trent Mobility and Independent Living Centre. The living lab hosted a bedroom, bathroom, lounge, kitchen, dining area and full-length stairs. In preparation for the trials, the living lab was assembled by expert clinicians to represent a typical daily living environment whilst ensuring that all necessary items were in place for the measurement task. Four expert clinicians took measurements for each item and reached consensus on the true mean values (gold standard) against which measurements recorded by participants could be compared.

Informed consent was obtained at the start of each trial session. Initially, participants were given a brief demonstration of the two measurement guidance tools (i.e. the Guidetomeasure app and booklet) and were given a tour of the living lab environment. They were then issued with one of the measurement guidance tools, a tape measure and asked to record the measurements of items as indicated by the measurement guidance tool. For the popliteal height, participants were asked to measure a seated person's popliteal height to allow comparisons for testing accuracy between the two measurement guidance tools. The total amount of time taken was noted on completion of the measurement task using each tool.

Participants were then asked to complete an adapted Systems Usability Scale (SUS) questionnaire [288] which included the 10 standard SUS statements and four additional bespoke statements specifically about the clarity of guidance they feel the respective measurement tools provide for the task of taking measurements. Participants were required to rate all statements using a 5-point Likert type scale ranging from 1 (strongly disagree) to 5 (strongly agree). Each participant then engaged in a second iteration of this procedure, using the alternative measurement guidance tool. A counterbalanced design was employed to control for order effects, i.e. alternating the order in which respective measurement tools were issued to participants at the start of each session. Once both measurement guidance tools had been used and associated SUS questionnaires completed, a post task interview was conducted with each participant to discuss their experiences of using the measurement guidance tools and the perceived challenges and opportunities of using these in practice. All interviews were recorded and transcribed verbatim.

7.1.3 Data analysis Protocol: Applied to Cohort 1 and 2

This data analysis protocol described in this section was used for both Occupational Therapists and older adult patient cohorts (in studies 3 and 4, respectively). IBM SPSS statistics package Version 20.0.0 was used to analyse the measurement data, task completion times, and SUS questionnaire survey responses. Measurement error values were calculated as the difference between participant measurement values and corresponding true mean values (gold standard). One-sample t-tests were applied to verify measurement accuracy (RQ1) i.e. whether the mean error differences were significantly different from the true mean values for each measurement guidance tool respectively. Error values were converted to absolute error values.

To establish whether there was a significant difference between the two measurement guidance tools, in terms of the accuracy consistency (RQ2), the Wilcoxon signed-rank test was applied to compare the ranked differences of absolute error values generated by both tools. The Wilcoxon signed rank test was conducted as the datasets were not normally distributed [208]. Paired sample t-tests were applied to test for differences in task completion times (RQ3) and to compare differences in individual SUS item responses (RQ4) and the two subscales that SUS is said to be made up of [290, 323] i.e. Usability (SUS items 1-3, 5-9) and Learnability (SUS items 4 & 10). Furthermore, overall SUS scores were calculated and interpreted according to the acceptability range, and the adjective and school grading scales [288]. This involved calculating a mean SUS representative value on a 100-point rating scale for each sample. These scores were then mapped to descriptive adjectives (Best imaginable, Excellent, Good, OK, Poor, Worst Imaginable), an acceptability range (Acceptable, Marginal-High, Marginal-Low, Not acceptable) and a school grading scale (i.e. 90-100 = A, 80-89 = B etc.). *The baseline adjective and acceptability ranges are derived from* a sample of over 3000 software applications [289].

Thematic template analysis [356] was used to analyse interview transcripts (RQ5). This analysis technique is deductive [234], where analysis is driven by a pre-defined template (a priori) of themes based on a theoretical framework and/or the analytical interest of the researchers [357]. For the OT study (cohort 1), the qualitative data analysis was both deductive (theory driven) and inductive (data driven), whereas the patient study was purely deductive. The first stage involved creating a template which used three key determinants of technology use as defined by the Unified Theory of Acceptance and Use of Technology (UTAUT) Model [306]. UTAUT is a widely used and empirically validated model of technology acceptance which integrates eight existing models and has been shown to account for 70% of user intentions to adopt and use new technologies. Hence the analysis considered the three key UTAUT determinants of intention to adopt new technology: Performance Expectancy (PE); Effort Expectancy (EE); Social Influence (SI). The entire corpus was perused and coded; identifying specific extracts from the data that related to the three UTAUT themes and other high-level emergent themes. The corpus was then perused iteratively through several stages of splicing, linking, deleting and reassigning sub-themes within the context of the high-level themes. Finally, a template covering the finalised themes and sub-themes was proposed. Conducting such analysis in this way is in congruent with ‘contextual constructivism’, a stance of which accepts that there are multiple interpretations of a given phenomenon that is dependent on the context in which data were collected and analysed [324].

7.2 Results: Occupational therapist evaluation study (Cohort 1)

7.2.1 Measurement accuracy

The first research question was to compare the relative accuracy of measurements recorded using the app and booklet measurement guidance tools (RQ1). The results of the comparison between the Guidetomeasure application and booklet, and the extent to which the respective recorded measurements are significantly different from the true mean values are presented in Table 7-3.

Table 7-3: Measurement accuracy for Guidetomeasure app and booklet guidance for OT cohort.

		App.						Booklet					
	True mean (cm)	Mean (cm)	St. Dev.	Mean error diff. (cm)	Df	t	Sig. (2-tail)	Mean (cm)	St. Dev.	Mean error diff. (cm)	Df	t	Sig. (2-tail)
Bath													
Length	170.00	169.52	1.05	0.48	34	-2.71	0.010	169.41	1.12	0.59	33	3.44	0.002
Internal Width	57.00	56.78	0.95	0.22	34	-1.71	0.097	56.36	0.78	0.64	34	-5.16	0.000
External Width	70.00	69.79	0.65	0.21	34	-2.40	0.022	69.63	0.49	0.37	34	-5.42	0.000
Height	55.60	55.55	0.49	0.05	33	-0.73	0.469	56.01	0.71	-0.41	34	3.44	0.002
Chair													
Height	46.50	46.64	1.09	-0.14	34	0.74	0.462	45.46	2.25	1.04	34	-2.74	0.010
Width	45.60	45.50	3.74	0.10	34	-0.15	0.879	45.22	2.98	0.38	34	-0.75	0.455
Depth	53.40	53.30	2.31	0.10	34	-0.27	0.790	53.86	2.02	-0.46	34	1.35	0.186
Toilet													
Height A (floor - bowl)	45.00	45.02	0.94	-0.02	34	0.11	0.915	44.26	1.18	0.74	34	-2.99	0.005
Height B (floor - seat)	47.50	47.16	1.09	0.34	34	-1.83	0.076	46.66	1.66	0.84	34	-3.71	0.001
Stairs													
Length	152.00	152.84	2.99	-0.84	34	1.67	0.104	150.71	6.17	1.29	34	-1.23	0.226
Bed													
Height	45.00	44.28	2.93	0.72	34	-1.46	0.153	44.85	3.59	0.15	34	-0.24	0.812
Anthropometric													
Popliteal height	44.50	44.28	0.79	0.22	34	-0.96	0.346	43.47	1.97	1.03	34	-3.11	0.004

*Indicates statitisically significant at < 0.05 level

Comparing the measurement guidance tool results, in all cases, with the exception of bath-external width, bath-internal width and chair-width, standard deviation values (denoted as SD) for the app were smaller than that of the booklet. Therefore, as an initial observation, this suggests that the app tended to generate more precise (but not necessarily accurate) measurements compared with the booklet. In reference to accuracy, for all cases, in absolute terms, the mean error differences were larger for the booklet compared with the app. This therefore means in absolute terms that the application generated more accurate measurements compared with the booklet for all 12 of the home furniture measurements.

The one sampled comparison of the Guidetomeasure app mean error differences against the true mean, reveals that in the majority of cases (i.e. ten out of 12), the mean error differences are not significantly different from the true means: bath-internal width ($p = 0.097$); bath-height ($p = 0.469$);

chair-height ($p = 0.462$); chair-width ($p = 0.879$); chair-depth ($p = 0.790$); toilet-height-A ($p = 0.915$); toilet-height-B ($p = 0.076$); stairs-length ($p = 0.104$); bed-height ($p = 0.153$); anthropometric-popliteal-height ($p = 0.346$). This indicates that in these cases, there is no evidence that the app produces inaccurate measurements at the 0.05 significance level. Two of the 12 cases are significantly different from the true mean values, suggesting that in these cases, the app produced inaccurate measurements at the 0.05 significance level.

The one sampled comparison of the booklet mean error differences with true mean reveals that four out of the 12 mean error differences are not significantly different from the true means: chair-width ($p = 0.455$); chair-depth ($p = 0.186$); stairs-length ($p = 0.226$); bed-height ($p = 0.812$). Whereas eight of the 12 cases are significantly different from the true mean values, indicating that in these cases, the booklet produced inaccurate measurements at the 0.05 significance level.

Overall, comparing the performance of the app and booklet, both measurement guidance tools produced inaccurate measurements for two similar items: bath-length; bath-external width. The booklet produced inaccurate measurements for a further six items bath-internal width; bath-height; chair-height; toilet-height-A; toilet-height-B; patient-popliteal height. The key difference between the two measurement guidance tools was that the booklet produced inaccurate measurements at the 0.05 significance level for all bath measurement items: bath-length ($p = 0.002$); bath-internal width ($p = 0.001$); bath-external width ($p = 0.001$); bath-height ($p = 0.002$), all toilet measurement items: toilet-height-A ($p = 0.005$); toilet-height-B ($p = 0.001$), one of the chair measurements: chair-height ($p = 0.010$) and patient-popliteal height ($p = 0.004$). With regards to the app, two measurements were produced for the bath (bath-length (p = 0.010); bath-external width (p = 0.022)), there were, however, no evidence of inaccuracy for the chair (chair-height (p = 0.462); chair-width (0.879); chair-depth (p = 0.790)) and toilet (toilet-height-A ($p = 0.915$); toilet-height-B ($p = 0.076$)) measurement items.

7.2.2 Measurement accuracy consistency

The second research question was to compare the accuracy consistency of measurements recorded using the two respective guidance tools (RQ2). The results of this analysis are presented in Table 7-4. When considering the median error differences between the two measurement guidance tools, in 8 of the 12 cases the median error value for the booklet was larger than that for the app, hence resulting in a negative median error difference in all eight cases: bath-internal width: (md err. diff. -0.97); bath-height ($Md = -0.08$); chair-height ($Md = -1.10$); chair-width ($Md = -1.00$); chair-depth ($Md = -0.11$); stairs-length ($Md = -0.10$); stairs-length ($Md = -0.18$); patient-popliteal ($Md = -0.10$). In the remaining four cases, there was no evidence of any difference between the median error values for the app and booklet. This indicates that the mid-point error values tended to be lower for the app compared with the booklet.

Table 7-4: Comparison of accuracy consistency for Guidetomeasure app and booklet for OT cohort.

	App.	Booklet	Paired differences					
	Md err. (cm)	Md err. (cm)	Md err. diff. (cm)	Df	Z	Sig. (2-tail)	Effect size (r)	Effect size magnitude
Bath								
Length	0.18	0.18	0.00	33	-0.035[b]	0.972	0.01	Trivial
Internal Width	0.15	1.12	-0.97	34	-1.857[b]	0.063	0.32	Medium - Large
External Width	0.15	0.15	0.00	34	-0.581[b]	0.561	0.10	Small
Height	0.32	0.40	-0.08	33	-1.162[b]	0.245	0.20	Small - Medium
Chair								
Height	0.70	1.80	-1.10	34	-3.667[b]	0.000*	0.63	Large
Width	1.26	2.26	-1.00	34	-0.725[b]	0.468	0.12	Small
Depth	0.94	1.05	-0.11	34	-1.046[b]	0.295	0.18	Small - Medium
Toilet								
Height A (floor - bowl)	0.51	0.51	0.00	34	-0.624[b]	0.532	0.11	Small
Height B (floor - seat)	0.55	0.55	0.00	34	-2.024[b]	0.043*	0.35	Medium - Large
Stairs								
Length	0.50	0.60	-0.10	34	-0.019[a]	0.985	0.00	Trivial
Bed								
Height	1.82	2.00	-0.18	34	-1.430[b]	0.153	0.25	Small - Medium
Anthropometric								
Popliteal height	1.22	1.32	-0.10	34	-2.821[b]	0.005*	0.48	Medium - Large
a. Based on positive ranks.								
b. Based on negative ranks								
*Indicates statitisically significant at < 0.05 level								

The Wilcoxon signed-rank test comparing the absolute error differences of the app and booklet measurements, reveals that in three out of the 12 cases, the app produced more consistently accurate measurements than the booklet: chair-height, z = -3.667, p = 0.000, with a large effect size r = 0.63; toilet-height-B, z = -2.024, p = 0.043, with a large effect size r = 0.35; patient-popliteal height, z = -2.821, p = 0.005, with a medium-large effect size r = 0.48. All z scores were based on negative ranks, with the exception of stairs-length; however, despite the scores being based on negative ranks, there were negative median error differences. In one of the 12 cases, the sum of ranked positive differences was lower than the sum of the negative ranked differences indicating that the app consistently produced more accurate measurements (i.e. lower measurement error differences) compared with the booklet. While most of the cases (11 of the 12) the sum of the ranked positives was higher than the sum of the negative ranked differences, the medium error differences show that the app produced less error differences compared with the booklet.

Overall, comparing the performance of the app and booklet in terms of accuracy consistency, the app outperformed the booklet in three of the 12 cases, which generated significantly more consistently accurate measurements than the booklet. In six of the remaining nine cases, although the differences were not significantly different in statistical terms, the app tended to generate smaller error differences than the booklet (indicated by the negative medium differences, but the z values being based on negative ranks). In the one remaining case (stairs-length) the app tended to generate smaller error differences than the booklet (indicated by the *z* value being based on positive ranks), however, there was no significant difference in the error differences for this particular measure. In four of the 12 cases, there were no differences in the error differences (indicated by the 0 medium difference scores). However, one of the four cases were significantly different at the 0.05 significance level.

7.2.3 Task completion time

The third research question was to consider whether there are any significant differences in the overall task completion time (measured in seconds) when using the respective measurement guidance tools (RQ3). The results of this analysis are presented in Table 7-5.

Table 7-5: Statistics of the task completion time using Guidetomeasure app. and booklet for OT cohort.

	App.		Booklet		Piared differences			
	Mean (Seconds)	St. Dev.	Mean (Seconds)	St. Dev.	Mean diff. (Seconds)	Df	t	Sig (2-tail)
Time	404.29	151.68	681.33	276.99	-277.04	34	-5.95	0.000*
*Statitisically significant < 0.05 level								

The result of the paired samples t-test comparing task completion times for the app and booklet measurement guidance tools reveals that participants required significantly less time to complete the interactive task when using the app ($M = 404.29$, SD 151.68) compared with the booklet ($M = 681.33$, *SD* 276.99), t (34) = -5.95 $p = 0.000$. The *SD* scores for the application and booklet revealed a high variance indicating that the amount of time it took participants to complete the measurements using both the guidance tools which varied more between participants using the booklet than using the application. A Pearson's *r* correlation coefficient comparison was performed to determine whether the relationship between years of experience, measurement accuracy, and task completion time may provide further insight into the large variance for the two tools.

7.2.4 Satisfaction and overall usability

The fourth research question was to measure how satisfied users are of the general usability of the app compared to the booklet (RQ4). The total SUS score for the Guidetomeasure app was 83.7 out of 100 (*SD* = 11.0), which, according to the evaluation criteria for SUS [289], indicates that the application delivers 'excellent' (Descriptive adjective), 'acceptable' (Acceptability range), and 'Grade B' (School grading scale) levels of usability. The total SUS score for the booklet was 70.4 (*SD* = 10.1), indicating 'good', 'acceptable', and 'Grade C' levels of usability. Figure 7-3 presents the SUS rating scale with the overall SUS scores for Guidetomeasure and the booklet.

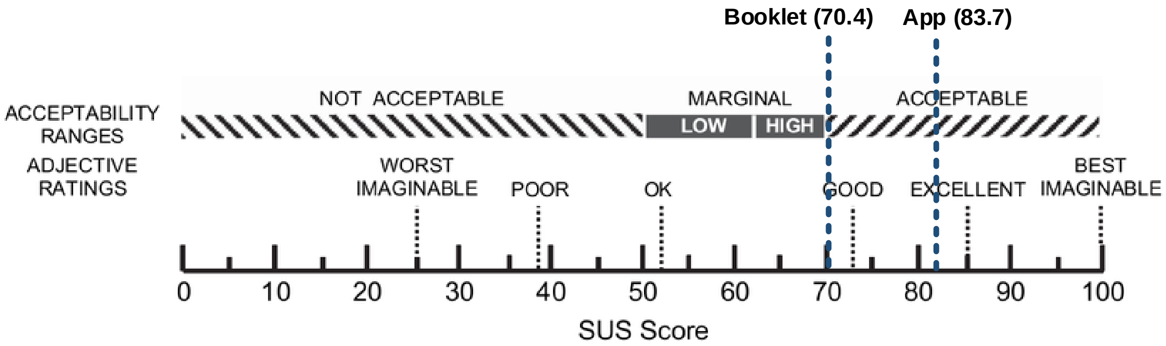


Figure 7-3: SUS rating scale with overall SUS results for Guidetomeasure app and booklet for OT cohort.

Follow-up analysis of individual SUS items for the application and the booklet were conducted to identify any specific usability issues that the participants experienced during the interactive task. Table 7-6 presents the individual SUS item results, differences (denoted as gap score) and corresponding significance values. All 10 SUS individual mean item scores and all four clarity of guidance items were above the neutral mid-point of 3.00, indicating that overall, participants tended to be positive about both measurement guidance tools. In all cases (i.e. SUS items and clarity of guidance items), the app achieved higher absolute mean scores compared with the booklet, which is signified by the positive gap scores. This further indicates that all of the ten SUS items, participants tended to be more positive about the application compared with the booklet. Whilst the participants tended to respond more highly for the application compared with the booklet in relation to SUS items S1, S5, S6, S8 and S9, the difference however in statistical terms were not significant. Five of the ten SUS items (S2-S4, S7 and S10) were significantly different, but in all cases the application significantly outperformed the booklet. For the clarity of guidance items, all of the items (A1-A4) were significantly higher for the app compared with the booklet. Above all, participants tended to be more enthusiastic about the application and felt that it delivered a better user experience for conducting their clinical work in relation to usability and learnability, hence the general trend from the descriptive statistical results, showing that the application outperformed the booklet.

Results for item S2, reveal that participants tended to be more positive about the application and that it was significantly less unnecessarily complex than the booklet ($p = 0.000$). Responses for S3, show that participants found the application to be more significantly easier to use compared to the booklet ($p = 0.000$).

For S4, participants responded that using the application is significantly less likely to require the support of a technical person to be able to use it compared to using the booklet (0.000). Responses to item S7, reveal that most people are significantly more likely to learn how to use the application very quickly than they are with using the booklet ($p = 0.051$).

Table 7-6: Guidetomeasure app. and booklet comparison of SUS scores for OT cohort.

SUS item	App. Mean	Booklet Mean	Gap score	Df	t	Sig. (2-tail)
S1: I think that I would like to use the app/booklet frequently.	4.23	3.83	0.40	34	1.48	0.147
S2: I found the app/booklet unnecessarily complex. [a]	4.51	3.83	0.68	34	3.86	0.000*
S3: I thought the app/booklet was easy to use.	4.34	3.34	1.00	34	4.18	0.000*
S4: I think that I would need the support of a technical person to be able to use the app/booklet. [a]	4.57	3.26	1.31	34	5.29	0.000*
S5: I found the various functions in the app/booklet were well integrated.	4.09	3.89	0.20	34	0.77	0.445
S6: I thought there was too much inconsistency in the app/booklet. [a]	4.46	4.17	0.29	34	1.89	0.067
S7: I would imagine that most people would learn to use the app/booklet very quickly.	4.11	3.66	0.45	34	2.02	0.051*
S8: I found the app/booklet very awkward to use. [a]	4.31	4.29	0.02	34	0.14	0.893
S9: I felt very confident using the app/booklet.	4.37	4.11	0.26	34	1.20	0.239
S10: I needed to learn a lot of things before I could get going with the app/booklet. [a]	4.49	3.43	1.06	34	4.24	0.000*
Clarity of guidance (additional items)						
A1: Using prompts (arrows) on the diagrams to assist with measurement was clear and easy.	4.57	3.94	0.63	34	3.51	0.001*
A2: Using the app/booklet improves the way I measure home furniture.	4.03	3.54	0.49	34	2.35	0.025*
A3: The instructions were clear and helpful.	4.23	3.80	0.43	34	2.12	0.041*
A4: I felt the diagrams clearly illustrated where I had to measure on the item/object.	4.34	3.86	0.48	34	2.62	0.013*

A1 – A4 bespoke items presented in addition to the 10 standard SUS items to evaluate clarity of guidance

[a] Responses of negative items reversed to align with positive items, higher scores indicate positive responses.

* Indicates statitisically significant < 0.05 level

Results for item S10 suggest that participants disagreed with having to learn a lot of things before being able to use the application, compared with the booklet (p = 0.000). Item A1, indicates that the arrow prompts in the application were significantly clearer and easier to use than the prompts presented on the booklet (p = 0.001). Responses to item A2 show that the application is significantly more likely to improve the way they measure home furniture, more so than the booklet (p = 0.025). For A3, results suggest that the instructions provided by the application were more clear and helpful as compared to the booklet (p = 0.041), and that the application clearly illustrated the instructions to measure home furniture significantly more compared to the booklet (p = 0.013).

With regards to the paired samples t-tests comparing SUS Learnability, Usability and Clarity and helpfulness of guidance constructs, the Cronbach's alpha scores for all of the respective SUS constructs and effectiveness of guidance construct were above the acceptable threshold value of 0.6 for small sample studies [292], however, item S2 for the usability construct was deleted from both questionnaire tool responses, so that the Cronbach's alpha score for the usability met the acceptable reliability threshold. The reason the corresponding item S2 was deleted for both tool was so that a like-for-like comparison could therefore be made between the app and booklet usability construct. Table 7-7 presents the results of the comparison of these respective constructs.

Table 7-7: Comparison of SUS constructs for OT cohort.

Construct	Items	Cronbach's alpha App	Cronbach's alpha Booklet	App. Mean	Booklet Mean	Gap score (App. - Booklet)	Sig. (2-tail)
Usability	SUS items 1-3, 5-9	0.61 (item 2 deleted)	0.65 (item 2 deleted)	4.31	3.89	0.42	0.000
Learnability	SUS items 4,10	0.69	0.61	4.53	3.34	1.19	0.000
Effectiveness of guidance	Effectiveness of guidance items 1-4	0.70	0.74	4.29	3.79	0.50	0.001

A1 – A4: items presented in addition to the 10 standard SUS items to evaluate effectiveness of guidance
* Statitisically significant < 0.05 level

The app achieved a significantly higher Usability score (*M* = 4.31, SD = 0.50) compared with the booklet (*M* = 3.89, *SD* 0.40), *t* (34) = 3.93 *p* = 0.000. For Learnability, the app achieved a significantly higher score (*M* = 4.53, *SD* = 0.70) compared with the booklet (*M* = 3.34, *SD* = 0.94), *t* (34) = 5.643, *p* = 0.000. For effectiveness of guidance, the app achieved a significantly higher score (*M* = 4.29, *SD* = 0.61) compared with the booklet (*M* = 3.79, *SD* = 0.70), *t* (34) = 3.801, *p* = 0.000. Indicating that overall, the app was considered to be significantly more usable and effectiveness of guidance compared with the booklet.

7.2.5 Perceived challenges, opportunities, adoption and use

The fifth research question was to ascertain user views of the app in terms of the perceived challenges and benefits and its clinical significance compared to its equivalent tool (RQ5). Five high-level themes emerged thematic template analysis: Performance Expectancy (PE); Effort Expectancy (EE); Social Influence (SI); Clinical Benefits (CB); Augment Clinical Practice (ACP). The information in parentheses includes a unique participant ID and years of experience. Figure 7-4 presents an overview of the high-level themes and associated sub-themes.

Performance expectancy

Participants reported that the application provided *enhanced measurement guidance*, simulating how it would be perceived in real-life which helped to better interpret the guidance. The 3D visualisation feature/functionality was perceived as clear and easy to use. Particularly the 3D models of the chair and toilet items were perceived as being clearer and more detailed in 3D form and hence more useful in identifying measurement points.

> *"… 3D's great the more real life it is, the easier it is to interpret…the clearer the instruction and the clearer the visual part, would make it easier to use. So hopefully, that would make it easier for*

everybody to adapt to. Obviously, everybody hasn't got technology to use an app, so that would have to be taken into consideration as well." (P35)

"It gives you the visual and you know the prompts on where to measure because sometimes you know, if I say to someone can you measure the depth of the chair, they may not interpret that correctly and therefore measure…I suppose the best one to use is the compression, you know, to have something compressed when you're sitting on it, to get a correct measurement, so that everybody would automatically because of having that prompt." (P29)

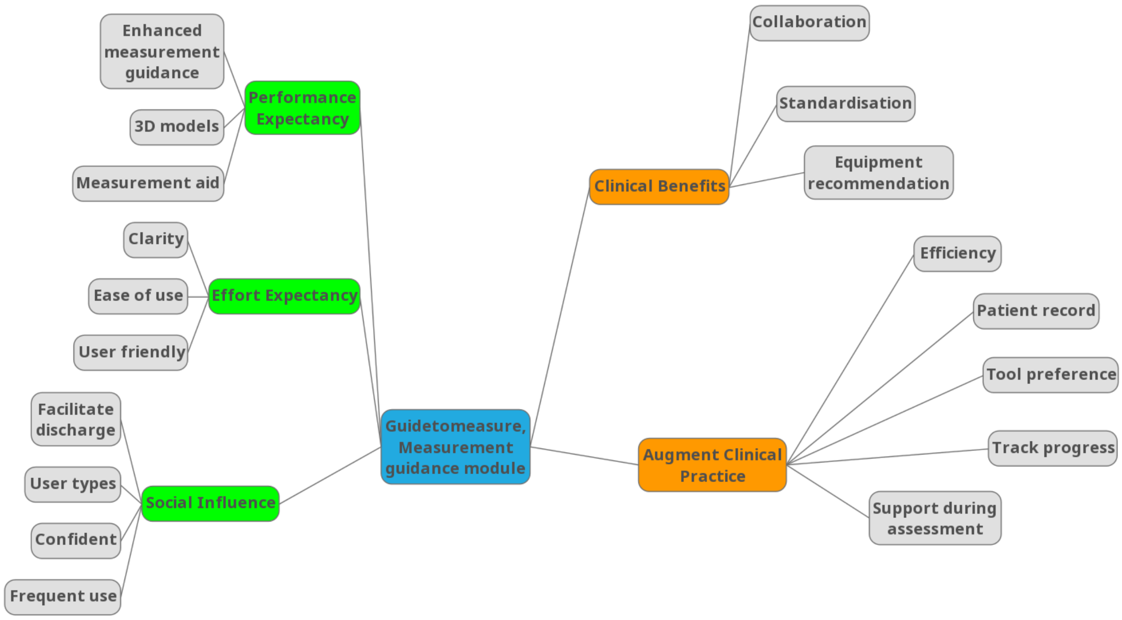


Figure 7-4: Thematic mind map of core themes and associated sub-themes for OT cohort.

Participants reported the clarity of the *3D models* in the app, particularly its additional dimension which enable users to make sense of the measurement guidance that the app conceptualises. One participant commented on the enhanced look and feel of the 3D model as being a notable distinction to that of the diagrams presented in the booklet and the app functionality to manipulate the view perspective as an aid to interpret the measurement guidance. Another participant highlighted the benefit of 3D in capturing the height of furniture items and other modifications to the home that are otherwise not effectively captured in 2D and the limitation of having an aerial view of a 2D drawing of the measurements captured.

...the 3D images were really good...I think they [the app and booklet] were just virtually the same…it was just more 3D in the app than it was on the paperwork…in the booklet it wasn't as clear as what the 3D app was and you couldn't move the diagrams on the booklet to get a better view (P35)

"…having worked previously with 3D models, they made sense to me. And I think that they would probably make sense to most people using the app as well. I think particularly if you're doing modifications, because the heights of things are important, sometimes that not always captured in 2D, particularly if like you're re-doing someone's kitchen for example, and you just had an overhead drawing of it, sometimes you're going to miss those heights of things, you know, the height of the sink and the…they're not always captured the same way." (P4)

Most participants felt that the app served as a useful *measurement aid*, as one participant said: "it [the app] is a quick prompt guide" and is also used to "generate reports". Due to the fact that the app was an electronic alternative to the booklet, it could therefore enable clinicians to generate electronic copies of assessments and support inter-professional collaboration. One participant was satisfied with the app which allows them to select their preferred unit of measurement to record in and that the user would be prompted if a measurement was missed during assessment. They also made reference to the 3D measurement guidance being consistent with the requirement measurements to collect as part of the EFAP.

"...in terms of clinically, it's definitely useful, especially if the app can be used to generate reports and it's just a quick prompt guide, as you go room to room, what to measure, that you've got the measurements...It's something that can't necessarily go missing, like paper sometimes can, if you've got an electronic copy that could be stored, that could be sent over by e-mail to different teams, to make it just that little bit more efficient than pen and paper." (P22)

"... I tried five I think different measurements and if I remember right, you could personalise that I had it on centimeters because that's what I prefer to do but I think I could have changed that to inches and so on if I had wanted to. And as I went through the different measurements, picked the room I was measuring, the information it asks for is just consistent with what's needed, the relevant things, and if you don't do one measurement, it will sort of prompt you a bit. So that's, it makes sure that you have all the stuff you need for everything you're measuring." (P4)

Effort Expectancy

Responses revealed that participants were satisfied with the *clarity* and ease of use of the app's instructions and navigation controls that it provides and demonstrated the extent of the app being usable suggesting that a user, with no prior exposure, could start using the app for its intended purpose.

"…the clearness of the models, the arrows to show you where to measure and the simplicity of the instructions. I think people who are able to pick that up, and I think as time goes by that will be more

and more people, they would find it easy because of its ease of use, and it instructs you to do what you need to do quite easily." (P9)

"... It's very quick…I'm used to using iPads and computers and things like that, so it's fairly easy for me to pick it up. It's quite clear to navigate through. So I don't think there are any major problems there." (P4)

Most participants commented on the *ease of use* of the application including its capability to record measurements, selection of guidance for furniture items and features to better interpret the measurement guidance. Participants were enthusiastic about the feature to select their preferred unit of measurement in which the measurements will be recorded, prior to the commencement of the measurement task, which made as one participant put it: "*It's very easy to use because there's no complicating factors*". Other participants found that the app to be clear and straightforward in providing 3D measurement guidance.

"It's very easy to use because there's no complicating factors...you can't really get it wrong, especially once you've chosen your, the way you're going to record it, in terms of inches or millimeters or centimeters, or whatever that is." (P2)

"Yeah, so it was easy to use, easy to select which furniture you were measuring, what measurements you needed to take. Yeah, so it was straightforward and clear with what information was needed." (P7)

Participants found the app's interface is *user friendly* to interact with and its associated functionality. For example, one participant noted that the arrow prompts were helpful and clear in providing instructions for taking measurements in the form of 3D visualisation and audio guide. Another participant felt that the app was just as easy to use as the booklet which hence made it user-friendly with no learning overhead required.

"I thought it was easy to use and not more complicated certainly than a pad or a form that you would otherwise fill in by hand. So yeah, the simplicity of it I think is makes it user-friendly." (P27)

"... It's very user-friendly and visual. There are kind of arrows telling you where you're measuring from. And then you've got your audio prompt when you're measuring ..." (P6)

Social Influence

Participants felt that the use of the app could be used by family members to help *facilitate discharge* of older patients from hospital so that clinicians could use such information gathered for appropriate assessments.

"…it could potentially be most useful for families, particularly if somebody is about to be discharged from hospital and OTs need that information. I can see a good role for it there." (P31)

Participant responses relating to *user types* highlighted some scenarios of how the two user types would use the app. One participant felt that, as a practitioner, they would be able to use the app on their own, however, in cases where they would need to collaborate with patients or the patient's family member then a walkthrough of the app and providing instructions for taking measurements would, therefore, be required.

"As a practitioner, I would use it on my own, but if I were showing it to a client or a family member or…I think I might walk them through it, although I don't know how much that really needs to be walked through it, I thought it was pretty self-explanatory with everything. But usually people just like a little bit of instruction, just so they get a vague of what they're doing, even if you just explain why you're taking the measurements." (P5)

Participants felt *confident* using the app to perform measurement tasks as part of the EFAP. One participant reported that their confidence of using the app is a direct result of their role as an OT because it complemented the tasks they perform during home assessments. In addition, they also expressed their satisfaction of using the app on independently, without the need for technical intervention.

"I was confident using the application, but the thing is because obviously I'm an OT, I knew what I was using it for, so I felt it was supplemented what I was doing. So yeah, I'm fairly happy with using that on my own." (P23)

Participants had rather interesting views of the app's frequent use in the EFAP. Taking measurements of patients and their home during assessments is, of course, a task often performed as part of the role of an OT, which participants felt the app would be beneficial as a tool to use frequently in the EFAP. Despite that most of the participants expressed the benefits of using the app, one participant, however, explains that clinical users could become familiar with what to measure which would not need to use the app frequently, but as a valuable way of recording measurements. It was also felt that app would be used more by those who do not take measurements as often as OTs.

"I think as an OT who's taking measurements all day long with every patient you work with and assessing people in their homes…so I think it would be beneficial to use it frequently" (P5)

"I would recommend it for use but not sure if I would use it myself. Purely because if you do it every day, you become very accustomed to knowing what you have to measure and you don't need to keep

> *looking back, although it's a valuable way of storing information. Yeah, I'd use it initially but then it becomes second nature when you do something a lot, it would be more appropriate for people that didn't do it very often." (P12)*

Clinical benefits

It was suggested that using the Guidetomeasure application in practice could improve *collaboration* with service users and other clinicians. Participant P3 felt that the app could be utilised by community-dwelling service users to self-assess their needs and share the resultant assessment data, which may enable clinicians to collaborate with users on possible options for recommendations which surface from analysis of the data collected. The app was also seen as a solution for reducing paper usage and sending patient assessment records to other clinicians based in different hospitals to deal with and prescribe equipment for patients that are sent by other clinicians.

> *"I think it's something that would probably start with the assessment centre clients, so they could use it at home and they could even send it in before the assessment and…if there are queries, they can, you know it might make the…more assessments could be done perhaps a little bit more efficiently or…we might decide, well OK, you need to do this first or that's not going to be easy or whatever. So there might be a little bit more dialogue before the person visits." (P3)*

> *"It cuts down on paper usage and you've got an electronic record then of any assessments, so that you could pull off a report or pull off the measurements and send them to other colleagues and people you know through the system. Because there's a lot of times we'll have patients that end up going into hospital and they'll have a different OT team looking after them there, you know so it would be useful for sending, you know information to your colleagues in other teams so they can prescribe correct equipment when the need arises." (P34)*

Participants felt that the app is a useful *standardisation* approach to the provision of assistive equipment in promoting consistency of measurements taken among stakeholders involved in this particular intervention.

> *"I think it's very useful to create a standardised approach to everybody because although we're all OTs, we will all do it very differently, so I think that's one side of it, the standardisation, everybody will be doing the same thing." (P12)*

> *"I think if it could become something that's used nationally, it would mean it would help ensure that there's more consistency between the measurements that professionals and patients and relatives have taken."(P7)*

Some participants suggested adding an *equipment recommendation* function to the application as it was felt that the app could be used for prescribing equipment rather than just a tool to assist with data collection. One participant commented that the app supports users with collecting information about the patient and taking measurements of their home furniture for equipment which is information that could be used for the app to provide recommendations based on the recorded data.

> *"There's information about the service user themselves and the equipment that you're measuring and the objects that you're measuring, it could come up with a recommended treatment prescription." (P14)*

Augment clinical practice

Participant P35 felt that most people could become skilful at using the app and that it provided *efficiency* in terms of reducing effort in recording measurements of home furniture items.

> *"Yeah, I think it's easy for people to become skillful at using it…and reduces the room for error in my opinion anyway." (P35)*

Participants reported on the benefits of the app correlating the recorded assessment data to the *patient record*. They commented that as the app is electronic it could help with documenting the assessments more effectively, particularly with storing assessment data directly to the patients' record.

> *"It would also benefit that if it was electronic, in the team I work for, we use electronic records, so if we could upload the data and attach it to the person's record, it would be of benefit and give us a clear document assessment really." (P12)*

Participants stated their *tool preference* and the underlying reasoning for their preference. One participant mentioned the benefits of the arrow prompt functionality in the app, as it instructs users on how to conduct measurement tasks via audio advice which is triggered by clicking on the arrow prompt, a valuable functionality not offered in the booklet.

> *"… I like the fact that app had the arrows so when you sort of clicked onto it…it told you where to measure from. You could also see it whereas the booklet didn't have that" (P35)*

Participants appreciated the capability of *tracking progress* being made during the home visit as a clinical user with the help of in-app functionality and could see the benefits of augmenting the assessments by using the app. One participant noted the usefulness of the arrow prompts changing colour and remained permanently marked as an indication of before and after recording measurements onto the app which in turn helped them in cases where they could be distracted by questions asked by patients and having to keep track of assessing multiple rooms in the home.

> *"…The arrows kind of changed colour and stayed permanently marked, so you knew what you'd recorded or when you go back into the app, if you move from room to room it's kind of difficult to keep track of these tabs because I know through experience when you're actually doing a home visit with somebody and they're asking you questions about their home or whatever and you're kind of moving from room and room, it was just kind of really difficult to keep a thread of yourself. How about when you're in a bedroom imagine it's changed colour or something like that, so you've got a, almost like a tick box process going on… (P22)*

Some participants reported on the capability of the app providing *support during assessment* in terms of guiding clinicians on taking measurements, enable clinicians to engage with patients or carers whilst conducting measurement tasks using the app and to flag up measurements that have not be recorded.

> *"…The arrows are there, showing you where you measure from and what to measure reminds you, especially if you're on an access visit and you've maybe got an anxious spouse who's asking lots of questions…going to work when you get home, trying to balance asking them questions, plus trying to write your measurements down and it's very easy to just forget one crucial measurement when you're trying to get back to the hospital and order equipment. Whereas when you've got that app in front of you that's kind of, showing you what you've measured, what you haven't measured, it's a good way of kind of keeping track on yourself." (P5)*

7.2.6 Discussion

This study evaluated the performance of the application in a user-based study, involving 35 OT participants and was conducted within a living lab environment to investigate whether using the app enabled clinicians to effectively (accuracy, and accuracy consistency) and efficiently (task completion time) record measurements compared with a 2D paper-based measurement guide equivalent, similar to what they currently use in practice. Furthermore, usability measures (SUS) and user perceptions of the guidance tools (post-task interviews) were obtained to explore comparative user satisfaction, and to ascertain perceived challenges, opportunities and intention to embrace a novel 3D measurement guidance app in practice.

The **first research question** explored the relative accuracy of measurements recorded using the app and booklet measurement guidance tools and the extent to which each of these tools generated measurements that were not significantly different from the true mean measurement values for each respective item. The results of this evaluation suggest that in most cases, using the app resulted in users taking more accurate measurements compared with the booklet in absolute terms. This was demonstrated by the mean error differences (in 11 out of the 12 cases) being lower when users used the app. Taking into account the results of the statistical significance differences, between the recorded measurements and the true mean values, there was a less notable difference in performance between the app and booklet. Two of the measurement guides performed equally well for the same two out of 12 measurements, however, the app outperformed the booklet on six additional measurements, five of which were toilet measurements and chair measurements (toilet-height-A, toilet-height-B, popliteal-height, chair-height, chair-width and chair-depth). Therefore, the app generated accurate measurements for all three chair measurements, two toilet measurements and the anthropomorphic measurement, compared with the booklet, which only generated two accurate measurements overall.

The height of the toilet and chair are important measurements as it reduces fall risk factors, which according to the literature are known areas where falls occur, and assists patients with on and off transfers [358-360]. The raised toilet seat which is prescribed via obtaining the toilet's height is found to be the most used equipment, with its use increasing with advanced ageing [361]. Furthermore, incorrect toilet height can lead to falls and impact patients ability to use the toilet [362]. The anthropomorphic measurement is also an important measurement as it is used in the formula to raise furniture items (e.g. toilet, bed and chair) that are deemed too low for on/off furniture transfers [298]. Improving accuracy in measurements of home furniture taken by OTs is an important outcome as it addresses the variability of assessment techniques used in health and social care across the UK [363], this being one of the contributing factors to equipment being abandoned. More specifically, it also ensures that equipment successfully fits the patient's needs and home environment, which as a result improves quality of life and potentially alleviating informal care burden (i.e. care provided by family members) [364]. It could also be argued that the app produced reliable measurements as it offered significant benefits over the 2D booklet and provided a standardised guide to taking measurements, which is consistent with the clinical literature advocating such solution to help resolve the high levels of equipment abandonment based on assessments performed by OTs [298].

The **second research question** compared the relative accuracy consistency of the two measurement guidance tools. The results revealed that, there were no cases in which the booklet outperformed the app in terms of accuracy consistency. In most cases that there was a median error difference, the app produced smaller median error values. There were four cases where the app and booklet both produced the same median error values; however, the app produced smaller mean errors for those cases compared with the booklet. In majority of cases where there was a median error difference between the app and booklet, the app tended to produce smaller error differences. This finding supports the results of the first research question in that the app produced smaller measurement errors compared with the booklet.

Comparing the statistical significance of differences in terms of consistency of measurement accuracy between the app and the booklet, the result revealed that the app significantly outperformed the booklet for three of the 12 measures. Furthermore, the measurements used for raising furniture items i.e. toilet, chair and anthropomorphic measurements, with the exception of the bed measurement, were consistently more accurate when using the app. In the cases where the consistency of measurement accuracy for the app was not statistically significant to the booklet, there were no median error differences between the app and booklet and that the app generated smaller median errors. In general, in all cases that there were differences in performance, this could be explained by the fact that the app outperformed the booklet either in absolute terms with regards to median error differences or in terms of the significant difference between median error differences. In practical terms, a notable difference in performance was seen in the chair measurement, which demonstrated a large effect size in favour of the app for the chair height measurement. The height of the chair is used in context of fall prevention interventions to raise the height of the chair to improve chair transfers for patients [365].

With regards to the chair height, the booklet was unable to provide sufficient taking measurements of the chair including compressed heights which may affected the measurements recorded using the booklet. However, the app provided both enhanced visualisation and audio instructions of taking the compressed height of the chair could have led to more accurate measurements being taken. This finding supports the idea and indeed highlights the significant practical value in replacing existing paper-based measurement guidance with 3D measurement guidance. Further investigation into the relative costs and benefits of utilising 3D measurement guidance in practice is therefore need, if this is to be successfully adopted by OTs to help augment assessments. The medium - large effect size achieved for the toilet height B and anthropomorphic measurements (popliteal height) adds further support for this notion. Obtaining accurate height of the chair is a key measure used for chair adaptation and to prevent fall risks [365]. This is also, however, achieved through recording the popliteal height which is a key measurement that clinicians use to calculate the appropriate height to raise furniture items (i.e. toilet, bed and chair) by [366].

Considering that the effect size (either large or medium-large) achieved for most of the items indicates the significant benefits offered by the 3D measurement guidance in enabling participants to more consistently take measurements as part of the EFAP. Several studies in the literature have augmented the 2D tools with 3D visualisation which reduced in increasing the accuracy of clinical tasks, and 3D representation of patients to accurately capture and access long-term data of their health status and to use the data to inform clinical decisions about the patient's care [260, 367, 368]. The improved accuracy consistency achieved by the app is an important outcome as it improves interpretation of measurement guidance to such an extent that it enables users to obtain more accurate measurements consistently, addressing incorrect measurements that result in high levels of equipment abandonment. Above all, these findings also confirm that clinicians measure inaccurately when using the 2D booklet tool and that clinicians measure differently than they do when using the app, thus highlighting the extent to which the app being a viable solution that promotes standardisation amongst clinicians that take measurements in the EFAP.

The **third research question** compared the task completion time for the app compared with the booklet, by measuring the ability of users to interpret the guidance and take measurements of the furniture items in less time using the app. The results revealed that the app enabled participants to complete measurement tasks significantly faster compared with the 2D equivalent. In reference to efficiency, there are benefits of using the 3D measurement tool. The results further indicated that the 3D measurement tool may constitute a promising alternative, resulting in less time to interpret the guidance, particularly in areas to measure that may be unclear or difficult to localise. Existing research has shown interest of improving the time spent performing assessments by augmenting home visits with mobile devices to improve service capacity in a health service [369]. The study results showed a reduction in waiting times. Acknowledging this previous finding, increasing efficiency of measurement tasks for clinicians is an important finding and has benefits to health and social care services as some home visits are perceived as “time consuming” [370] where clinicians’ time might be taken up on unforeseen phenomena that is not accounted for as part of carrying out the EFAP. Having a solution such as the app could reduce the time spent during home visits considering the fact that time constraints impacted upon occupational therapy practice [370].

The **fourth research question** evaluated the comparative usability and satisfaction of the measurement guidance tools via the SUS questionnaire instrument. The results revealed that the app outperformed the booklet in terms of the overall SUS score: app - 83.7 versus booklet 70.4. This resulted in both the app and booklet achieving ‘excellent’ and ‘acceptable’ levels of usability at grade ‘B’ overall for the app (school grading scale) versus grade ‘C’ for the booklet. Whilst the booklet achieved acceptable levels of usability, it was, however, one grade and adjective rating below the app. The individual SUS item results revealed that there was a significant response of the app being significantly less complex (S2), easier to use (S3), significantly less likely to require the support of a technical person to be able to use the app (S4), most people are significantly more likely to learn how to use the application very quickly (S7), requiring a significantly lower learning overhead (S10).

Although the remaining SUS items were not significant, the booklet, however, did not significantly outperform the app on any individual SUS item. In terms of SUS sub-scales, the app was reported to be significantly more usable (Usability), easy to learn (Learnability) and provided significantly better clarity of guidance. These results are rather encouraging particularly as new technologies must be perceived as easy to use if clinicians are to accept and adopt the technology in clinical practice [371]. This study obtained promising behaviour/responses which highlights insights that could contribute to maximizing the acceptance and implementation of the use of the guidetomeasure app in practice, to improve quality of care and outcomes, and to reduce the overheads in the healthcare system and equipment abandonment rates. Furthermore, this could perhaps be attributed to the current version of the app being informed by early engagement with clinicians in both the design and evaluation phases to ensure that end-users' needs were incorporated into a more 'finely tuned' app. The results also show that clinicians reported that the app was more usable (according to the usability measure) than the booklet, which highlights their acceptance of the app, considering that usability is a key factor in OTs decision to adopt technology in practice [372]. This is a very important result as the app was empirically evaluated against a currently used and familiar method used to conduct the EFAP in practice, which clinicians are likely to adopt as it is compatible with existing practice [312]. This also highlights that the app augments what is currently used which indicates that its use in practice is likely to have significant value in obtaining and delivering quality assessments that suit patient needs, but also satisfies the increasing need for clinicians to integrate technologies that optimise, automate existing tools [371] and enabling the shift towards patient-centred model.

The **fifth research question** aimed to investigate clinicians' perceptions of the app and the perceived limitations, benefits, and intentions to embrace the measurement tool in practice. In terms of *Performance Expectancy* and the perceived usefulness of the app, participants noted that the visual quality of measurement guidance and functionality to better coordinate the assessments offered by the app are well-received improvements to that provided by the booklet. More specifically, the app was seen to offer an enhanced guidance of the measurement points to help the user to make sense of what is required by visualising the guidance of how it would be perceived in reality. This finding is rather promising, but not surprising considering that existing research that employed 3D visualisation for fall prevention and other related areas in healthcare have found its use to enhance 2D conventional methods and provide a more detail view for assessment and treatment that has led to patient satisfaction and outcomes [260]. Participants saw the app being able to generate electronic copies of assessments and support inter-professional collaboration as a significant benefit over the booklet. This finding is supported by clinicians' interests improving clinical provision by using technology reported in the literature [373].

In reference to *Effort Expectancy*, the functionality offered by the app which enables clinicians to manipulate the view perspective of the 3D guidance models and audio-based instructions minimises the effort and learn overhead required for following the guidance during home assessments.

Participants were enthusiastic about the look and feel and clarity of the instructions that the application provides, specifically the arrow prompts illustrating areas to measure which makes it easy to use and as a result would enable most people to use the app without having prior knowledge of its use. Furthermore, participants felt the app was easier to use compared to the booklet as capability to enable users to better interpret the measurement guidance, having a user-friendly interface without having significant learning overhead. This finding is particularly important given that the application was developed to enhance its 2D conventional method via the use of 3D models and associated prompts to improve interpretation measurement guidance. As such, this finding seemed to be consistent with the results of existing research that looked at the significant value of employing 3D visualisation for treatment and assessment tools adopted by patients and clinicians in other neighbouring areas.

Factors that affect practice through use of the app and user behavioural intentions were discussed at length concerning the *social influence* theme. Some participants commented on the possibility of family members using the app to facilitate the discharge of patients from hospital to help with a smoother transition from hospital to an adapted home environment that accommodates the patients founded functional needs. It has become common practice for clinicians may ask family members to take measurements of the home on behalf of the patient [293]. This, therefore, highlights areas of opportunities for a supportive tool such as the research artefact to be used by stakeholders in the EFAP. Most participants reported that they felt they could use the app independently, but expressed the need for a walkthrough of the app would be required when working closely with patients and/or their family members. Particularly, family members would be involved in cases where older adults would find measuring their popliteal height themselves challenging. Participants highlighted their confidence of using the app correlates with the app containing guidance that help them to perform tasks that they routinely carry out during the EFAP in practice. Clinicians would adopt technologies, providing that the innovation matches clinical practice and support their role as a healthcare professional [275]. Interestingly, whilst participants found the app useful tool for the EFAP, they felt that clinical users would become familiar with the expected measurements to take from the patients' home and would, therefore, be no need to use the app frequently and would benefit those that do not measurements as often as OTs.

In terms of *clinical benefits*, clinicians reported that they felt the app could improve collaboration with other clinicians and service services, all of which could equally contribute to exploring several options for equipment recommendations based on the data collected. The application was perceived as an 'environmentally friendly' solution in terms of reducing excess paper usage in practice and as means of integrating either clinician-led assessments or self-assessment data to patient record available in a centralised location whereby other clinicians have access to these records to deal with patient uptake. This is an important finding as it is consistent with the government mandate for the NHS to 'go paperless' by 2020 [374] and highlights the existing issues of the healthcare system being fragmented in terms of NHS trusts running as separate entities [374]. Participants felt that the app provides a standardised approach to the equipment provision in order to improve consistency of the taking of measurements for stakeholders involved in the EFAP. This finding corresponds to that of the findings in the previous study (in Chapter 4) where standardisation of the measurement guidance is seen as a potential solution to address the heterogeneous practice of EFAP delivery across UK NHS trusts and to promote accuracy of measurements, ensuring that the equipment best fits the needs and environment of the patient. This is a particularly crucial as equipment prescribed to patients is rejected due partly to the inappropriate fit of equipment as a result of misinterpretation of guidance and absence of standardised measurement practice [299], of which previous research emphasise on the need for improved quality and standardised approach to the equipment provision [299]. Further adaptations were suggested by participants, in particular, to incorporate equipment recommendation functionality into the app to assist stakeholders with the prescription of equipment. This is an interesting finding as the data that the app would need to provide such functionality, it already records. The design and evaluation of this functionality is, therefore, provided in the next chapter.

With regards to *augmentation of clinical practice*, participants felt that the app provides the capability to reduce existing inefficiencies with recording measurements through the use of helpful arrows prompts and flagging up measurement items that are not recorded, which alleviates the cognitive effort on the OTs behalf to keep track and provide more opportunities for engaging with patients. Participants expressed their preference of using the app to carry out the EFAP as the significant benefits it offers over the 2D booklet such as the depth cues, arrow prompts and audio instructions providing guidance to users, all of which the booklet currently lacks. The application provides the technological infrastructure to streamline the stored assessments to the patient record. The digitisation of patient records and the inclusion of patient's self-care data is becoming much more widespread in other areas in healthcare such as general practice [374], as could be used as a point of reference of how the setup of the patient records in the EFAP could be framed.

7.3 Results: Older adult evaluation study (Cohort 2)

7.3.1 Measurement accuracy

The first research question was to compare the relative accuracy of measurements recorded using the app and booklet measurement guidance tools (RQ1). The results of the comparison between the Guidetomeasure application and booklet, and the extent to which the respective recorded measurements are significantly different from the true mean values are presented in Table 7-8. Comparing the measurement guidance tool results, in all cases, with the exception of bath-external width, standard deviation values for the app were smaller than that of the booklet. Therefore, as an initial observation, this indicates that the app tended to generate more precise (but not necessarily accurate) measurements compared with the booklet. With regards to accuracy, for all cases, in absolute terms, the mean error differences were larger for the booklet compared with the app, with the exception of toilet-height-B which was -0.19 (or 0.19 absolute mean error difference) for the app and 0.17 for the booklet. This indicates that in absolute terms, the app generated more accurate measurements compared with the booklet for 11 of the 12 measurements.

Table 7-8: Measurement accuracy for Guidetomeasure app and booklet guidance for older adult cohort.

		App.						Booklet					
	True mean (cm)	Mean (cm)	St. Dev.	Mean error diff. (cm)	Df	t	Sig. (2-tail)	Mean (cm)	St. Dev.	Mean error diff. (cm)	Df	t	Sig. (2-tail)
Bath													
Length	170.00	169.69	1.18	0.31	33	-2.19	0.036*	169.30	1.36	0.70	33	-3.00	0.005*
Internal Width	57.00	56.50	1.16	0.50	33	-2.52	0.017*	56.02	2.08	0.98	33	-2.75	0.009*
External Width	70.00	70.05	0.89	-0.05	34	0.31	0.761	69.94	0.81	0.06	34	-0.41	0.684
Height	55.60	55.70	0.78	-0.10	34	0.78	0.442	55.00	3.25	0.60	34	-1.07	0.291
Chair													
Height	46.50	46.23	0.75	0.27	33	-2.12	0.041*	45.29	2.08	1.21	32	-3.33	0.002*
Width	45.60	46.13	2.08	-0.53	33	1.50	0.144	48.58	3.39	-2.98	32	-3.57	0.001*
Depth	53.40	52.34	3.37	1.06	33	-1.84	0.076	50.31	4.97	3.09	32	-3.57	0.001*
Toilet													
Height A (floor - bowl)	45.00	44.81	1.50	0.19	33	1.23	0.227	44.63	1.85	0.37	33	-1.24	0.262
Height B (floor - seat)	47.50	47.69	0.89	-0.19	33	-0.76	0.455	47.33	1.29	0.17	33	-1.11	0.466
Stairs													
Length	152.00	152.75	2.96	-0.75	33	-0.83	0.157	150.03	11.38	1.97	33	-1.01	0.321
Bed													
Height	45.00	46.06	2.85	-1.06	33	-2.18	0.037*	47.47	3.29	-2.47	33	0.72	0.000*
Anthropometric													
Popliteal height	44.50	44.05	0.79	0.45	34	-3.30	0.002*	45.20	1.59	-0.70	34	2.55	0.015*

*Indicates statitisically significant at < 0.05 level

The one sampled comparison of the Guidetomeasure app mean error differences against true mean, reveals that in the majority of cases (i.e. seven out of 12), the mean error differences are not significantly different from the true means: bath-external width (p = 0.761); bath-height (p = 0.442); chair-width (p = 0.144); chair-depth (p = 0.076); toilet-height-A (p = 0.227); toilet-height-B (p = 0.455); stairs-length (p = 0.157). Indicating that in these cases there is no evidence that the app produces inaccurate measurements at the 0.05 level. Five of the 12 cases are significantly different from the true mean values, indicating that in these cases, the app produced inaccurate measurements at the 0.05 level.

The one sampled comparison of the booklet mean error differences with true mean reveals that five out of the 12 mean error differences are not significantly different from the true means: bath-external width (p = 0.684); bath-height (p = 0.291); toilet-height-A (p = 0.262); toilet-height-B (p =

0.466); stairs-length (*p* = 0.321). Seven of the 12 cases are significantly different from the true mean values, indicating that in these cases, the booklet produced inaccurate measurements at the 0.05 level.

Overall, comparing the performance of the app and booklet, both measurement guidance tools produced inaccurate measurements for five similar items: bath-length; bath-internal width; chair-height; bed-height; patient-popliteal height. The booklet produced inaccurate measurements for a further two items: chair-width; chair-depth. The main difference between the two measurement guidance tools was that the booklet produced inaccurate measures at the 0.05 level for all chair measurement items: chair-height (*p* = 0.002); chair-width (*p* = 0.001); chair-depth (*p* = 0.001), whereas the app produced one inaccurate measurement for chair-height (*p* = 0.041), but there was no evidence of inaccuracy for the remaining two chair measurements: chair-width (*p* = 0.144); chair-depth (*p* = 0.076).

7.3.2 Measurement accuracy consistency

The second research question was to compare the accuracy consistency of measurements recorded using the two respective guidance tools (RQ2). The results of this analysis are presented in Table 7-9. When considering the median error differences between the two measurement guidance tools, in 8 of the 12 cases the median error value for the booklet was larger than that for the app, hence resulting in a negative median error difference in all eight cases: bath-internal width: (md err. diff. -0.12); bath-height (*Md* = -0.12); chair-height (*Md* = -1.56); chair-width (*Md* = -2.25); chair-depth (*Md* = -6.26); toilet-height A (*Md* = 0.01); bed-height (*Md* = -3.00); patient-popliteal (*Md* = -0.60). In one case, the median error for the app was larger than the booklet, resulting in a positive median error difference: bath-external width (*Md* = 0.17). In the remaining three cases, there was no difference between the median error values for the app and booklet. This indicates that the mid-point error values tended to be lower for the app compared with the booklet.

The Wilcoxon signed-rank test comparing the absolute error differences of the app and booklet measurements, reveals that in half of the cases (six out of the 12), the app produced more consistently accurate measurements than the booklet: bath-length, *z* = -1.974, p = 0.048, with a medium-large effect size *r* = 0.34; chair-height, *z* = -4.745, *p* = 0.000, with a large effect size *r* = 0.83; chair-width, *z* = -3.270, *p* = 0.001, with a large effect size *r* = 0.57; chair-depth, *z* = 3.105, *p* = 0.002, with a large effect size *r* = 0.54; bed-height, *z* = -2.365, *p* = 0.018, with a medium-large effect size *r* = 0.41; patient-popliteal height, z = -2.382, *p* = 0.017, with a medium-large effect size *r* = 0.41. All *z* scores were based on positive ranks, with the exception of bath-external width, which further confirms that which was indicated by the negative median error differences, that in the majority of cases (11 of the 12) the sum of ranked positive differences was lower than the sum of negative ranked differences indicating that the app consistently produced more accurate (i.e. lower measurement error differences) compared with the booklet.

Overall, comparing the performance of the app and booklet in terms of accuracy consistency, the app outperformed the booklet in six of the 12 cases, generating significantly more consistently accurate measurements than the booklet.

Table 7-9: Comparison of accuracy consistency for Guidetomeasure app and booklet for older adult cohort.

	App.	Booklet	Paired differences					
	Md err. (cm)	Md err. (cm)	Md err. diff. (cm)	Df	Z	Sig. (2-tail)	Effect size (r)	Effect size magnitude
Bath								
Length	0.18	0.18	0.00	33	-1.974[a]	0.048*	0.34	Medium - Large
Internal Width	1.00	1.12	-0.12	33	-.650[a]	0.516	0.11	Small
External Width	0.32	0.15	0.17	34	-0.022[b]	0.983	0.00	Trivial
Height	0.28	0.40	-0.12	34	-1.345[a]	0.179	0.23	Small - Medium
Chair								
Height	0.49	2.05	-1.56	33	-4.745[a]	0.000*	0.83	Large
Width	1.15	3.40	-2.25	33	-3.270[a]	0.001*	0.57	Large
Depth	0.64	6.90	-6.26	33	-3.105[a]	0.002*	0.54	Large
Toilet								
Height A (floor - bowl)	0.55	0.55	0.00	33	-.942[a]	0.346	0.16	Small - Medium
Height B (floor - seat)	0.50	0.51	-0.01	33	-1.950[a]	0.051	0.34	Medium - Large
Stairs								
Length	1.00	1.00	0.00	33	-1.541[a]	0.123	0.27	Small - Medium
Bed								
Height	1.00	4.00	-3.00	33	-2.365[a]	0.018*	0.41	Medium - Large
Anthropometric								
Popliteal height	0.60	1.20	-0.60	34	-2.382[a]	0.017*	0.41	Medium - Large
a. Based on positive ranks.								
b. Based on negative ranks								
*Indicates statitisically significant at < 0.05 level								

In five of the remaining six cases, although the differences were not statistically different, the app tended to generate smaller error differences than the booklet (indicated by the *z* values being based on positive ranks). In the one remaining case (bath-external width) the booklet tended to generate smaller error differences, however, there was no significant difference in the error differences for this measure.

7.3.3 Task completion time

The third research question was to consider whether there are any significant differences in the overall task completion time when using the respective measurement guidance tools (RQ3). The results of this analysis are presented in Table 7-10.

Table 7-10: Statistics of the task completion time using Guidetomeasure app. and booklet for older adult cohort.

	App.		Booklet		Piared differences			
	Mean (Seconds)	St. Dev.	Mean (Seconds)	St. Dev.	Mean diff. (Seconds)	Df	t	Sig (2-tail)
Time	572.67	249.66	800.57	285.14	-227.90	34	-3.95	0.003*
*Statitisically significant < 0.05 level								

The result of the paired samples t-test comparing task completion times for the app and booklet measurement guidance tools reveals that participants required significantly less time when using the app (*M* = 572.67, SD 249.66) compared with the booklet (*M* = 800.57, *SD* 285. 14), *t* (34) = -3.95 *p* = 0.003. The *SD* scores for the application and booklet revealed a high variance indicating that the amount of time it took participants to complete the measurements using both guidance tools varied considerably between respective participants. A Pearson's *r* correlation coefficient comparison was performed to determine whether the relationship between age, measurement accuracy, and task completion time may provide further insight into the large variance for the two tools. However, no statistical significance was found between any of these variables.

7.3.4 Satisfaction and overall usability

The fourth research question was to evaluate the usability of the app compared with the booklet (RQ4). The overall SUS score for the Guidetomeasure app was 81.1 out of 100 (*SD* = 12.4), which, according to the evaluation criteria for SUS [289], indicates that the application delivers 'excellent' (Descriptive adjective), 'acceptable' (Acceptability range), and 'Grade B' (School grading scale) levels of usability. The overall SUS score for the booklet was 73.7 (*SD* = 12.1), indicating 'excellent', 'acceptable', and 'Grade C' levels of usability. Figure 7-5 presents the SUS rating scale with the overall SUS scores for Guidetomeasure and the booklet.

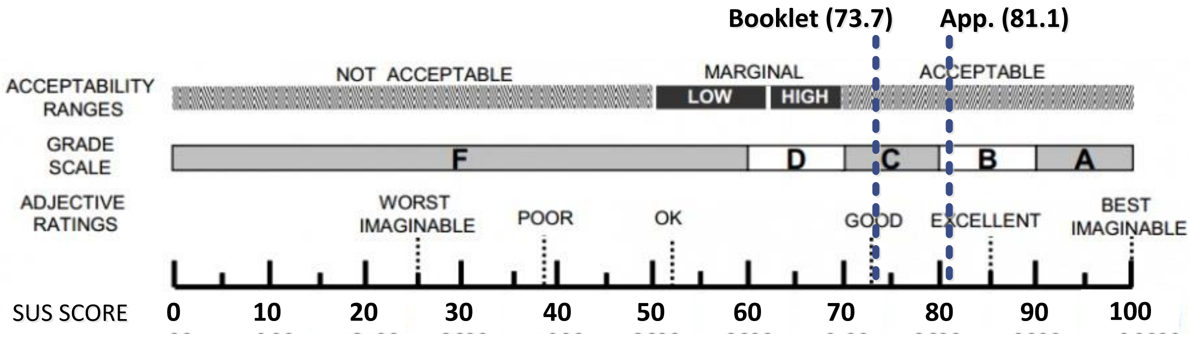


Figure 7-5: SUS rating scale with overall SUS results for Guidetomeasure app and booklet for older adult cohort.

Follow-up analysis of individual SUS items for the application and the booklet were conducted to identify any specific usability issues that the participants experienced during the interactive task. Table 7-11 presents the individual SUS item results, differences (denoted as gap score) and corresponding significance values.

Table 7-11: Guidetomeasure app. and booklet comparison of SUS scores for older adult cohort.

SUS item	App. Mean	Booklet Mean	Gap score	Df	t	Sig. (2-tail)
S1: I think that I would like to use the app/booklet frequently.	3.68	3.09	0.59	33	2.05	0.048*
S2: I found the app/booklet unnecessarily complex.[a]	4.35	3.71	0.65	33	3.53	0.001*
S3: I thought the app/booklet was easy to use.	4.15	3.29	0.85	33	3.46	0.002*
S4: I think that I would need the support of a technical person to be able to use the app/booklet.[a]	3.78	4.00	-0.22	33	-1.37	0.182
S5: I found the various functions in the app/booklet were well integrated.	4.03	3.47	0.56	33	2.69	0.011*
S6: I thought there was too much inconsistency in the app/booklet.[a]	4.44	4.06	0.38	33	1.38	0.178
S7: I would imagine that most people would learn to use the app/booklet very quickly.	3.88	4.04	-0.18	33	-1.06	0.296
S8: I found the app/booklet very awkward to use.[a]	4.24	3.82	0.41	33	2.07	0.046*
S9: I felt very confident using the app/booklet.	4.29	4.06	0.24	33	1.76	0.088
S10: I needed to learn a lot of things before I could get going with the app/booklet.[a]	4.47	4.12	0.35	33	2.17	0.038*
Clarity of guidance (additional items)						
A1: Using prompts (arrows) on the diagrams to assist with measurement was clear and easy.	4.41	3.97	0.44	33	2.08	0.045*
A2: Using the app/booklet improves the way I measure home furniture.	4.12	3.41	0.71	33	3.88	0.000*
A3: The instructions were clear and helpful.	4.09	3.18	0.91	33	6.71	0.000*
A4: I felt the diagrams clearly illustrated where I had to measure on the item/object.	4.18	3.12	1.06	33	5.24	0.000*
A1 – A4 bespoke items presented in addition to the 10 standard SUS items to evaluate clarity of guidance						
[a] Responses of negative items reversed to align with positive items, higher scores indicate positive responses.						
* Indicates statitisically significant < 0.05 level						

All 10 SUS individual mean item scores and all four clarity of guidance items were above the neutral mid-point of 3.00, indicating that overall, participants tended to be positive about both measurement guidance tools. In all cases (i.e. SUS items and clarity of guidance items), the app achieved higher absolute mean scores compared with the booklet, with the exception of items S4 and S7. This

indicates that for eight of the ten SUS statements, participants tended to be more positive about the application compared with the booklet. However, participants tended to report that using the booklet was less likely require technical support (S4) and may require less time overhead when learning how to use the tool (S7) although in statistical terms, these differences were not significantly higher for the booklet, S4 (p = 0.182) and S7 (p = 0.296). Six of the ten SUS items (S1-S3, S5, S8, and S10) were significantly different, and in every case the app significantly outperformed the booklet. For the clarity of guidance items, all of the items (A1-A4) were significantly higher for the app compared with the booklet.

Results for item S1, reveal that participants were significantly more positive about using the app frequently, compared with the booklet (p = 0.048). Responses for S2, reveal that participants tended to be more positive about the app and that it was significantly less unnecessarily complex than the booklet (p = 0.001). For S3, participants found the app significantly easier to use compared to the booklet (p = 0.002). Results for S5 reveal that participants felt the various functions provided by the app to be better integrated than the booklet (p = 0.011). Responses to item S8 suggest that participants found the app significantly less awkward to use than the booklet (p = 0.046). Results for item S10 indicate that participants disagreed with the statement that the app required them to learn a lot of things before being able to use it, compared with the booklet (p = 0.038). Item A1, indicates that the arrow prompts presented within the app were more clear and easy to use than the booklet (p = 0.045), and that the app improves the way they measure home furniture (A2), more so than the booklet (p = 0.000). Results for item A3, reveal that the app provides more clear and helpful instructions as compared to the booklet (p = 0.00), and that the app is more clearly illustrated where measurements need to be taken to and from compared with the booklet (p = 0.000).

With regards to the paired samples t-tests comparing SUS Learnability, Usability and Clarity of guidance constructs, the Cronbach's alpha scores for Learnability and Clarity of guidance were above the acceptable threshold value of 0.6 for small sample studies [292], however, the Cronbach's alpha score for Learnability was below the threshold and therefore will not be considered further. Table 7-12 presents results of the comparison of these respective constructs.

Table 7-12: Comparison of SUS constructs for older adult cohort.

Construct	Items	Cronbach's alpha		App.	Booklet	Gap score	Sig.
		App	Booklet	Mean	Mean	(App. - Booklet)	(2-tail)
Usability	SUS items 1-3, 5-9	0.93	0.64	4.10	3.67	0.43	0.000*
Learnability	SUS items 4,10	-	-	-	-	-	-
Clarity of guidance	Clarity of guidance items 1-4	0.94	0.84	4.20	3.42	0.78	0.000*
A1 – A4: items presented in addition to the 10 standard SUS items to evaluate clarity of guidance							
* Statitisically significant < 0.05 level							

The app achieved a significantly higher Usability score (*M* = 4.10, SD = 1.13) compared with the booklet (*M* = 3.67, *SD* 1.11), *t* (34) = 4.35 *p* = 0.000. For clarity of guidance, the app achieved a significantly higher score (*M* = 4.20, *SD* = 1.26) compared with the booklet (*M* = 3.42, *SD* = 1.18), *t* (34) = 7.546, *p* = 0.000. Indicating that overall, the app was considered to be significantly more usable and provide better clarity of guidance compared with the booklet.

7.3.5 Perceived challenges, opportunities, adoption and use

The fifth research question was to explore user views about the perceived challenges and opportunities of using the 3D app as a measurement guide and attitudes towards adopting this tool in practice (RQ5). Three high-level themes emerged thematic template analysis: Performance Expectancy (PE); Effort Expectancy (EE); Social Influence (SI). The information in parentheses includes a unique participant ID, gender, age. An overview of the high-level themes and associated subthemes are presented in Figure 7-6.

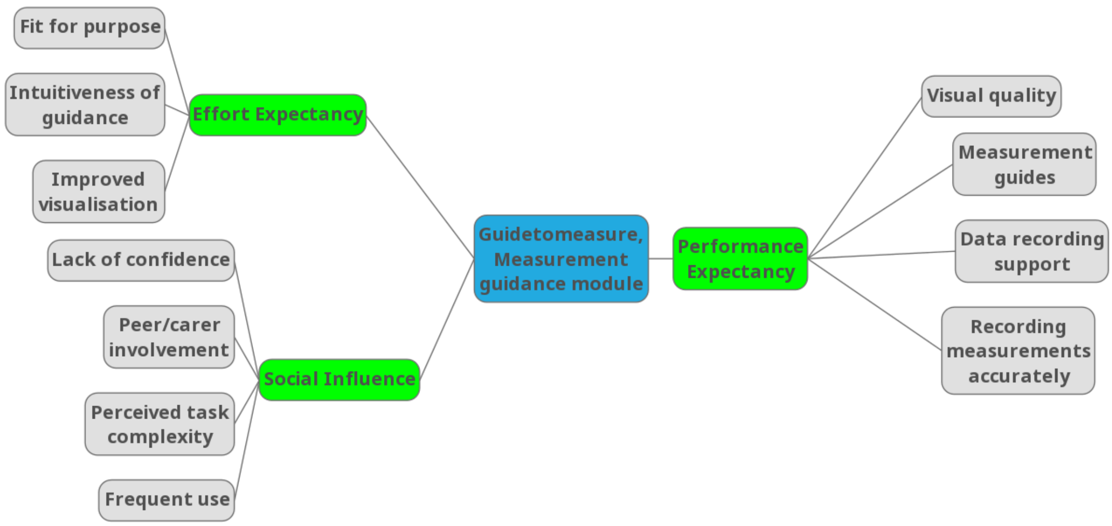


Figure 7-6: Thematic mind map of core themes and associated sub-themes for older adult cohort.

Performance expectancy

Participants reported that the *visual quality* of the guidance provided by the app was particularly useful and was a noticeable improvement compared with the booklet. Particularly the 3D models of the chair and toilet items were perceived as being clearer and more detailed in 3D form and hence more useful in identifying measurement points. Some participants also reported that the measurement guidance annotations on the 3D models appeared to offer a more precise indication of the measurement points. One participant commented that they were able to recall the details of the 3D images presented in the app much more readily than those presented in the booklet.

> *"…it wasn't clear on the chair, and on the toilets it wasn't clear where the top of the toilet was…not as clear as on the app. If you see, on the app I think it shows you the lid up, whereas…actually I can't remember what was on the booklet…it's quite funny really maybe because it was in 3D…I can remember the way everything was on the app but I can't remember on the booklet." (P5, F, 56)*

> *"…You could actually see the image that you were measuring in 3D, yes. Whether it was the stairs, whether it was the chair…the toilet…it showed you exactly where to measure in a 3D image." (P32, F, 70)*

In terms of how the performance of the *measurement guides* may be improved, it was suggested that currently there may be a mismatch between the style of items of furniture presented in the measurement guidance and the style of the actual real-life items being measured. Therefore, one suggestion made, was to offer users the option of choosing the style of item of furniture that that is to be measured prior to being presented with measurement guidance for that item.

> *"Would you be able to change chairs…it's not the type of chair that I've got at home" (P28, F, 89)*

Participants found that the app provided useful *data recording support* particularly the on-arrow annotation of recorded measurements, along with the associated real-time audio advice. One participant noted the usefulness of the arrow prompts on the app as they offered them perception of depth which in turn helped them to feel more confident that they had identified the precise locations for measurement.

> *"…I think that's what I liked about it…you could press on the arrow and then just tap your measurements in…I also remember listening to a voice which told you where to measure. That sort of guided me in a way" (P7, F, 55)*

> *"… Another improvement [over the booklet] was the fact that the arrows showed exactly where you were supposed to be measuring from. If you look at the bath [in the booklet], it was a little bit difficult to know whereabouts the internal measurement was because the bath was wider away from the taps than it was at the other end, and also the length of the bath, was it an internal length or was it an external length?…but the actual app did show that it was the external length…" (P16, F, 70)*

Some participants reported feeling a bit more confident and reassured that they were *recording measurements accurately* in part as a consequence of being able to manipulate, check and recheck the viewing perspective of the item, and visualise landmarks on items more precisely. This was a feature that was noted as being missing in the 'flat' 2D measurement guidance provided by the booklet.

> *"… You don't have to read like you do with the booklet. Measurements on the app would be easier to see because you can see around where it matches to…on the booklet you're limited I think because its just flat" (P12, M, 58)*

Effort expectancy

In terms of the effort required to utilise the measurement guidance tools, participants considered both tools to be *fit for purpose*. No concerns were voiced about the 3D representations used by the app, with the exception of one participant, who stated that the arrow prompts on the app for the chair needed to be made clearer. Indeed, overall participants noted that the chair was the item that posed the greatest challenge in the measurement task, i.e. for both guidance tools.

> *"I did, the only one I would say I was a bit confused with was the chair, because it, I don't think it was clear, it's sort of measuring the depth of it, you know where the chair is underneath where that arrow was?" (P3, F, 60)*

The multimodal nature of the guidance provided by the app, for example, the interactive 3D models capable of rotation, pan and zoom coupled with the real-time audio instruction were noted as enhancing the *intuitiveness of guidance* and reducing the overall effort required to grasp and interpret the intended meaning of the instruction provided by the app. Conversely, with regards to the booklet, participants noted that the necessity for the user to read, comprehend and memorise the text-based instruction prior to carrying these instructions out, which was seen as a drawback.

> *"It's not, it's the writing, you don't have to do the writing and it gives you the arrows, it's showing you where you have to measure across. So it's clear." (P12, M, 58)*

> *"I think the 3D model was quite good and showed you were exactly to place the tape measure … being able to move the view around also helped" (P7, F, 55)*

Most participants commented on the ease of use of the application including its helpfulness which, some suggested, facilitated a better understanding of the necessary process required to record data. Participants were enthusiastic about the reduced level of effort required to follow the instructions provided on the application. Several references were made to Guidetomeasure offering more of an *improved visualisation* of the measurement guidance over its predecessor. For example, participants commented on the bath being the clearest guidance provided on the application, hence requiring least effort to interpret, as the quality of models and their 3D representation bears more resemblance with how one would perceive instructions if they were provided by a clinician in a real-life setting. There were, however, some participants who expressed that for some items of furniture/individual measurements, the app had no real benefit over the booklet, but also noted that this was not all cases and that in others the app provided significant added benefit.

> *"So on paper you just get this is the height and here is the height, and in fairness that's probably all you need, I mean you know in some instances there was no advantage with the app, was there? You could see it just as easily on paper as you could on the app. But I think the fact that you could move the image around on the app, made some of the measurements easier to see what it exactly it is you're measuring." (P22, M, 74)*

Social Influence

Some participants expressed a *lack of confidence* in measuring items, in part due a fear of recording the measurement inaccurately and an awareness that this could, in a real-world setting, result in suboptimal adaptation of their home. Participants reported to have questions of confidence both with the app and the booklet. Considering the importance of this task, some participants' felt more comfortable with the idea of a third party taking measurements. Indeed, one participant stated that they would simply refuse to engage in a self-assessment activity such as this.

> *"Yeah, but to be honest, I would intend on using both but I couldn't measure on my own, not accurately… to have something that needs doing, I would need it to be done properly and I wouldn't feel confident doing it on my own, well I wouldn't do it." (P7, F, 55)*

Many were comfortable with the idea of carrying out the self-assessment measurement task on their own. However, others stated that although they were not opposed to carrying out self-assessments, they would have more confidence in the measurements they provided if there was at least some peer/carer involvement or input to provide a second opinion the recorded measurements, as they felt this would be more likely to obtain more accurate results and also provide them with some peace of mind.

> *"I don't think it requires…if someone's not confident, then it's good to have a second opinion, but if you're confident with the system and confident with your measurements, then its fine." (P11, M, 71)*

Furthermore, there were some concerns raised about the complexity of the task of taking measurements and the prospect of individuals carrying out these tasks on their own. Again, regardless of the guidance tool being used, the 'mechanics' and *perceived task complexity* of carrying out the measurement task seen as a potentially challenging task, which for some patients would require assistance from another individual.

> *"My problem is, if like me and a couple of other people, who live on their own and have, and are elderly, it's hard to measure, it really is hard to measure. But that's nothing to do with the app, that's to do with the actual mechanics of...the actual measuring. So, having someone to help would be good." (P19, m, 71)*

7.3.6 Discussion

Similar to study 3, this present study evaluated the performance of the application in a user-based study involving 34 older adult participants conducted within a living lab environment to investigate the extent to which the app enabled participants to effectively (accuracy, and accuracy consistency) and efficiently (task completion time) record measurements using the 3D app compared with a 2D paper-based measurement guide equivalent that is currently used in practice. Furthermore, usability measures (SUS) and user perceptions of the guidance tools (post-task interviews) were sought to investigate comparative user satisfaction, and to identify perceived challenges, opportunities and intention to adopt the new application in practice.

The **first research question** explored the relative accuracy of measurements recorded using the app and booklet measurement guidance tools and the extent to which each of these tools generated measurements that were not significantly different from the true mean measurement values for each respective item. The results of this study revealed that in the majority of cases, the app enabled users to take more accurate measurements compared with the booklet in absolute terms. This was demonstrated in the first instance by the mean error differences (in 11 out of 12 cases) being lower when taken using the app. When considering the results of the statistical significance of differences, between the recorded measurements and the true mean values, there was a less notable difference in performance between the app and booklet. Both measurement guides performed equally well for the same five out of 12 measurements; however, the app outperformed the booklet on two additional measurements, both of which were chair measurements (chair width and height). Therefore, the app generated accurate measurements for all three chair measurements, compared with the booklet, which only generated one accurate measurement overall. Interestingly, the post-task interviews revealed that the chair was noted as the item of furniture that participants found most difficult to measure in accordance with the guidance.

Although participants reported that they found it difficult to follow guidance given by both the app and the booklet, it seems that the guidance provided by the app was more effective in enabling participants to take accurate measurements of this item, whereas the difficulties participants experienced using the booklet resulted in lower levels of accuracy being achieved overall. The most important measurement, in terms of reducing the risk of falls, is chair height as it impacts the patient's ability to rise to stand from the chair and requires faster and more trunk flexion movements for chair transfers [359, 360]. More generally, enabling improvement of measurement accuracy achieved by patients self-assessing as part of the EFAP is an important outcome as it reduces the waiting times and enable patients to take ownership of their care and wellbeing. Overall, it could also be the litmus test for readiness of patients to self-assess and contribute to equipment prescriptions equally as their clinical counterpart would as stakeholders within the EFAP in practice.

The **second research question** compared the relative accuracy consistency of the two measurement guidance tools. The results revealed that, there were no cases in which the booklet outperformed the app in terms of accuracy consistency. In all cases that there was a median error difference, the app produced smaller median error values. This further supports the findings from the first research question, that the app generated smaller measurement errors compared with the booklet. Specifically, all cases where there was a difference between the app and booklet median error, the error differences were smaller for the app. When comparing the statistical significance of differences in terms of consistency of measurement accuracy between the app and the booklet, the result was that the app significantly outperformed the booklet for six of the 12 measures. Furthermore, all chair measurements were consistently more accurate when using the app, as were all measures for the bed and the anthropomorphic measurement. Overall, in all cases that there were differences in performance, this could be explained by the app outperforming the booklet either in absolute terms with respect to median error differences or in terms of significance of difference between median error differences. In practical terms, a notable difference in performance was seen in the chair measurements, which demonstrated a large effect size in favour of the app for all three chair measurements. Participants were able to provide accurate measurements considering the complexity of taking measurements of the chair height once it was compressed. Not following the instructions for the chair would have influenced the accuracy and reliability of the record measurements. Given the important role that appropriate chair height plays in the context of fall prevention interventions [358], this finding supports the notion that there may be significant practical value in replacing existing paper-based measurement guidance with 3D measurement guidance. Therefore, further investigation into the relative costs and benefits of deploying 3D measurement guidance in practice is needed.

The medium-large effect size achieved for the bed and anthropomorphic measurements (popliteal height) adds further support for this notion. Indeed, accurate bed height adaptation is considered key for preventing a range of extrinsic fall risk factors [5, 366] and popliteal height is a particularly crucial measure which is required in order to calculate adapted chair height, bed height, toilet height [298]. Given that the largest effect size was achieved with the item that participants reported to pose the biggest challenge (the chair) suggests that the 3D measurement guidance enabled participants to more consistently take accurate measurements for more complex measurement tasks. The surgical methods research field is a health research domain that has expended considerable research effort into exploring the impact of 2D versus 3D visualisations on clinical task performance. This finding is supported by Storz et al. [375] who found that, compared with 2D equivalents, surgeon task accuracy improved significantly when using 3D visualisations, particularly when carrying out complex surgical tasks. These findings are further supported by a recent literature survey comparing the result of 31 articles comparing relative task performance using 2D and 3D visualisations [376]. This is a promising result as it shows that the app can enable patients to take accurate measurements of their home furniture and self. Therefore, it could allow patients to take more control over decisions made about equipment prescribed, which helps to realise the personalisation agenda [69]. The improved accuracy consistency achieved by the app is an important outcome as it addresses the issue with the measurement being taken by patients being called into question in previous research [307]. However, it is worthy to note that despite the patients being able to assume this new role, there would be cases where some would need help by other in taking measurements, particularly the popliteal height which is said to be a challenging for patients with impairments.

The **third research question** compared the task completion time for the app compared with the booklet. The results revealed that the app enabled participants to complete measurement tasks significantly faster compared with the 2D equivalent. Therefore, in terms of efficiency, there appear to be significant advantages in using a 3D measurement tool. Once again, this finding is supported by numerous surgical methods comparing 2D versus 3D visualisation tools, which found that task completion time was reduced in the 3D visualisation condition [377-379]. Making self-assessment tasks more efficient for patients is an important finding as it enables patients who are increasingly being given the responsibility to deliver self-care and self-assessments, whilst reducing patient waiting times, cost and burden on the healthcare system. This also provides a means of efficiently recording measurements during the time in which patients require assistance in carrying out daily living tasks via the use of equipment. For example, if the assessment is being conducted on behalf of the patient who is in the midst of being discharged from hospital as a result of a fall.

The **fourth research question** evaluated the comparative usability of the measurement guidance tools via the SUS questionnaire. The results revealed that the app outperformed the booklet in terms of the overall SUS score: app - 81.1 versus booklet 73.7. This resulted in both the app and booklet achieving ‘excellent’ and ‘acceptable’ levels of usability at grade ‘B’ overall for the app (school grading scale) versus grade ‘C’ for the app. The booklet score however was only marginally within the ‘excellent’ range bordering on ‘good’. The individual SUS item results revealed that there was a significant positive preference in terms of frequency of use (S1), with the app being reported as significantly less complex (S2), easier to use (S3), better integrated (S5), less awkward (S8), requiring a lower learning overhead (S10). The booklet did not significantly outperform the app on any individual SUS item. In terms of SUS sub-scales, the app was reported to be significantly more usable (Usability) and provided significantly better clarity of guidance. These are promising results, particularly when considering that existing technology-assisted self-assessment/self-care healthcare systems must be perceived as easy to use if they are to be widely adopted by older adults [74, 312]. Given that the older adult participants reported that the technology-based measurement guidance tool was more usable (according to the above criteria), is perhaps a surprising result, given that older adults are typically considered to be more resistant to new health related technologies compared with younger cohorts [74], and more familiar with 2D paper-based forms typically used for self-care and assessment tasks [17]. However, it should be noted, that one of the inclusion criteria for this study was that participants were already familiar with mobile touch screen devices, impacted on the result. The proportion of older adults, however, that use mobile touch screen devices is increasing steadily and will continue to do so going forward [380]. The finding that the app is considered to be more a usable self-assessment tool that the booklet currently used in practice is an important finding as it indicates that its use in practice is likely to be of benefit as there is a need to move away from patients as a passive recipient of health care towards patient-centred models where the patient is often responsible for carrying out important aspects of their own care. Identifying and developing tools that help enable this to become more of a reality are needed, and what is presented here enhances clinical practice in a way that existing tools are do not provide.

The **fifth research question** aimed to explore users' views of the app and the perceived challenges, opportunities, and intentions to adopt the measurement tool in practice. In terms of *Performance Expectancy* and the perceived usefulness of the application, participants noted that the visual quality of measurement guidance provided by the app was a welcomed improvement to that provided by the booklet. In particular, annotations in situ with the 3D models were seen to offer more precise indications of the points to be measured and useful data recording support in the form of on-arrow annotations of measurements and real-time audio instruction were also seen as particularly useful functionality. Previous studies have shown that the combination of visual aids and audio features are both useful and effective in enhancing older users experience while interacting with software applications, particularly for those who have lower health literacy. Furthermore, audio prompts have been used as an effective means of assisting older adults with the task of navigating and interacting with 3D clinical applications [321, 323]. The finding that users generally perceived the app delivered numerous additional features that were perceived as useful is promising, particularly given that 'perceived usefulness' is considered to be one of the most important determinants of a new technology being adopted by older adult users [74].

In terms of Effort Expectancy, the functionality enabling users to manipulate viewing position, rotate and zoom in on measurement landmarks was linked to reducing the overall effort necessary to comprehend the measurement instruction and make for a more intuitive set of guidance. Participants also noted that they felt more confident that the measurements they were taking were accurate when using the 3D app guidance tool, in part due to the rotation and zoom functionality which made it possible to check and recheck measurement points from various perspectives, coupled with the real-time audio instruction. Indeed, existing research using 3D visualisation for improving the visual quality of clinical tools and self-reporting accuracy has similarly found significant value in these interactive features in the areas of back pain assessment [63, 260, 261] and wound care [381]. The issue of user confidence in carrying out this task featured strongly when considering user perceptions relating to Social Influence theme. Some users reported that they would not feel confident being given the responsibility of engaging in the self-assessment task and would require a third party to be involved to check the accuracy of the measurements they had taken. User confidence and taking ownership of such tasks is a particularly important issue, given the recent update of the health care act which stipulates that "capacity must be assumed" for those responsible for carrying out ADL around the home and that patients must take ownership of their own care within reason, if they are capable of doing so [325]. If capacity is to be assumed and patients are to embrace their new responsibilities as self-carers, it is crucial that they are provided with the best possible tools and guidance in order to have the confidence to fulfil their new responsibilities. According to some participants in this study, the app did enhance their level of confidence in the task, however, the app does not appear to be a silver bullet for this issue, as some users reported that they would not feel confident using either measurement guidance tool. As discussed in section 4.1.4, 3D scanning technology could potentially be used in conjunction with the proposed artefact to automatically measure furniture items as a way of increasing confidence in patients or indeed clinicians of obtaining accurate measurements. This may reduce the likelihood of human error introduced to and fatigue when physically taking measurements, particularly patient users conducting assessments with the app. However, while this is a potential avenue to be explored (more details in section 9.5), scanning the environment/real-life target object would need to be performed proficiently to obtain 3D model of the object constructed to scale in order to extract measurements of the model. This is also outside the scope of this research.

7.4 Limitations for study 3 and 4

A potential limitation of these studies is that, in the measurement task, the performance of participants in both user cohorts could have been impacted by the time period between their exposure to each condition and the taking and recording of furniture measurements at least twice using both guidance tools (conducted on the same day). It is possible that the OTs – or, indeed, older adults - could have memorised the measurements taken during exposure to the first condition. In particular, the performance of the older adult cohort could have been affected by fatigue with taking measurements. The researcher encouraged participants to take regular breaks during the experiment and ensured that the order in which the furniture items were measured was completely randomized to counteract any effect of the abovementioned issues impacting the results.

Another limitation of these studies is that the follow-up interviews were conducted separately from the user trials and think-after sessions were not carried out as time did not permit. However, observational notes and written descriptions of participants' experiences using both measurement tools to complete the tasks were obtained. The interviews were carried out over the telephone within a maximum period of two weeks after the user trial sessions. This provided participants with a chance to reflect on their experience of using the app before the interview. Studies in the literature have suggested that follow-up interviews may provide participants with the opportunity to validate researchers' observations or interpretation of qualitative data collected during the experiment [382, 383]. While the goal of collecting qualitative data was not to generalise, transferability sought and improved through providing 'thick description' such as including depth in the written description of the context, collection and analysis of the datasets [384]. Furthermore, employing thematic analysis allowed for a 'thick description' to be provided across the dataset, however, the individual accounts of using both tools could have potentially been lost, thus impacting the reporting of participant experiences. With this in mind, the variant of thematic analysis used to ensure that a broad description of individual participant experiences was provided rather than making theoretical assertions and avoid encountering the issues above.

It is recognised that the findings of the older adult study, in particular, cannot be generalised with respect to using the app to take measurements, as the numerous impairments that this population is likely to suffer from could impact upon patients' ability to measure. As older adult participants in this study did not exhibit any health conditions that affected their ability to measure, which is an issue likely to arise in real life case, the findings cannot, therefore, be extrapolated/generalised to the rest of the general older adult population. There were comments made by both user cohorts that some older adults who found taking measurements of themselves, and indeed their home environment, challenging would require assistance from others (i.e. informal carers, such as family members, or clinicians) to achieve these tasks. Detailed analysis of the different patient groups who may have impairments or experience difficulty with physically taking measurements could be explored further in future research and the app adapted accordingly to accommodate them (as stated as future research in section 9.5).

7.5 Conclusion

This chapter reported on two studies which evaluated the clinical utility of the Guidetomeasure app (measurement guidance), in terms of its effectiveness (RQ1 and RQ2), efficiency (RQ3), and user satisfaction of usability (RQ4) compared with the existing state of the art 2D booklet, with clinician and patient participants. Furthermore, participant experiences and views of using the app were also investigated (RQ5). As part of the study, the user cohorts engaged in a measurement task within a living lab environment which included five key furniture items, which participants measured using the app and booklet in a counterbalanced order. The effectiveness of the app was assessed by comparing the relative accuracy of measurements recorded using the app and booklet guidance tools. The efficiency was measured through comparison of the task completion time using both guidance tools. The user satisfaction of the usability of the app was evaluated via the statistical analysis of participant responses to the SUS instrument. Participants' perceptions with regard to the app's challenges, opportunities, and adoption in practice were investigated using thematic analysis of follow-up semi-structured interviews which were conducted separately from the user-based trials.

Based on the results of RQ1, it was revealed that the app provides significant benefits over its 2D equivalent in its visualisation capabilities. This enabled both participant groups to take measurements more accurately than using the booklet in most of the cases. Whilst a considerably low mean error difference between the guidance tools was achieved in the studies, clinicians took more accurate measurements using the app compared with older adults, who, despite expressing difficulties following guidance for both tools, were able to take several accurate measurements using the app. The results of RQ2 revealed that the app significantly outperformed the booklet in terms of accuracy consistency, producing fewer median errors in both studies. Interestingly, older adults were consistently able to take more accurate measurements by using the app than what OTs were able to achieve using both tools. This may be attributable to the diversity of years' experience and specialty in the small cohort of OT participants. With regards to the RQ3, the results revealed that the app enabled both user cohorts to complete the measurement tasks quicker than when using the booklet. Perhaps unsurprisingly, when using the app, OTs completed the tasks quicker than the older adults. This is possibly due to the OTs greater familiarity with the EFAP; which is likely to change as more patients are asked to take measurements, whilst the onset of functional decline becomes more apparent and in turn requires equipment to be prescribed, as part of the EFAP.

For RQ4, the results showed that both cohorts of participants were more satisfied with the general usability of the app, compared with the booklet. OTs attributed a higher total SUS score for the app than the total SUS score provided by older adult participants. Based on the outcomes of RQ5, participant perceptions on the perceived challenges, opportunities, and behavioural intentions of using the app in practice were revealed. OTs believed that not only does the app enhance the way in which users perceive the measurement guidance compared with the booklet; it also provides a standardised approach to taking measurements, coordinates assessments more effectively, enables better collaboration with stakeholders, and potentially allows for integration of measurements into patient records. Equally, older adults considered that the improved visualisation capabilities provided by the app, along with its arrow prompts and audio instructions improve the experience of, and performance achieved, in taking more accurate measurements. Being able to manipulate the view perspective of the 3D models was a benefit well received by users, as it reduced the cognitive load required to interpret the guidance. However, patient users expressed a lack of confidence in taking their own measurements and felt more comfortable with a third party to verify accuracy of those taken.

The findings in this study give support for the potential use of the app in clinical practice and provide insight into its benefits over the 2D booklet currently in clinical use. OTs can employ the app to carry out more efficient, accurate, and consistent assessments for fitting assistive equipment. Furthermore, the app could also be used to enforce standardisation among OTs participating in the delivery of the EFAP. Older adults can use the app to be more involved in their care by taking measurements for the provision of minor assistive equipment. However, it is important to note that it is, to a certain extent, expected that carers or clinicians assess patients if the latter's impairments/disability prohibits their ability to self-assess. As the findings of this chapter highlighted, the app improves the way in which the assessments are collected.

7.6 Chapter summary

This chapter reported two user-based studies with clinicians and older adult patients, which empirically evaluated the measurement guidance module (described in Chapter 6) against the 2D conventional booklet and explored its challenges opportunities and users' intention to adopt the new application in practice. The results generated from the studies are promising and adds to the literature by providing evidence, suggesting that the Guidetomeasure could prove useful in improving interpretation of guidance, thus enabling users to take more accurate furniture measurements in the EFAP. The next chapter presents study 5 which evaluates the recommendation module with clinical users compared with existing approaches used for the provision of assistive equipment prescription.

Chapter 8
An equipment recommendation module for prescribing equipment sizes within the EFAP: results from a pilot study

8.1 Introduction

The first and second studies (described in Chapters 4 and 5, respectively) undertaken in the earlier stages of this research presented a tailored mobile 3D visualisation application to provide measurement guidance to both clinicians and patients alike, as part of the EFAP. They also evaluated the general usability of the app and explored the benefits and drawbacks of utilising mobile 3D visualisation technology to augment 2D measurement guidance diagrams. Amongst other feedback, further extension of the app's functionality to help accurate prescribing of the item being measured was identified as a key improvement for the two user cohorts. Consequently, as an outcome of both studies, it was reported that implementing additional functionality to support prescribing equipment sizes after taking measurements could eradicate aspects of EFAP related to equipment prescriptions that are often subject to human error.

Chapter 6 described the revised design of the app and its underlying system architecture, incorporating outcomes of the first and second studies and further consultations with clinicians and interaction designers. As the EFAP is made up of two core phases (namely, taking measurements and prescribing equipment), the app was divided into two separate modules (these being measurement guidance and recommendations) to mirror the EFAP. The second module contains a prescription algorithm, which was developed together with clinicians involved in this research. In parallel to this, the UI design, 3D equipment models, and associated functionality were implemented into the app to visualise the equipment installed. A walkthrough of this module was given to demonstrate its use.

The third and fourth study (presented in Chapter 7) evaluated the clinical utility, efficiency, effectiveness, and accuracy and accuracy consistency of measurements recorded by patient and clinical users of the app compared with a 2D paper-based booklet tool. Furthermore, satisfaction with the general usability of both tools was also measured comparatively. Whilst the app improved accuracy and accuracy consistency of measurement-taking, functionality to support with prescribing equipment sizes were frequently mentioned by both user cohorts in both a clinical and patient-led EFAP context.

The fifth study (presented in this chapter) seeks to empirically evaluate the effectiveness of the recommendation module together with clinicians based on real-life patient profiles. As discussed in Chapters 4 and 5, a high level of assistive equipment prescribed as a result of carrying out the EFAP is abandoned by patient users [18, 54, 56], due to the ‘poor fit’ between the equipment and the individual using it, as result of inaccurate measurements taken using 2D paper-based tools.

In order to prescribe equipment appropriately, measurements are used to determine whether the height of furniture either facilitates or hinders functional independence. For example, to recommend a chair raiser, the OT will measure the height of the patient’s leg (popliteal height) and the height of the chair. The OT calculates the difference between those two measurements and this provides the height that the chair must be raised. However, this process is as error prone as the 2D guidance tools that result in the recording of inaccurate measurements. Handling numerical values for prescriptions is a widely known issue in healthcare [385]. Other studies have proposed interactive technologies that support clinicians with making clinical decisions about their patients through automation. They present a number of recommendations to the clinicians, based on data that is fed into the system about the patient [385]. This simulates clinical reasoning in the selection process and consequently recommends equipment to fit the patient and their home environment. There are a number of clinical algorithms that have been proposed in the literature to support the provision of assistive equipment, specifically in the OT context [386, 387]. However, none have been empirically tested or directly address the issues with accurate collection of measurements before prescribing equipment sizes. This researcher knows of no mechanisms proposed to augment prescribing equipment sizes based on the collection of key measurements of the patient and their home environment.

8.1.1 Aim

In order to address objective O5 outlined in section 1.3, the aim of the pilot study in this chapter is to evaluate the performance of the recommendation module compared with conventional recommendation methods currently used in practice. This study explores the relative effectiveness of the application, and perceptions of it in terms of user satisfaction and attitudes towards the adoption and use of this new technology (app-based prescription) in practice. Specifically, the following research questions are addressed in this study:

- RQ1. Does the recommendation module typically provide more accurate recommendations of equipment sizes compared with conventional methods (using no app)?
- RQ2. Does the recommendation module typically provide consistently accurate recommendations compared with recommendations provided without the use of any aid?
- RQ3. How satisfied are users with the general usability of the recommendation module and its capability to assist users with prescribing equipment?

RQ4. What are occupational therapists' views of the recommendation module, in terms of the perceived challenges, opportunities, and their intention to adopt and use this new technology in practice?

The remainder of this chapter is structured as follows: Section 8.2 presents details of an equipment prescription algorithm developed to assist with prescribing assistive equipment to service users. Section 8.3 presents the pilot study, along with the methods used to investigate the effectiveness of the app to accurately recommend equipment sizes, explore clinician user satisfaction and identify perceived challenges, opportunities, and intentions to use the app in practice. Section 8.4 presents the evaluation results of the main pilot study. Section 8.5 discusses the results and findings in the context of the five key research questions and limitations of the study. Conclusions are drawn with details of the contributions this study has made to the area in Section 8.6.

8.2 Design of the equipment prescription algorithm

According to findings from the previous studies, integration of additional functionality into the app was suggested to facilitate prescribing equipment sizes based on measurements and associated assessment data recorded. Like interpretation of the measurement guidance, recommendation of equipment can also be prone to human error by incorrect calculation of its size. This can lead to inaccurate prescription, even if the correct measurements have been recorded. In response to this, an equipment prescription algorithm has been designed (integrated into the recommendation module presented in Chapter 6) and informed by the evidence-based guidance material, factsheets from different NHS trusts, assessment guidance websites [388], and close liaison with clinicians whose expertise lies primarily within the EFAP. Once the formulas used to prescribe equipment for the five key furniture items were captured, the prescription algorithm was then developed using C# programming language. Figure 8-1 shows an overview of the developed algorithm for computing equipment sizes for the five furniture items and the point at which minor or major recommendations/adaptations to the home are made. This section then proceeds with an algorithmic description of the flowchart presented in Figure 8-1.

The prescription algorithm is mainly for minor equipment prescriptions, particularly for *transfer support* and climbing up and down the *stairs*. *Transfer support* includes assisting patients with getting on and off or in and out of furniture items/areas in the home. Patients are prescribed lifting mechanisms (i.e. hoist and sling) if their they are less able, dependent on caregivers to perform daily living tasks and puts a huge strain for patients to move themselves and the carer. Therefore, an OT assessment for major recommendation is required in these cases.

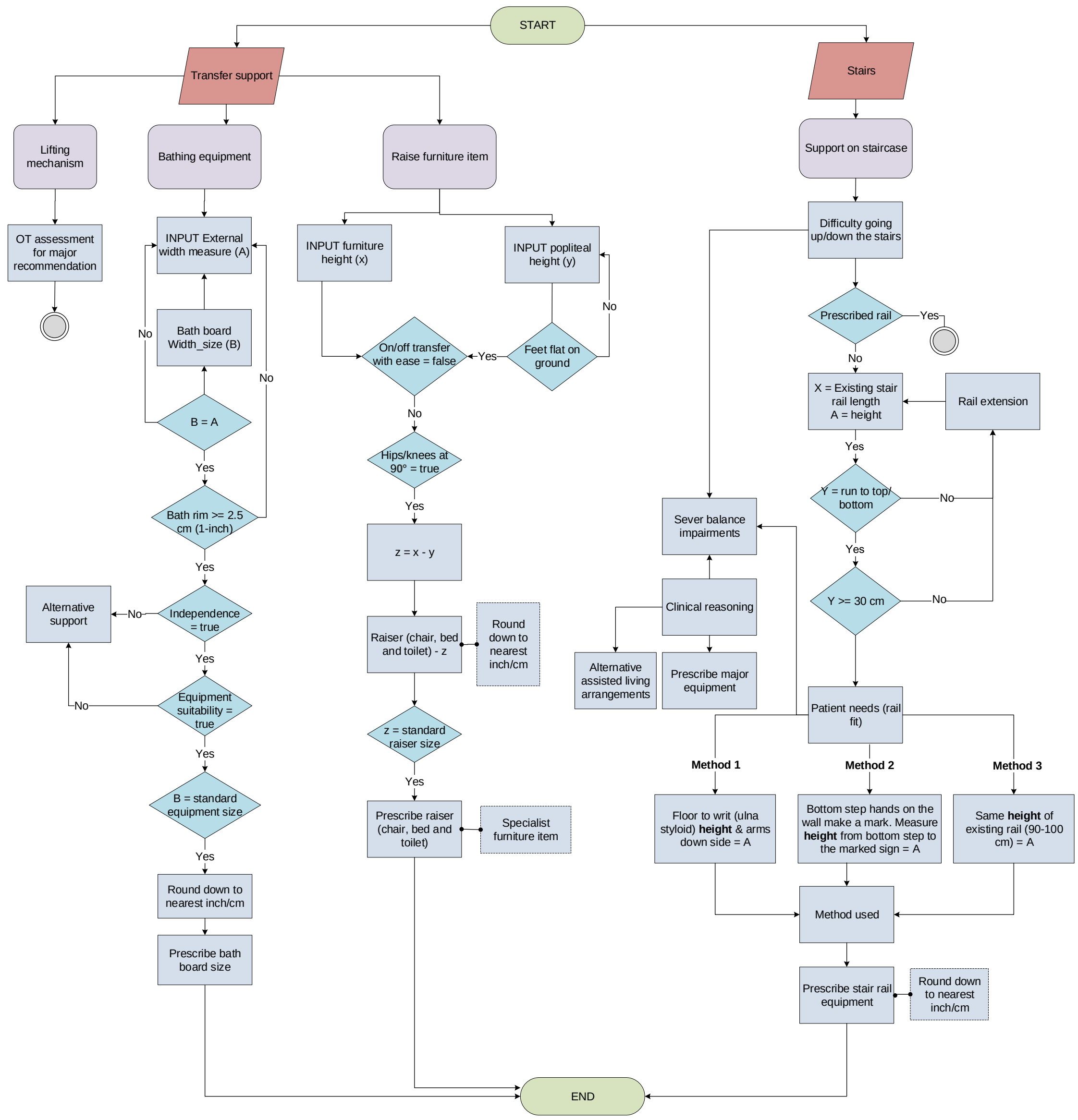


Figure 8-1: Flowchart of the equipment prescription algorithm.

Patients requires ***bathing equipment*** would need the external width of the bath (A) in order to prescribe an equipment for support whilst bathing such as a bath board (width size (B)). If the A = B and the bath rim >= 2.5 cm (1-inch) and the independence of the patient is true then check the equipment suitability is true, else recommend an alternative support. If the equipment suitability is not true then the algorithm would prompt the user to consider prescribing an alternative support, but if it is true then the algorithm would proceed with checking the equipment size condition. The variable is rounded down to the nearest cm/inch. Models of standard bath board sizes are located in persistent storage to check if the rounded value of *a* equals to a standard bath board size. If this is true, then the algorithm prescribes a bath board with appropriate size to the patient.

To ***raise furniture items*** (i.e. chair, toilet and bed), the algorithm checks whether the patient is able to perform on and off transfers with ease is set to true then the user is prompted to check the input measurements. However, if the value is false then the algorithm proceeds with checking patients posture/sitting position. It then requires the furniture height (x) and popliteal height (y) measurements inputs. If the patients *hips and knees are not at 90-degree angle* then the value of *x minus y* would be assigned to the variable *z*, else if the hips and knees are at a 90-degre angle then the algorithm would infer that the existing furniture item had been raised and would be terminated at this point and prompt the clinical user. Once z is calculated, the algorithm will then *round it down to the nearest cm/inch* or convert z into cm, if the inputs were measured in mm. The z variable is then checked against a classification model that contains classes of the standard furniture raiser sizes. If *z is equal to a standard furniture raiser size*, the algorithm then prescribes a furniture raiser with a suitable size to fit the patient.

For patients that need ***support on the staircase***, the algorithm checks if *the difficulty going up/down the stairs* assessment data item value is set to *true* then the proceeding condition would be executed, else if the patient exhibits severe balance impairments then additional clinical reasoning is conducted by clinicians for alternative support arrangements. In the event that the existing prescribed rail condition is true then the algorithm is terminated at this point, as it would assume that there is already equipment that supports the patient with climbing up/down the stairs. If the condition is false, then the existing stair rail length and height inputs would be assigned to variables x and a, respectively. Depending on the patient needs, the clinical users have an option of three methods to choose from for computing the appropriate height of the prescribed rail. Method 1, measuring the floor to the wrist (ulna styloid) whilst arms are down by side to obtain the suitable height which is then assigned to variable d. Method 2, patients are instructed to stand at the bottom step of the stairs placing their one hand nearest onto the wall and to mark this point on the wall for reference. The height from the bottom step to the marked sign is taken and assigned to variable k. Method 3, the value of variable a (height of the existing stair rail) is assigned to variable g and is checked whether the value is between 90 -100 cm. Once a method has been used, variable x measurement is round down to the nearest inch/cm. The models of standard stair rail equipment sizes are persisted in storage for use in the proceeding condition. If x is equal to a standard stair rail equipment size, then a check for rail extension is executed. If the rail extensions continue past the top and bottom steps is true and if those extensions are greater than or equal to 30 cm, then the algorithm would prescribe a stair rail equipment with an appropriate size to fit the patient.

8.3 Method

This section provides details of the data collection and analysis protocol used to address the specific research aims of this study. Figure 8-2 provides an overview of the protocol.

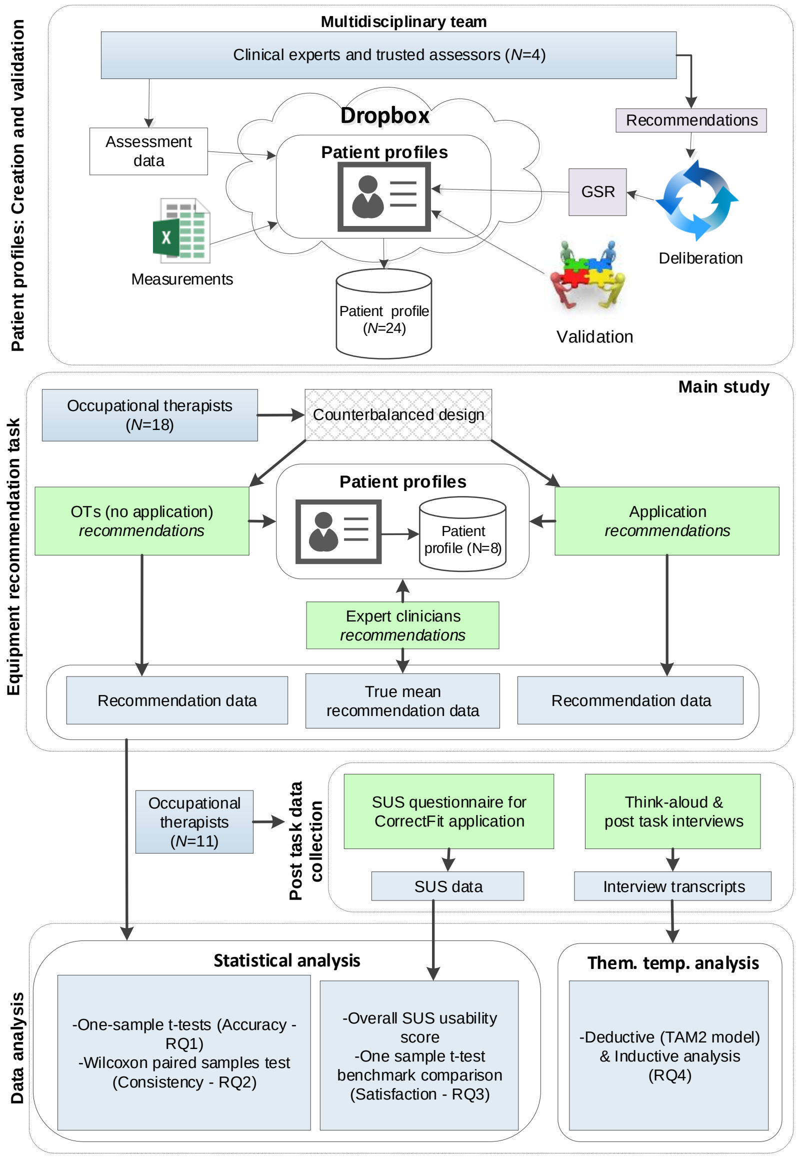


Figure 8-2: Overview of the user trial session, methods and process.

8.3.1 Patient profiles: Creation and validation

A repository of patient profiles was used as the primary source of patient data upon which recommendation decisions were made by clinicians in this study. Therefore, the first step was to create patient profiles in a rigorous way that represent the full range of patient data upon which equipment recommendations are made. This process involved a number of consultations with a *multidisciplinary team* (*N*=4) of two *clinical experts* and two *trusted assessors* from different NHS trusts and the Disabled Living Foundation (DLF) within the area of London. Convenience sampling [389, 390] was used to recruit experts who had a wealth of expertise in the provision of assistive equipment (referred to as assistive technology in the clinical literature [391, 392]) and home visit assessments. Three of the participants were female and one was male. Patient profiles were constructed and a repository of the same was developed. This served as real-life data input to validate/verify the accuracy and consistency of the recommendations provided by the equipment prescription module in the app, as compared to the conventional methods that OTs currently use to prescribe equipment. Experts were given *measurements* recorded from previous user-based trials (see Chapter 7) in the form of a spreadsheet as a supporting framework, along with clinicians' reflections on their experiences in the EFAP (*assessment data*). These reflections were used to construct the content in the patient profiles in a way that allowed the module to be evaluated for its capability to support users in terms of prescribing accurate equipment sizes.

The process of constructing patient profiles contained the use of fictitious content and data based on real-life patient cases. This was to ensure that the profiles were representative of the older population at risk of falling and who require a form of aid/equipment to support them with daily living tasks. Furthermore, this technique was employed to simulate clinicians carrying out EFAP in the app, as the resources that could accompany the app and the data collection strategy were costly and beyond those allocated for this research. The profiles were stored on the shared cloud service *Dropbox* and were accessible by multiple experts in order that they could check whether the content was legible, realistic, and representative of older adults in need of assistive equipment. These experts were encouraged to make changes to the material where necessary (and to make a new copy of the file, add an underscore, and append their initials to the filename if they did make changes). Through the *validation* phase, it was found that reaching an agreement on the profiles which represented the older population was initially problematic, as their construction was based on conflicting subjective accounts. The changes the experts made were based on their own experiences, as opposed to checking of the measurements to see if their recommendations were needed. Explicit instructions were, therefore, given to the experts to check through the material to see if the measurements and content were sufficiently complementary to warrant equipment recommendations. Going through iterations of construction and validation lasted the period of one month and resulted in a total sample of 24 profiles, eight of which were used for the evaluation. Figure 8-3 shows examples of the developed patient profiles.

Pearl – with COPD
Age: 80
Gender: male
Height: 5 ft 7
Weight: 13 st

Background and context
Pearl, aged 80, had a total hip replacement 10 years ago and now experiencing pain and derestriction in her movement. No history of falls. Had previously been provided with a bathlift but no longer able to swing her legs across the side of the bath.

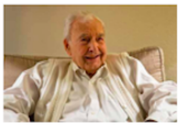
Personal and home furniture measurements
Toilet height (lid to floor) – 381 mm/ 38.1 cm/ 15 inches
Chair height – 457.2 mm/ 45.72 cm/ 18 inches
Chair width – 528 mm/ 52.8 cm/ 20.8 inches
Chair depth – 459.7 mm/ 45.97 cm/ 18.1 inches
Popliteal height – 381 mm/ 38.1 cm/ 16 inches
Bath height - 431.8 mm/ 43.18 cm/ 17 inches
Bath length – 1778 mm/ 177.8 cm/ 70 inches
Bath internal width – 569 mm/ 56.9 cm/ 22.4 inches
Bath external width – 698.5 mm/ 69.85 cm/ 27.5 inches
Bed height – 431.8 mm/ 43.18cm/ 17 inches
Stair length – 1498.6 mm/ 149.86 cm/ 59 inches

Assistive equipment
(Tick the measurement unit you are using)
CM ☐ MM ☐ Inches ☐

Please tick the equipment and the size of the equipment you are recommending

Bath board ☐ size
Raised toilet ☐ size
Toilet frame ☐ size
Stair rail ☐ size
Chair raiser ☐ size
Bed raiser ☐ size

Other *(e.g. other assistive devices)*



Mike – with history of falling
Age: 94
Gender: Male
Height: 6 ft 1
Weight: 15 st

Background and context
Frail with history of falling
Mental health issues from WWII. Cared for by his sister and mother. Mother now deceased and sister in hospital
Mobilising slowly indoors, unsteady, low blood pressure on standing.
Mobility (gait and stairs)

Personal and home furniture measurements
Toilet height (lid to floor) – 381 mm/ 38.1 cm/ 15 inches
Chair height – 457.2 mm/ 45.72 cm/ 18 inches
Chair width – 528 mm/ 52.8 cm/ 20.8 inches
Chair depth – 459.7 mm/ 45.97 cm/ 18.1 inches
Popliteal height – 482.6 mm/ 48.26 cm/ 16 inches
Bath height - 431.8 mm/ 43.18 cm/ 17 inches
Bath length – 1778 mm/ 177.8 cm/ 70 inches
Bath internal width – 569 mm/ 56.9 cm/ 22.4 inches
Bath external width – 698.5 mm/ 69.85 cm/ 27.5 inches
Bed height – 431.8 mm/ 43.18cm/ 17 inches
Stair length – 1498.6 mm/ 149.86 cm/ 59 inches

Assistive equipment
(Tick the measurement unit you are using)
CM ☐ MM ☐ Inches ☐

Please tick the equipment and the size of the equipment you are recommending

Bath board ☐ size
Raised toilet ☐ size
Toilet frame ☐ size
Stair rail ☐ size
Chair raiser ☐ size
Bed raiser ☐ size

Other *(e.g. other assistive devices)*

Figure 8-3: Examples of two patient profiles developed by expert clinicians. Link to Guidetomeasure repository on GitHub [393].

After developing the profiles, experts provided recommendations that were considered the gold standard recommendation (GSR) for each corresponding profile. These were later used for statistical analysis. Developing the GSRs involved *deliberation*, where experts assessed each other's recommendations to arrive at a consensus of recommendations. The GSR was used as a benchmark to carry out comparisons between clinician recommendations and recommendations provided by the app. It is worth noting that each expert was randomly assigned (using a web-based randomised number generator) to a specific set of profiles (using the IDs) to provide recommendations. This set of profiles was taken from a repository of profiles that did not contain those to which they contributed; this was a way of reducing bias.

8.3.2 Equipment recommendation task

8.3.2.1 Participants

Eighteen participants were recruited via a range of sources, including existing contacts with clinical leads ('gatekeepers') from different NHS trusts (to disseminate the invite to their colleagues) and local authorities within the UK and OT groups on social networking websites (e.g. Facebook and LinkedIn). Purposive and convenience sampling strategies were used for the study, for which a total of 18 OTs was recruited. This sample size could possibly be considered to be small; it is, however, congruent with other similar healthcare-related studies in the literature [196]. The inclusion criteria for participants was as follows: (1) they should have relevant clinical experience of carrying out home assessments and prescribing assistive equipment to community-dwelling older adults; (2) they should be a proficient English speaker; and (3) they should be familiar with using smart-phones, tablets, laptops or desktop computers, either in their personal or professional life. Nine participants were female (81.8%, N=9) and two were male: the large majority of female participants in the study sample reflects, to a large extent, the female-dominated OT profession [286]. The mean score of clinicians' years of experience equated to a range from 2.5 to 35 years, and they possessed a range of specialisms. Participants were not offered an incentive for their participation. All 18 participants took part in the first phase of the study, which involved prescribing equipment to the patient profiles using the app and then without the app. However, for the usability study (the second phase), seven participants from the original sample size dropped out of the second phase (P6, P9, P10, P11, P13, P15 and P17) due to the time constraints of working in different NHS trust and social services; this resulted in a remaining sample of 11 participants. Table 8-1 provides the demographics and summary of participant profiles for this study.

8.3.2.2 Protocol and instrumentation

A within-subjects *counterbalanced design* was used to verify the accuracy and consistency of the recommendations provided by using the Guidetomeasure app, as compared to recommending equipment based on the patient profiles without the app.

The study was conducted in a controlled lab setting at the Homerton University Hospital in East London. In setting up the lab, all 24 of the patient profiles were printed onto A3-size paper; two

Table 8-1: Summary of participant profiles.

Part. ID	Gender	Years Exp.	Specialty
#P1	F	20	Community
#P2	F	10	Community
#P3	M	3	Older people
#P4	M	7	Adult social care, manual handling
#P5	F	17	Adult social care, equipment
#P6	F	4	AT/telecare
#P7	F	24	Community
#P8	F	16	Community
#P9	F	29	Community housing
#P10	F	25	Community enablement/older people
#P11	F	13	Community
#P12	F	12	Local Authority/community work
#P13	F	10	Community
#P14	M	2.5	Older people
#P15	F	15	Intermediate care
#P16	F	35	Community/physical adults
#P17	F	4.5	Intermediate care
#P18	F	16	Community

Android tablet devices with the Guidetomeasure app installed were also provided for participants to use. Four expert clinicians provided recommendations for each patient profile and reached consensus on the true mean values (GSR) against which recommendations provided by the app could be compared. Informed consent was sought at the start of each session. Firstly, participants were given a brief walk-through of the Guidetomeasure app, particularly the recommendation module, and were shown all the patient profiles. They were then asked to prescribe equipment based on the patient profiles using the app. Each participant then engaged in a second iteration of this procedure, providing recommendations without the app.

A counterbalanced design was employed to control for order effects, i.e. alternating the order in which respective recommendation conditions were presented to participants at the start of each session. Each participant was asked to look through each profile and recreate a prescription provided by the app to ensure that it matched each profile to reduce bias. Each session was conducted individually and lasted approximately 60 minutes in duration. Participants were asked to think aloud while using the app. This technique is well-established and is employed to gather users' initial thoughts when interacting with an application in real-time. Using this technique allows the collection of user preferences and provides the opportunity to gain valuable insights into the reasoning behind their actions and thoughts. Participants were not rushed and were reminded to provide comments while interacting with the application. Standard think-aloud open-ended questions, such as "What are you thinking?" and "What are you doing now?", were asked to elicit their thoughts and avoid long periods of silence [287]. The data was triangulated with observational notes taken during the sessions, which were also audio-recorded. Four participants dropped out at this point of the study due to work pressures and staffing limitations in their respective NHS trust/social services, which highlights the issue of the lack of resources in healthcare and social care services [20].

Subsequent to the sessions, participants were asked to complete an adapted Systems Usability Scale (SUS) questionnaire [288]. This included the 10 standard SUS statements and three additional specifically-tailored statements with their views about the effectiveness of the equipment prescription functionality in the app in terms of it assisting them with providing equipment to fit patients' needs. Each participant was required to rate all statements using a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Each SUS item was modified in accordance with the SUS practitioner guidelines by replacing the word 'system' with 'Guidetomeasure app' and the word 'cumbersome' in SUS item 8 ("I found the Guidetomeasure app to be very cumbersome to use") with the word 'awkward' [290]. Once both recommendation conditions had been fulfilled and the adapted SUS questionnaire completed, a *post-task interview* was conducted with each participant to discuss their experiences of using the app. The interviews explored the perceived challenges and opportunities of using the app for equipment recommendations in practice. They included discussions relating to the nature of EFAP, technology acceptance, and clinical value and role which they could foresee the app play in enhancing their practice. All interviews were recorded and transcribed verbatim into text format.

8.3.3 Data analysis

The IBM SPSS statistics package Version 20.0.0 was used to analyse the recommendation data and SUS questionnaire survey responses. Recommendation error values were calculated as the difference between participant recommendation values and corresponding true mean values. One sample t-tests were applied to verify recommendation accuracy (RQ1) i.e. whether the mean error differences were significantly different from the true mean values for each condition respectively. Error values generated from RQ1 were converted to absolute error values. To establish whether there was a significant difference between the app and its non-use in terms of accuracy consistency (RQ2), the Wilcoxon signed-rank test was applied to compare the ranked differences of absolute error values generated by both conditions. One sample t-tests were applied to compare differences between individual SUS item responses and the mid-point value of three on the 5-point Likert scale (RQ3) and the two sub-scales that SUS is said to be underpinned by [290, 323] – i.e. Usability (SUS items 1–3, 5–9) and Learnability (SUS items 4 and 10) constructs. Furthermore, overall SUS scores were calculated and interpreted according to the acceptability range and the adjective and school grading scales [288]. This involved calculating a mean SUS representative value on a 100-point rating scale for each sample. These scores were then mapped onto descriptive adjectives (Best Imaginable, Excellent, Good, OK, Poor, and Worst Imaginable), an acceptability range (Acceptable, Marginal-High, Marginal-Low, and Not Acceptable) and a school grading scale (90–100 = A, 80–89 = B, etc.).

The baseline adjective and acceptability ranges are derived from a sample of over 3,000 software applications [289].

Thematic template analysis [356] was used to analyse think-aloud data and the associated interview transcripts (RQ4) using Microsoft Excel 2013. This enabled patterns in the dataset to be identified and categorised. Analysis of these qualitative datasets was both inductive, as the development of the themes was data-driven, and deductive [234], as analysis was driven by a pre-defined template (a priori) of themes based on a theoretical framework and linked to the analytical interest of the researchers [357]. The first stage involved creating a template that used the three key predefined codes specified by the Technology Acceptance Model 2 (TAM2) [394]. Hence, analysis considered the clinicians' perceptions of the Guidetomeasure app in the context of the two high-level TAM2 themes (PU and PEOU) and additional themes that emerged. TAM2 is an extension of the original TAM model and integrates other theoretical factors – namely, cognitive instrumental processes and social influence processes – and accounts for up to 60% of user intentions to adopt and accept new technologies [394]. This was a focused study gaining clinicians' feedback concerning the relevance and output quality of the app in terms of facilitating prescribing equipment within the EFAP. The TAM2 model was, therefore, better aligned with the purpose of the study than other technology acceptance models in the literature and the theoretical models used in previous studies in the thesis. The entire corpus was examined and coded to identify specific extracts from the data that related to the two predetermined TAM2 themes and other high-level themes that emerged. The corpus was then perused iteratively through several stages of splicing, linking, deleting, and reassigning sub-themes within the context of the high-level themes. Sub-themes in the context of individual participants' accounts were considered, as well as examination of the data across participant responses. Finally, a template covering the finalised themes and sub-themes was proposed. Conducting the analysis in this way is congruent with 'contextual constructivism', a stance that accepts that there are multiple interpretations of a given phenomenon dependent on the context in which data was collected and analysed [324] (associated with the interpretivism paradigm discussed in Chapter 3).

8.4 Results

8.4.1 Patient profiles used for evaluation

All participants completed the equipment recommendation task which involved providing recommendations based on the patient profiles with and without the use of the application. Expert clinicians were encouraged to reflect on their experience working with patients where they had to calculate numerical values as part of prescribing equipment to fit the needs and home environment of patients. A total of 24 patient profiles were developed with expert clinicians. In addition to gold standard recommendations (GSR) for each respective profile, eight were used for evaluating the application's consistency and reliability for providing accurate recommendations. Table 8-2 provides the sample of the eight patient profiles used for the equipment prescription task.

Table 8-2: Patient profiles and their respective gold standard recommendations.

Profile ID	Name	Age, occupation	Simulated scenarios	Gold standard recommendations
#1	John	67, Teacher	COPD and degenerative spinal disease. Walks with a single crutch. Has fallen in the hallway in the past. Has difficulty with transferring on and off the sofa and toilet. The sofa had already been raised but he was not sitting with knees and hips at 90 degrees. Sofa height = 18-inch/45.72cm/457.2mm and Popliteal height = 21-inch/53.34cm. Toilet height = 18.6 inch/47.24cm	3-inch chair raiser, 2-inch raised toilet seat
#2	Carol	76, Retired	She has extensive arthritis in her back, knees and hips and walks with a stick. She is 5'4" and 9 stone. Her stair case as one rail on the left which is at a height of 900mm/ 90cm/35.4 inches. Popliteal height = 20.5-inch/520.7mm/52.07cm. Toilet and chair height = 16-inch	Raised toilet seat = 4-icnh, Raise chairs=4-inch, Stair rail 90cm
#3	Henry	79, Retired	Had a stroke with weakness to his left side. Walks using a stick. Popliteal height = 20.5-inch. Bed height = 18-inch	Bed raised by 75mm/7.5cm/2-inch
#4	Graham	75	Admitted into hospital as a result of a fall, Mobility issues, stair length = 60-inch/1524mm/152.4cm. Popliteal height = 20.5-inch/520.7mm/52.07cm. Toilet height = 18.5/	Raise toilet seat 2-inch with frame, stair rail = 60-inch
#5	Jenna	69	Hip replacement. Difficulties getting in and out of bath. Difficulties with chair transfers and toilet transfers. Stands with upper limb support and mobilises with a stick.	Bathboard 29" with rail. Raised toilet seat with frame. Toilet seat raiser - 6-inch. Bed is high, no raisers required.
#6	Winston	73	Winston suffers with prostate cancer and lives alone. He walks with a limp due to a severe fall incident he had 10 years ago. He has been given a walking stick but needs help with transfers in the home. Popliteal height = 22-inch. Bed height = 24-inch	Grab rail. Stair rail = 59-inch. Bath board = 27-inch. Bed raiser = 2-inch
#7	Sigmund	77	Sigmund has recently been into hospital for an operation. He has been discharged home but has had to make some changes to his living arrangements as at present he is unable to go upstairs. His family wish to have a bed downstairs but there is a gas fire in the room. Popliteal height = 23.5-inch	Bed height = 2-inch. Stair rail. Toilet raiser = 2-inch
#8	Julie	62	Julie lives alone and suffers from minor spinal damage which restricts her movement and as a result she is very worried about falling. Stair length = 1498.6 mm/ 149.86 cm/ 59 inches. Popliteal height = 20.5-inch. Chair height = 18.5-inch. Bed height = 16-inch	Chair raiser - 5.08cm/2-inch, Bed raiser - 10.16cm/4-inch

8.4.2 Recommendation accuracy

The **first research question** was to compare the relative accuracy of recommendations provided by application and those of the OTs without the use of the app. The results of the comparison between the two treatment conditions, and the extent to which the respective recommendations are significantly different from the true mean values, are presented in Table 8-3.

Table 8-3: Recommendation accuracy for recommendation module and no app condition.

Profile ID	GSR		App.						No App.					
	Equipment	**True mean (cm)**	**Mean (cm)**	**St. Dev.**	**Mean error diff. (cm)**	**Df**	**t**	**Sig. (2-tail)**	**Mean (cm)**	**St. Dev.**	**Mean error diff. (cm)**	**Df**	**t**	**Sig. (2-tail)**
	Chair raiser	7.62	7.03	1.86	0.59	16	1.11	0.282	7.33	0.83	0.29	17	1.46	0.163
#1	Raised toilet seat	5.08	5.06	0.08	0.02	17	1.17	0.259	5.05	0.04	0.03	17	2.92	0.010*
	Raised toilet seat	10.16	10.15	0.06	0.01	17	1.00	0.331	7.62	3.59	2.54	17	3.00	0.008*
	Raise chairs	10.16	10.15	0.05	0.01	17	1.00	0.331	9.03	2.79	1.13	17	1.72	0.104
#2	Stair rail	90.00	90.28	1.20	-0.28	17	-1.00	0.331	90.28	1.20	-0.28	17	-1.00	0.331
#3	Bed raiser	5.08	5.07	0.03	0.01	17	1.46	0.163	5.93	2.61	-0.85	17	-1.37	0.187
	Raised toilet seat	5.08	4.98	0.30	0.10	17	1.39	0.183	4.80	0.47	0.28	17	2.57	0.02*
#4	Stair rail	152.4	152.42	0.04	-0.02	17	-1.84	0.083	152.42	0.04	-0.02	17	-1.84	0.083
	Bathboard	73.66	69.99	17.49	3.67	16	-1.85	0.083	71.54	17.88	2.12	17	0.50	0.622
#5	Raised toilet seat	15.24	14.36	3.59	0.88	16	1.46	0.163	14.89	0.59	0.35	17	2.56	0.020*
	Stair rail	149.86	150.14	0.82	-0.28	17	-1.46	0.163	150.42	1.09	-0.56	17	-2.20	0.042*
	Bath board	68.58	68.93	0.59	-0.35	17	-2.56	0.020*	69.25	1.02	-0.67	16	-2.73	0.015*
#6	Bed raiser	5.08	5.01	1.11	0.07	17	0.27	0.790	4.30	1.24	0.78	17	2.65	0.017*
	Bed raiser	5.08	4.87	0.49	0.21	17	1.84	0.083	4.59	0.64	0.49	17	3.29	0.004*
#7	Raised toilet seat	5.08	5.36	0.54	-0.28	17	-2.20	0.042*	5.64	0.65	-0.56	17	-3.69	0.002*
	Chair raiser	5.08	5.72	1.00	-0.64	17	-2.70	0.015*	5.72	1.00	-0.64	17	-2.70	0.015*
#8	Bed raiser	10.16	9.58	0.64	0.58	17	3.84	0.001*	9.58	0.64	0.58	17	3.84	0.001*

*Indicates statitisically significant at < 0.05 level

Comparing the two recommendation condition results, in all cases (except for profile #1 and one of the two scores for profile #5), standard deviation values for the app were smaller than that of the no app condition. Therefore, as an initial observation, this signifies that the app tended to generate more precise (but not necessarily accurate) recommendations compared with the no app condition. In reference to accuracy, for majority of the cases, in absolute terms, the mean error differences were larger for the no app condition compared with the app. Exceptions were profile #1_raised toilet seat (0.02 for app and 0.03 for no app), profile #2_raised chair (0.01 for app and 2.54 for no app), profile #2_stair rail (0.01 for app and 1.13 for no app), profile #4_stair rail (0.10 for app and 0.28 for no app), profile #6_bed raiser (0.07 for app and 0.78 for no app), and profile #7_bed raiser (0.21 for app and 0.49 for no app). In absolute terms, this indicates that the app generated more accurate recommendations compared with the no app condition for 11 of the 17 recommendations.

The one sampled comparison of the app mean error differences against true mean reveals that in the majority of cases (i.e. fourteen out of 17), the mean error differences are not significantly different from the true means: profile #1_chair raiser (p = 0.282); profile #1_raised toilet seat (p = 0.259); profile #2_raised toilet seat (p = 0.331); profile #2_raised chair (p = 0.331); profile #2_stair rail (p = 0.331); profile #4_raised toilet seat (p = 0.183); profile #4_stair rail (p = 0.083); profile #5_bathbaord (p = 0.083); profile #5_raised toilet seat (p = 0.163); profile #3_bed raiser (p = 0.163); profile #6_stair rail (p = 0.163); profile #6_bed raiser (p = 0.790); and profile #7_bed raiser (p = 0.083). This shows that in these cases there is no evidence that the app produces inaccurate recommendations at the 0.05 level. The remaining four cases are significantly different from the true mean values, indicating that the app produced inaccurate recommendations at the 0.05 level.

The one sampled comparison of the no app condition mean error differences with true mean reveals that six out of the 17 mean error differences are not significantly different from the true means: profile #1_raised chair (p = 0.163); profile #2_raised chair (p = 0.104); profile #2_stair rail (p = 0.331); profile #3_bed raiser (p = 0.187); profile #4_stair rail (p = 0.083); and profile #5_bathboard (p = 0.622). Eleven of the 17 cases are significantly different from the true mean values, indicating that in these cases, the no app condition prescribed inaccurate recommendations at the 0.05 level.

Overall, comparing the performance of the app and the no app condition, both tool conditions produced inaccurate recommendations for four similar profiles, namely: #6_bathboard; #7_raised toilet seat; #8_chair raiser; and #8_bed raiser. The no app condition produced an inaccurate recommendation for a further six profiles: #1_raised toilet seat; #2_ raised toilet seat; #2_ raised chair; #4_raised toilet seat; #6_ bed raiser; and profile #7_ bed raiser. The main difference between the two recommendation conditions was that the no app condition produced inaccurate prescriptions at the 0.05 level for all profile recommendations: #6_stair rail (p = 0.042); profile #6_ bath board (p = 0.015); profile #6_bed raiser (p = 0.017), profile #7 recommendations: #7_bed raiser (p = 0.004); and #7_raised toilet seat (p = 0.002), whereas the app produced two inaccurate recommendation for profile #5_raised toilet seat (p = 0.020) and profile #6_raised toilet seat (p = 0.042), but there was no evidence of inaccuracy for the remaining profile two recommendations: profile #6_stair rail (p = 0.163); profile #6_bed raiser (p = 0.790); and profile #7_bed raiser (p = 0.083).

8.4.3 Recommendation accuracy consistency

The second research question was to compare the accuracy consistency of recommendations provided using the two respective treatment conditions (app vs. no app). The results of this analysis are presented in Table 8-4.

Table 8-4: Comparison of accuracy consistency for the app and no app.

Profile ID	App. Md err. (cm)	No App. Md err. (cm)	Paired differences Md err. diff. (cm)	Df	Z	Sig. (2-tail)	Effect size (r)	Effect size magnitude
#1	0.00	0.00	0.00	16	-.730a	0.465	0.18	Small
	0.04	0.00	0.04	17	-1.069a	0.285	0.26	Small - Medium
#2	0.00	0.00	0.00	17	-2.444b	0.015*	0.59	Large
	0.00	0.00	0.00	17	-1.473b	0.141	0.36	Medium - Large
	0.00	0.00	0.00	17	.000c	1.000	0.00	Trivial
#3	0.00	0.00	0.00	17	-1.412b	0.158	0.34	Medium - Large
	0.00	0.00	0.00	17	0.000c	1.000	0.00	Trivial
#4	0.00	2.54	-2.54	16	-3.000a	0.003*	0.75	Large
	0.00	0.00	0.00	16	-1.933b	0.053*	0.48	Medium - Large
#5	0.00	0.00	0.00	17	-1.933b	0.053*	0.47	Medium - Large
#6	0.00	0.00	0.00	17	-.816b	0.414	0.20	Small
	0.00	0.00	0.00	16	-1.667b	0.096	0.42	Medium - Large
	0.00	0.00	0.00	17	-.284b	0.776	0.07	Small
#7	0.00	0.00	0.00	17	-1.633b	0.102	0.40	Medium - Large
	0.00	0.00	0.00	17	-2.000b	0.046*	0.49	Medium - Large
#8	0.00	0.00	0.00	17	.000c	1.000	0.00	Trivial
	0.13	0.13	0.00	17	.000c	1.000	0.00	Trivial

a. Based on positive ranks.
b. Based on negative ranks
c. The sum of negative ranks equals the sum of positive ranks.
*Indicates statitisically significant at < 0.05 level

When considering the median error differences between the two recommendation conditions, in all cases there were no differences between the median error values for the app and no app except for profile #17_1 (*Md* err. diff. = -2.54). This indicates that the mid-point error values tended to be the same irrespective of the condition to which participants were allocated.

The Wilcoxon signed-rank test comparing the absolute error differences of the app and no app condition recommendations revealed that in some of the cases (five out of the 17), the app produced more consistently accurate measurements than the no app condition: profile #2_raised toilet seat (z = -2.444, p =0.015, with a large effect size r = 0.59); profile #5_bath board (z = -3.000, p = 0.003, with a large effect size r = 0.75); profile #5_raised toilet seat (z = -1.933, p = 0.053, with a medium-large effect size r = 0.48); profile #3_bed raiser (z = -1.933, p = 0.053, with a medium-large effect size r = 0.47); and profile #7_raised toilet seat (z = -2.000, p = 0.046, with a medium-large effect size r = 0.49). Ten of the z scores were based on negative ranks, three of the z scores were based on positive ranks, and the remaining four z scores were based on the sum of the negative and positive ranks that were equal. In majority of cases (11 of the 17), the sum of ranked negative differences was lower than the sum of the positive ranked differences, indicating that the app consistently produced more accurate (i.e. lower recommendation error differences, except for profile #5_bath board) compared with the no app condition.

Overall, comparing the performance of the app and no app condition in terms of accuracy consistency, the app outperformed the no app condition in five of the 17 cases, generating significantly more consistently accurate measurements than the no app condition. In eight of the remaining 12 cases, although the differences were not statistically significant, the app tended to generate smaller error differences than the no app condition (indicated by majority of the *z* values being based on negative ranks). In the four remaining cases (profile #2_stair rail; profile #4_stair rail; profile #8_raised chair; and profile #8_bed raiser) the app and no app conditions error differences tended to be the same; however, there was no significant difference in the error differences for these cases.

8.4.4 Satisfaction and overall usability

The third research question was to compare the satisfaction and overall usability of the app against the neutral mid-point of the 5-point Likert-type scale. The overall SUS score for the recommendation prescription module was 83.6 out of 100 (*SD* = 8.7). According to the evaluation criteria for SUS [289], this indicates that the application delivers 'excellent' (Descriptive adjective), 'acceptable' (Acceptability range), and 'Grade B' (School grading scale) levels of usability. Figure 8-4 presents the SUS rating scale with the overall SUS scores for the app.

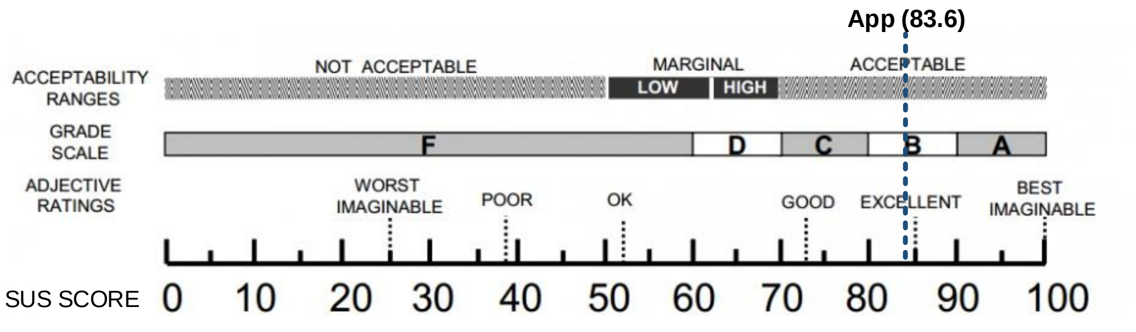


Figure 8-4: SUS rating scale with overall SUS results for Guidetomeasure app.

Follow-up analysis of individual SUS items for the application were conducted to identify any specific usability issues that the participants experienced during the interactive task and whether the item scores are significantly greater than the neutral mid-point of 3.00 on the 5-point scale. Table 8-5 presents the individual SUS item results, differences (denoted as gap score), and corresponding significance values.

Table 8-5: Guidetomeasure app. and booklet comparison of SUS scores.

SUS item	Mid-point	App. Mean±SD	Gap score	Df	t	Sig. (2-tail)
S1: I think that I would like to use the correctfit app frequently.	3.00	3.36±1.50	0.36	10	0.80	0.441
S2: I found the correctfit app unnecessarily complex.a	3.00	4.55±0.69	1.55	10	7.45	0.000*
S3: I thought the app/booklet was easy to use.	3.00	4.45±0.69	1.45	10	7.02	0.000*
S4: I think that I would need the support of a technical person to be able to use the correctfit app.a	3.00	3.82±0.98	0.82	10	2.76	0.020*
S5: I found the various functions in the correctfit app were well integrated.	3.00	4.36±0.50	1.36	10	8.96	0.000*
S6: I thought there was too much inconsistency in the correctfit app.a	3.00	4.73±0.47	-1.73	10	12.26	0.000*
S7: I would imagine that most people would learn to use the app/booklet very quickly.	3.00	4.45±0.69	1.45	10	7.02	0.000*
S8: I found the correctfit app very awkward to use.a	3.00	4.82±0.40	1.82	10	14.91	0.000*
S9: I felt very confident using the app/booklet.	3.00	4.73±0.65	1.73	10	8.86	0.000*
S10: I needed to learn a lot of things before I could get going with the correctfit app.a	3.00	4.45±0.52	1.45	10	9.24	0.000*
Equipment recommendation (additional items)						
A1: Using the correctfit app to assist with recommendations was clear and easy.	3.00	4.82±0.40	1.82	10	14.91	0.000*
A2: Using this correctfit app improves the accuracy of recommendations I provide.	3.00	3.82±0.98	0.82	10	2.76	0.020*
A3: The format in which the recommendations are presented were clear and helpful.	3.00	4.18±0.60	1.18	10	6.50	0.000*

A1 – A3 bespoke items presented in addition to the 10 standard SUS items to evaluate equipment recommendation
[a] Responses of negative items reversed to align with positive items, higher scores indicate positive responses.
* Indicates statitisically significant < 0.05 level

All 10 SUS individual mean item scores and all three clarity of equipment recommendation items were above the neutral mid-point of 3.00, indicating that, overall, participants tended to be satisfied and positive about the app. From a statistical standpoint, in all cases (i.e. SUS items and clarity items) the mean app scores were significantly higher than the mid-point benchmark.

Item S1 asked participants to response to how frequently they were likely to use the application. Although the mean app scores were higher than the mid-point benchmark by 0.36, the difference was not significant ($p = 0.441$). Results from item S2 reveal that participants responded positively to the app and that it was significantly less 'unnecessarily complex' ($p = 0.000$). For S3, participants responses revealed that the application's ease of use was significantly higher than the mid-point ($p = 0.000$). Results for S4 showed that participants tended to disagree with the notion that a technical person was needed to be able to use the application ($p = 0.000$). For S5, participants felt that the various functions that the app provides are well integrated and scored significantly above the mid-point ($p = 0.000$). Participants disagreed significantly with (S6) that the application had too much inconsistency ($p = 0.000$). Participants agreed with S7, that most people would learn to use the application significantly quickly (p = 0.000). Results for item S8 indicate that participants disagreed strongly with the idea of the application being awkward to use (p = 0.000). Responses to item S9 show that participants tended to agree strongly that they were confident using the application (p = 0.000). Results for item S10 indicates that participants disagreed significantly with the idea of it being necessary to learn a lot of things before being able to use the application (p = 0.000). Item A1, shows that participants reported that using the app to assist with recommendations was clear and easy, significantly above neutral (p = 0.000) and that using the application improved accuracy of recommendations (A2); more than what they provide without this tool (p = 0.000). Responses to item A3 reveal that the format the recommendations are presented in are clear and helpful (p = 0.000).

Analysis of SUS Learnability, Usability, and Equipment recommendation constructs reveal that the Cronbach's alpha scores for all constructs were above the acceptable threshold value of 0.6 for small sample studies [292]. Table 8-6 presents results of the respective constructs.

Table 8-6: Comparison of SUS constructs.

Construct	Items	Cronbach's alpha App	Mid-point	App. Mean	Gap score (Mid-point -	Sig. (2-tail)
Usability	SUS items 1-3, 5-9	0.73	3.00	4.43	-1.43	0.000*
Learnability	SUS items 4,10	0.40	3.00	4.14	-1.14	0.000*
Equipment recommendation	Clarity of guidance items 1-3	0.63	3.00	4.27	-1.27	0.000*
A1 – A3: items presented in addition to the 10 standard SUS items to evaluate equipment recommendation function						
* Statitisically significant < 0.05 level						

The results for SUS Usability, Learnability, and Equipment recommendations revealed that all three constructs achieved mean scores significantly above the neutral mid-point value of 3.00: namely, of 4.43 (p = 0.000), 4.14 (p = 0.000), and 4.27 (p = 0.000) respectively. This indicates that users were positive about the Usability and Learnability of the application and the clarity of the recommendation it provides.

8.4.5 Perceived challenges, opportunities, adoption, and use

Five high-level themes emerged from the thematic template analysis: Perceived Usefulness, job relevance (PU); Perceived Usefulness, output quality (PU); Perceived Ease of Use (PEOU); Application Functionality (AF); and Consideration Factors (CF). The information in parentheses includes a unique participant ID and years of experience. Figure 8-5 presents sub-themes within the core themes and a sample of selected quotes that substantiate these resultant themes.

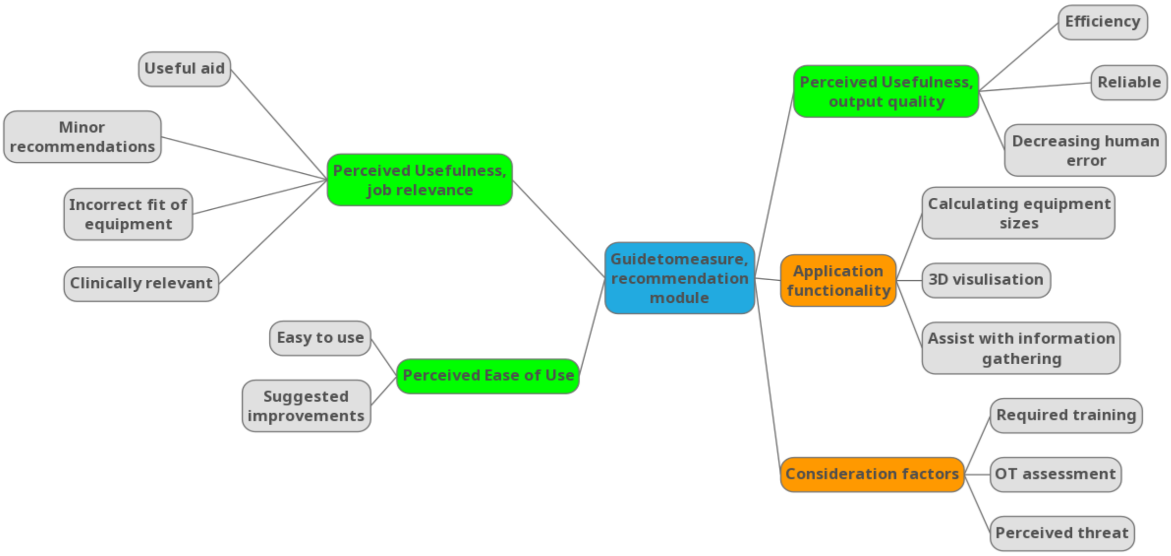


Figure 8-5: Thematic mind map of inductive and deductive themes and sub-themes.

Perceived Usefulness, job relevance

Most participants felt that the app was a *useful aid*, particularly for older adults to self-assess for minor equipment. Participants commented on the use of the app for prevention of falls and other areas in health and social care where service users would need a tool to help with the self-assessment of equipment. Another participant noted that the app could be used by inexperienced trusted assessors to help shape the way in which they conducted their assessments in practice.

> *"I can see its use in prevention of falls and a proactive approach that perhaps GP Surgeries or pharmacies could advertise to assist purchasing of equipment privately." (P1)*

> *"...In future re-enablement trusted assessors may find this useful particularly when starting out in practice." (P4)*

Participant P7 spoke about older adults using the app independently for *minor recommendations* and expressed reluctance about patients using the app to perform assessments that required measuring multiple variables more complex than minor recommendations. The participant suggested other facilities to be added to the app if the benefits of using it to facilitate OTs to carry out different levels of assessments were to be realised.

> *"As for older adults using it would have to be for minor recommendations and not for assessments that require multiple variables to be considered like for an example a sit lift... but something like a grab rail or a shower that would be fine…there is (sic) other equipment that I would say that needs to be added to the app." (P7)*

A number of participants discussed the importance and implications of having *incorrect fit of equipment.* In particular, participants provided examples of their experience with clients who had experienced falls due to prescribed equipment being unfit for the client's needs; they also recalled other cases which resulted in severe outcomes.

> *"I do think it's an important issue to look at. I mean I've had clients that have fallen because of the device not fitting their needs and that's not in the worst case. I think it's a key issue we (are) dealing with here…incorrect measurements could lead to severe outcomes so it's certainly not trivial" (P9)*

There was a view that the app could be *clinically relevant* as it includes features to support aspects of the OT role, and, equally, that of older adults to independently make assessment and purchase equipment privately. However, it was noted that if the app is to be used by older adults independently then a disclaimer should be applied to the effect that a clinician should be consulted for scenarios that may warrant clinical expertise to conduct the assessment.

> *"It's somewhat relevant for my role as an OT as it covers some parts of what I do. However, (I) do think it would be also useful for older people to be more proactive if making private purchases from pharmacies. If going that route, a disclaimer regarding OT assessment or support with appropriate use due to risks e.g. transferring in and out of the bath." (P14)*

Perceived ease of use

All participants felt positive about using the app and found it *easy to use*. Participants commented on the ease of selecting furniture items to take measurements and prescribing equipment to fit patients by choosing the equipment on the app. The prompts to users for outstanding measurements not recorded were a feature well-received by participants and were seen as particularly helpful when performing the necessary tasks. There was no mention of concerns with any aspect of the app's ease of use as it was described as clear and straightforward in the instructions it provided to the users.

> *"It was easy to use, easy to select which furniture you were measuring, what measurements you needed to take and select equipment you want to prescribe to the service user…it was straightforward and clear with what information was needed." (P13)*

> *"I found it pretty easy to use…you could record things quite easily and it would run you through to make sure you haven't missed things" (P7)*

Some participants *suggested improvements* be included in the next version of the app. Participant P14 commented on adding available styles of equipment and furniture items, illustrating alternative stair cases and specialist furniture in cases where standard equipment is unsuitable. Participant P3 suggested adding a video demonstration of how the equipment is installed and used in the home. Participant P7 remarked that adding equipment to the app for major adaptions could be used to support cases where patients have complex needs.

> *"… Add things like installation of rails, alternate stair options, measuring of different types of sofa chairs, perching stool and high back chair options as adaptations when chair raisers are not safe to install." (P14)*

> *"Video example of illustrating how equipment is installed and used…" (P3)*

> *"If it had more equipment to choose from to help with major adaptations…I could see me using it with my clients with quite complex needs." (P7)*

Application functionality

Participants felt that the app could reduce the variation in techniques for recommending equipment by automating the process of calculating equipment sizes to accurately prescribe equipment (P7). Participant P16 commented that the app could enable patients who could self-assess to use the app independently, provided it was for minor equipment. They also felt that it could serve as a tool for addressing issues where there was a waiting times for home assessment referrals.

> *"Reduces differences in the process of recommending 'styles' or techniques so all recommendations are calculated to the same template/process." (P7)*

> *"It is great for those that do have support or are able to use the app independently to reduce wait for social services referrals for minor equipment only in non-complex cases." (P16)*

Participants were enthusiastic about the *3D visualisation* guidance and prescription offered by the app, which provided a more enhanced alternative to interpreting 2D guidance diagrams with unreadable textual descriptors and colliding arrow prompts. These were reported to be problematic, and the app made them much easier to visualise.

> *"Love the 3D element which takes away from poorly drawn diagrams and scraps of paper with illegible writing! Also, easier to see where measurements are required vs. a 2D with multiple lines over it." (P1)*

The app was perceived as a support tool for measuring key areas in the home and to *assist with information gathering* in a structured form that could be carried out by other clinicians and unqualified practitioners. Hence, participant P3 felt that the app provided a means by which to standardise measurement-taking, which could allow other users to collection information on behalf of clinicians, patients, and their family members.

> *"Regularly measuring areas captured by app, useful in that (it) can standardise measurements so could send out assistants or students to capture information if family/partner unable to." (P3)*

Perceived Usefulness, output quality

Participants viewed the app as improving efficiency in terms of reducing the number of visits required to patient' homes, since it enabled some of the assessments to be done by patients or carers; thus, enabling quicker provision of equipment recommendations. Participant P7 felt that, as the assessment for minor recommendations could be done in absence of a clinician via the use of the app, this could reduce the time they would typically use to take measurements for recommending equipment.

> *"Reduces workload of visits to property, with regular use then confidence in app would allow faster provision of recommendations." (P3)*

> *"This could support with knowing home environment and measurements to reduce time required for access visits for recommending equipment." (P7)*

Some participants perceived the app recommendations as being *reliable* as the measurements in which it helps users to record, and the assessments that clinicians would typically carry out during home visits. It was noted that the recommendations provided by the app should be informed by functional assessments and other variables that impacts equipment use in the home (participant P11).

> *"I think the app recommendations are reliable as the measurements recorded and with an in-person assessment…functional assessment and consideration of other variables." (P11)*

Participants made several references to the app reducing human error and suggested where it could provide value and be utilised in practice. The app was seen as beneficial in helping to reduce the inherently error-prone task of calculating measurements, so as to facilitate OTs and other clinicians in taking more accurate measurements and prescribing equipment better suited to patient needs. However, one participant noted that the accuracy of prescriptions is determined by the person taking the measurements. They suggested a video tutorial as an in-app feature to complement the 3D guidance models which illustrate measurement-taking to further improve accuracy.

> *"Rapid response would be useful to aid the OT/ PT/ NS in where to measure and prescribe equipment to reduce risk of human error in measurements." (P13)*

> *"…reliable as person holding tape measure! Example video of measurements may assist accuracy." (P3)*

Consideration factors

Possibly as a result of the diverse profile of users in the older adult population, participant P1 felt that their client group and family carers may not be suitable target audience for the app, due to the *required training* to be able to use the app compared to a more familiar tool such as a leaflet to conduct assessments.

> *"This could be useful, however with my client group could be (a) limited market due to need for family and training to use, versus quick provision of leaflet." (P1)*

Participants were enthusiastic about the app being used in practice to help deliver *OT assessment* for patients who require equipment for assisted living. One participant viewed the app as potentially valuable in addressing some of the issues that currently face the health service and contribute to inaccurate equipment being prescribed to patients. However, the participant felt apprehensive about the possible loss of clinical reasoning if OT assessments were not carried out.

> *"I would love to see it used by health care professionals or family members of those in hospital to reduce need for access visits to property. I do worry that the holistic views and clinical reasoning of OT could be lost if nil OT assessment was completed in line with this app?! But very useful to reduce time of assessment, waiting lists for home assessment for very minor equipment and reduce error of service user ordering wrong equipment and wasting money that they could have spent elsewhere by getting the right measurements first time." (P16)*

When discussing the potential challenges of this application in practice, the responses of several participants alluded to it being potentially a *perceived threat* to the role of an OT in supporting older adults' independent living. Participant P3 believed that their role as clinicians could be replaced by patients using the app independently, removing key aspects of what makes the role of OTs crucial in understanding patients' lifestyles, which contribute to deciding on recommendations to fit their needs. Participant P9 was intrigued about the outcomes of assessments carried out using the app and tools currently in use; also of other clinicians' preferences for using both tools; and wondered if a patient would know who to contact in the event where equipment needed to be repaired.

"Could take away the personal factor and clinical reasoning of the professional in hand and from building rapport with client to understand their lifestyle needs and those of their families." (P3)

"Would be good to know preferences of what would like to be provided, are they able to maintain equipment, do they know who to contact if any repairs, will they have a review at home to see if they are safe using the equipment?" (P9)

8.5 Discussion

This study evaluated the recommendation module (described in Chapter 6). This is an integrated novel approach that generates equipment size prescriptions based on measurements stored in the measurement guidance module. The algorithm that underlies the module was formally presented in section 8.2. To the researcher's knowledge, this module is the first to provide users with equipment size prescriptions based on assessment/measurement data. To evaluate the performance of the recommendation module, a pilot study involving 18 OT participants was undertaken to investigate the extent to which the app enabled participants to effectively (i.e. with regard to accuracy and accuracy consistency) recommend equipment sizes compared with no app conditions. Furthermore, usability measures (SUS) and user perceptions of the recommendation module (post-task interviews) were obtained to investigate user satisfaction, complemented by in-depth qualitative evaluation which generated insights into the relevance, output quality, and intentions to adopt the app-based assessments and prescriptions in practice.

The **first research question** explored the relative accuracy of recommendations generated using the app module and no app and the extent to which each of these conditions generated recommendations that were not significantly different from the true mean recommendation values for each patient profile. The results of this study revealed that, in most cases, the app module provided more accurate recommendations in comparison to users providing recommendations with no app in absolute terms. This was exemplified, firstly, from the mean error differences being lower (in 11 out of 17 cases) when the app module was used. Considering the statistical significance differences between the provided recommendations and the true mean values, the results show that there was a less notable difference in performance between the app module and no app. Both recommendation conditions performed equally well for the same three out of 17 profiles items (profiles: #6, #7 and #8). However, the app module outperformed the no app on seven additional profile items; specifically, the raised toilet seat, stair rail and bed raiser equipment recommendations. Therefore, the app module generated accurate recommendations for four profiles which required toilet seat and bed raiser equipment to be prescribed, compared with the no app module condition which generated only one accurate equipment size overall. Several references were made to the app module's capability of providing accurate equipment sizes in the post-task interviews. Also, that using the app module reduced the inherently error-prone task of calculating equipment sizes without aid. This is testament to the app module's capability of prescribing equipment sizes based on the recorded measurements and automating the calculation of equipment size prescriptions based on clinically-defined thresholds without calculating numerical values for prescriptions, which is commonly subject to human error.

Although there is little evidence in the literature of the effectiveness of existing tools used for home assessment provision [395] as seen in this study with the no app approach performance, the app module seemed more effective in providing accurate equipment size recommendations that fit the needs of the patient profiles. This is a very promising result, as it indicates that the app module can enable clinicians to recommend more accurate equipment sizes compared with what they currently use. It is also built upon prescription methods that clinicians use in their daily practice, accepted and marked as a familiar means of prescribing equipment to patients. Further, it could also result in equipment matching the needs of the patient and their environment and reduce extrinsic fall risk factors (as per its intended purpose) which would otherwise be present and pose a threat to the patients' wellbeing due to inappropriately prescribed equipment [396, 397]. Raising the toilet and bed by use of accurate assistive equipment is important as it facilitates daily living tasks [398], reduces fall risks as a result of furniture item transfers, and improves patients' ability to transfer on and off furniture items within the home [399]. These findings are further supported by existing research in this area, with patients experiencing difficulty with toilet transfers due to absence of assistive equipment and reported fear of falling - a major cause for concern for older adults who live alone [400]. Furthermore, evidence in the literature has shown patients who abandon unsuitably prescribed equipment compensate by using other nearby furniture items to help with support/transfers [55]. Prescribing accurate bed raisers may potentially reduce falls that occur at the bedside [362].

Above all, it seems possible that the results for the no app performance are due to calculating equipment sizes without aid, which is inherently error-prone and results in inaccurate numerical value prescriptions. Existing research has found that error-handling mechanisms embedded in health-related software applications for number entry and error-resolution in prescriptions are a useful check against these being less vulnerable to human error by clinicians when providing these [385]. Indeed, prompting the clinical user to rectify a number entry error has been shown to be a useful method as they are likely to make far fewer errors [401]. In anticipation of this, error-checking functionality has been integrated within the app module (see Chapter 6 for details).

The **second research question** compared the relative accuracy consistency of the two recommendation conditions. The results revealed that there were no cases in which the no app condition outperformed the app module in terms of accuracy consistency. Whilst, in most cases, there was a median error difference, the app consistently produced smaller median error values. This complements the findings of the first research question, namely that the app module generated smaller recommendation errors compared with the no app condition. Specifically, in all cases where there was a difference between the app module and no app median error, the error differences were smaller for the app module. When comparing the statistical significance of differences in terms of consistency of recommendation accuracy between the app module and no app, the results show that the app module significantly outperformed the no app condition in five of the 17 cases. Although eight of the remaining 12 cases were not statistically significant, the app module generated smaller error differences than the no app condition. Furthermore, raised toilet seat recommendations for profiles 7, 17, and 20 were consistently more accurate when using the app module, as were bath board and bed raiser recommendations for profiles 8 and 17. In practical terms, a notable difference in performance was seen in profiles 7, 17, and 20, which demonstrated large and medium-large effect sizes in favour of the app module for raised toilet seat recommendations. Given the importance of raised toilet seat equipment as an environmental improvement for fall prevention [402], this finding supports the notion there may be significant practical value in using the app module to allow users to prescribe minor equipment, compared with existing tools.

The large and medium-large effect sizes achieved for prescribing bath board and bed raiser equipment in respect of profiles 8 and 17 further strengthens the app's practical value. Accurate equipment to assist with on and off transfers, such as bed raiser and raised toilet seats, are key devices that are prescribed by clinicians to prevent extrinsic fall risk factors; typically located in areas where patients conduct daily living tasks using these furniture items [362]. Indeed, accurate bath board equipment is another preventive measure for fall risks in the home and helps patients who suffer from muscle weakness, a contributing factor to a fall that occurs within the home [386]. Although other profiles for which the bed raiser and raised toilet seat were prescribed produced smaller errors using the app module, the differences between the app module and no app in terms of consistency of recommendation accuracy were not statistically significant. One possible factor that enabled participants to more consistently prescribe accurate equipment sizes using the app module is that the prescription algorithm generating equipment sizes is likely to reduce human errors introduced in calculating equipment sizes, providing that the recorded measurements are collected accurately. Many studies in the literature have proposed clinical algorithms to facilitate clinicians in selecting equipment to prescribe to older patients who exhibit difficulties with performing daily living tasks

[386, 387, 403-406]. These algorithms, however, do not consider measurements a part of ensuring the equipment matches the patient and their environment, and their inner workings are unreported and tend to be a ‘black box’.

Based on participants’ feedback in the post-task interviews, 3D visualisation of the equipment enabled them to visualise the equipment installed. This was reported to be a beneficial feature for patients to self-prescribe for minor equipment. Existing research has found that 3D visualisation is useful in demonstrating devices that facilitate assisted-living care and illustrate guidance for performing complex self-care tasks [257, 404]. Prescribed rehabilitation exercises have also shown promise in improved care delivery and potential for better healthcare outcomes [407-409]. This finding also highlights the app’s potential use as it affords users with the ability to prescribe equipment likely to be compatible to patient needs and suitable for their home environment. Adopting the application for equipment provision could lead to significant benefits in fall prevention, considering its growing importance and outcomes including better quality of life [410, 411], independence and decrease of functional decline [412] and reducing the risk of falling [3, 413]. This could also reduce the cost implications of incorrect prescription of equipment [414, 415] as the app automates the prescription of minor equipment - functionality that is not offered in any existing tool.

The **third research question** evaluated the usability of the recommendation module within app via the SUS questionnaire instrument. High levels of usability and user satisfaction were revealed through the SUS and clinician feedback. Acceptance was found to be high relating to the use of the app due to the benefit and value it offered for prescribing minor equipment. The analysis of the SUS data revealed that the sample attributed a score of 83.6/100 to the app for Usability, achieving ‘excellent’ and ‘acceptable’ levels of usability at grade ‘B’ overall. The individual SUS item results revealed that there was a significant positive preference, with the app being reported as significantly less complex (S2), easier to use (S3), could be used without the support of a technical person (S4), was better integrated (S5), had degree of consistency (S6), could be learnt to use very quickly (S7), was less awkward (S8), confident in use (S9), and required a lower learning overhead (S10). The additional items showed that using the app to assist with recommendations was clear and easy (A1), improved accuracy of recommendations (A2), and that the format in which equipment recommendations are presented was clear and helpful (A3); with all items being higher than the mid-point of value three on the 5-point Likert scale.

In terms of the two SUS sub-scales, OTs also tended to strongly agree with statements related to the Usability and Learnability of the application, and with the app providing equipment recommendations. The SUS results highlighted a general consensus that the application was easy to use, straightforward in learning to use it, and that it provided clear and helpful functionality for equipment recommendations. These are promising results, particularly when considering that clinicians are more likely to engage with technology-assisted healthcare systems in practice if they perceive it to be easy to use and fit for purpose [416]. It is possible that these results are due to clinician involvement and close interaction throughout the design and development of the app which ensured that it was fit for purpose and also contributed to its enhanced usability. The finding that the app is regarded as a usable tool for measurement guidance, as well as prescribing equipment to assist with the EFAP, is an important finding as its use in practice is likely to be of considerable value if it offloads part of the manual effort in calculating equipment sizes and reduces the inherent human error in handling numerical values.

The **fourth research question** aimed to explore users' views of the app and the perceived challenges, opportunities, and intentions to adopt the app in practice. In terms of *Perceived Usefulness, job relevance*, participants remarked on the app being a useful aid for older adults to use to self-assess for minor equipment and applied in neighbouring clinical areas to facilitate clinicians and trusted assessors with more effective equipment prescriptions. Importantly, some participants commented on the possible severe outcomes as a result of inappropriate equipment prescriptions to fit the patient and their home environment due to inaccurate measurements. Although the recommendation module was seen as clinically relevant, with most participants articulating that the app could be used by patients to self-assess for minor equipment, there was reluctance shown towards patients using it to self-assess for major equipment as multiple variables and complex clinical reasoning was considered necessary to be applied. Participants suggested a disclaimer to be added to the app as a safeguard mechanism, advising patients to consult a clinician for cases that require more complex clinical reasoning, including major equipment prescriptions and assessments not to be conducted without clinical intervention. Interestingly, participants often expressed their reluctance for patients using the app in its current form to self-assess for major equipment, despite being told that clinicians are the target audience for this module as it is used in conjunction with clinical reasoning skills. However, this uncovers opportunities for the app to be used to support clinicians with major equipment prescriptions. In fact, some participants suggested adding more functionality to the app to facilitate clinicians to perform more complex EFAP assessments. This is an important finding which is likely to support clinicians' and patients' actual adoption of the app to perform app-based prescriptions in the EFAP context.

Regarding *Perceived Usefulness, output quality*, clinicians see the use of the app as a means to improve the efficiency of home visits by patients self-assessing for minor equipment, either by using the app themselves or carers perform the assessments on their behalf, thus reducing the number of visits and demand on clinicians. This is particularly valuable as this finding is consistent with existing research evidence for augmenting home visits with mHealth technology to reduce waiting times and completion time of home visits, as demand is greater than the capacity [369]. Participants highlighted the app recommendations being as reliable as the measurements it helps to record and for the need to observe patients' functional abilities in and around the home, instead of relying solely on the app to provide recommendations for complex cases. One participant suggested a video illustration feature in the app to further assist with accurate measurement-taking. Given the widely reported issues of equipment abandonment, with inaccurate measurements being the principal issue, the two studies reported in Chapter 7 showed promising results of the app generating accurate measurements compared with the booklet.

In terms of *Perceived ease of use*, participants generally appreciated the recommendation module and the 3D minor equipment prescription models. In particular, participants commented on the support which the app provides in more easily collecting required data as part of equipment prescription process and the prompts to the user wherever measurements were not recorded. There were a number of suggestions to further develop the app to include illustrations (either through video or animation) to demonstrate how equipment is installed and used in the home and specialist furniture items in cases where minor equipment is unsuitable, providing measurement guidance that caters for multiple furniture item types and include major equipment for patients with more complex needs. Previous research has shown that clinicians are likely to adopt/use a software app providing it is fit for purpose and also easy to use [273, 416].

When discussing the *application functionality*, it was noted that the app could help to reduce the heterogeneity of equipment prescription techniques used across NHS trusts by standardising how equipment sizes are calculated to ensure prescriptions are accurate. This is an important finding given the need for standardising the assessment practices within the EFAP overall and address equipment abandonment levels [18]. Participants also saw the benefit it provides for patients who are physically capable of self-assessing for minor equipment independently. Enabling patients to self-assess could reduce the need for clinicians to perform assessments and potentially reduce demand for clinical intervention [417]. This situation was exampled by participant P7, who dropped out due to time demands for assessment referrals. Participants were enthusiastic about the 3D visualisation capability of the app to better visualise areas to consider when prescribing equipment otherwise absent in the existing paper-based tools, as they contain what was referred to as 'poorly drawn diagrams' and illegible textual descriptions. These findings seemed to be consistent with the results of previous research that explored the use of 3D technology as an alternative to existing 2D tools to provide functionality to better visualise ways of managing and treating health conditions in healthcare domain areas [248, 260]. Further, this is also aligned with the government agenda in the UK for the NHS to become paperless by 2020 [418]. This research is a step towards realising that agenda in the EFAP context.

With reference to *consideration factors*, participants noted the training needed prior to patients or their family members being able to use the app, compared with a more familiar tool such as a measurement guidance leaflet. The cost of training patients and their family members in use of the app for the EFAP [22, 293] could be counterbalanced by the significant benefits that the it offers over its 2D processor, as it has shown promise in improving the quality and provision of the EFAP. Some participants saw the app as being a tool that could replace OT assessment, and, in turn, a potential threat to the OT role. The view was expressed that it is pivotal to understand not just patients' functional abilities, but their lifestyle to inform the equipment prescription. Existing research shows that the role of an OT is important as they apply clinical reasoning which takes account of personal factors, including characteristics, symptoms, and social support when prescribing equipment [419]. Having patients apply such reasoning could be somewhat problematic since they lack the clinical expertise necessary for prescribing major equipment. The recommendation module serves as an adjunct for clinicians to better assess for equipment prescriptions and not a replacement for the crucial role of an OT. Future research should therefore concentrate on the investigation of unpacking the clinical reasoning that is employed for major equipment if the app is to be redesigned or repurposed and used for such cases by clinicians (see section 9.5 for an explanation of this future endeavour).

8.5.1 Limitations

The researcher recognises the limitations of the study. First, the sample size is relatively small, although, as previously noted, it was over the acceptable sample size necessary to provide useful feedback of software applications in usability studies [285]. Second, most of the participants in the sample were female. This is primarily attributed to the field of occupational therapy being a female-dominated profession [286]. This pilot study was, however, concerned with the app being able to provide recommendations, rather than recruitment of a large sample of users to use the app module to recommend equipment. Furthermore, profiles largely containing synthetic data about patients and only used different cases which warranted the need for equipment. It is possible that the conclusions drawn from this study may not be generalisable for recommending equipment to patients in real-world scenarios. Therefore, due care should be taken in generalising the results of this study towards large-scale adoption or clinicians' perceptions of the use of the app in clinical practice. It is acknowledged that different conclusions could possibly be drawn when considering a large sample and performing evaluation 'in the wild'. A follow-up study is, therefore, encouraged to prove these findings.

Third, seven participants dropped out after the recommendation task due to the work pressures in their respective practices. This is not surprising since OTs represent only 2% of the health and social care workforce, but manage approximately 35% of older adult referrals to local community services [295, 420]. Fourth, this pilot study was conducted in a lab environment with the use of patient profiles containing synthetic patient data used for evaluating the recommendation module. Conducting this study 'in the wild' would have required many resources to accompany the app, without a degree of confidence of its acceptance in a pilot study before a more elaborate user trial study. Fifth, the last interview was conducted over the telephone due to the participant's work commitments, due to reasons related to the rationale given previously. Observational notes taken during the sessions to complement the qualitative data collected could have reduced possible distortion of the data from carrying out the last interview over the telephone. Sixth, participants may have evaluated the general usability via SUS instrument of the other aspects of the app, rather than the recommendation module specifically. The recommendation module was separated in anticipation of encountering this potential issue.

8.6 Conclusion

In conclusion, this study evaluated the performance of the recommendation module to prescribe equipment sizes compared with conventional tools ('no app' condition) in a pilot study involving 18 OT participants who engaged in the recommendation task, and explored their perceptions of, and intention to adopt, the app module in practice. Effectiveness in terms of comparing the accuracy and accuracy consistency of recommendations provided by both conditions were comparatively evaluated. User satisfaction of the general usability of the app was evaluated via the statistical analysis of responses to the adapted SUS instrument. This study also investigated clinicians' perceptions of, and intentions to use, the app module, its relevance to the EFAP, and improving the output quality of equipment prescriptions (evaluated via the thematic analysis).

In terms of recommendation accuracy, the results revealed that the app module enabled participants to provide significantly more accurate recommendations for most of the patient profiles compared with the no app condition. The app module provided accurate recommendations with lower mean errors differences (i.e. between the app module and expert recommendations) compared with the no app condition. With regards to recommendation accuracy consistency, the results showed that there were no cases in which the no app condition outperformed the app module. In most cases, the app consistently produced significantly accurate recommendations with smaller median error values, compared with the no app condition. These findings provide valuable insights into the effectiveness of the app module in terms of its practical value in enabling clinicians to prescribe more accurate minor equipment recommendations compared with what they currently use in practice. Furthermore, it is also likely to reduce the error-prone task of computing equipment sizes, and, consequently, enable more accurate equipment recommendations aligned with the needs of the patient and their home environment.

With reference to the user satisfaction, the SUS results revealed that clinicians were very positive about the app module's usability and learnability. Levels of usability and acceptance were found to be high regarding the user-friendliness of the app and its capability of providing minor equipment recommendations. Based on the post-task interview results, clinicians were positive towards the app being used by patients to self-prescribe minor equipment, relevant to clinicians who prescribe equipment to older patients, and reducing the number of OT home visits by getting patients more involved in their own care. Moreover, the results also revealed that the 3D equipment models were perceived as a significant benefit in visualising equipment installation in the patient's home, data collection, and standardising equipment prescriptions to reduce the heterogeneous techniques used across the health and social care sector. Interestingly, clinicians saw the app as a potential threat to their role as OTs, irrespective of being told the app was designed as an adjunct to better support the roles in the EFAP. The outcomes of the current study were discussed in terms of its implications and recommendations to practice, followed by a discussion on the limitations of the current study.

8.7 Chapter summary

This chapter reported a pilot study (study 5), which evaluated the recommendation module (introduced and described in Chapter 6) against the standard recommendation approaches with clinicians by using patient profiles as data input for prescribing assistive equipment. The underlying prescription algorithm in the module was described in detail. The results showed that the app was more effective in accurately providing equipment prescriptions and was usable of satisfactory standard according to the clinician feedback. Chapter 9 brings this thesis to close by discussing the research findings, linked to the objectives outlined in the first chapter, the three contributions that this research makes to the domain and acknowledge the limitations and proposes solutions as direction for future research.

Chapter 9
Conclusion

9.1 Introduction

This final chapter summarises and concludes the overall research undertaken in this thesis, discusses the findings of the research with respect to the objectives outlined in Chapter 1, and contributions made to the research domain. An overview of the thesis is given in section 9.2, providing a brief synopsis of each chapter. Section 9.3 presents the key research findings more broadly and specifically from each chapter in relation to the research objectives that were outlined in Chapter 1. Section 9.4 highlights the three contributions that this research makes to the research sphere and clinical practice, and finally discusses the research limitations encountered during this undertaking and proposes a number of future research directions in section 9.5.

9.2 Thesis summary

Chapter 1 introduced the research problem and provided the context of study in order to justify the focus of the research reported in this thesis. An overview of the falls prevention domain was given, and the need for applying ICTs to environmental assessment interventions to overcome extrinsic fall risks explained, by means of exploring the extrinsic fall-risk assessment process (EFAP) in the field of Occupational Therapy. Of the many challenges identified in the literature survey, the most prominent challenges that were selected framed the focus of this research and were proposed to be addressed within the EFAP context, by augmenting its existing 2D paper-based tools via the use of mobile 3D visualisation technology. The overall aim of the research and objectives were then outlined, followed by a description of the research approach employed. The expected contributions that this research makes were presented in brief. This chapter then concluded with a roadmap of the thesis.

Chapter 2 offered a comprehensive review of the state of the art of the fall prevention technology landscape and a conceptual framework derived from and used to survey a range of fall prevention technology systems proposed in the research literature. Each of the components/themes of the survey and framework were discussed in turn. The gaps that were found in the literature were explained; the main challenge being the lack of effort hitherto expended on systems that incorporate environmental assessment interventions to help overcome extrinsic risk factors in the home. These gaps and the proposed recommendations provided the basis for conducting studies reported in the subsequent chapters.

Chapter 3 presented the research approach that was employed to achieve the overall research aim and objectives. The research process, designed in line with the design science research cycle steps, was explained. A mixed-methods approach was employed with methods utilised for data collection and analysis related to the interpretivist and positivist paradigms. The lab settings in which the experiments were carried out with participants were introduced. The general and ethical considerations by which this research abided were discussed, including a rationale for recruiting participants linked to a particular demographic. Further, the software development methodology used to design and develop the research artefact was discussed. This chapter was then summarised in the conclusion section.

Chapter 4 reported on the first user design and exploratory study with occupational therapists. A bespoke 3D measurement aid prototype was designed, and OTs perceptions of the prototype were explored, particularly with regard to usability and the feasibility, challenges, and opportunities of utilising the artefact to support the EFAP in practice. The developed prototype as a measurement aid was showcased. The results indicated that the usability of the prototype scored highly, giving improved interpretation/recording measurements and enhanced collaborative practice. Further, recommendations for using the prototype in practice were identified and user requirements to implement the prototype provided a basis for further evaluation.

Chapter 5 discussed the second study with older adult patients, which, like the first, was related to the design of a prototype and exploration of the benefits and drawbacks of using it in the EFAP. Details of the design phase and a walkthrough of the prototype was given in Chapter 4, as the same prototype was used in this study. The results showed that patients were satisfied with the usability of the prototype and appreciated the benefits of using 3D visualisation technology to better interpret the measurement guidance to perform measurement-taking more accurately. This chapter ended with a proposed set of user requirements to further modify the app and findings emerged from the study from the patient perspective, mapped to ‘implications to clinical practice as a result of using the app.

Chapter 6 described the process of refining the prototype that was designed and evaluated in studies one and two (reported on in Chapters 4 and 5, respectively). It explained the involvement of the two user cohorts and detailed how their feedback informed the newly refined artefact. The revised underlying system architecture was presented and explained, after which the measurement guidance and recommendations modules were discussed together with a walkthrough of the application modules.

Chapter 7 presented the third and fourth studies and evaluated the effectiveness, efficiency, and satisfaction of the Guidetomeasure app compared with an existing 2D measurement guidance paper-based tool currently used in practice by OTs and patients. Further, the studies were conducted within a living lab environment. After evaluating the performance of the app, follow-up semi-structured interviews were undertaken to identify the challenges, opportunities, and intentions to use the app in practice. The findings highlighted that the app enabled the user cohorts to take more accurate measurements of key furniture items in less time, and with greater satisfaction regarding the usability and learnability, compared with the booklet. High-level findings in relation to the research questions across the studies were drawn and a summary of the chapter provided. More specifically, each study reported in this chapter summarised the findings in terms of implications and recommendations to practice.

Chapter 8 provided the fifth and final study, evaluating the effectiveness of the recommendation module in the app for prescribing minor equipment accurately, compared with the existing approaches used for equipment prescriptions. After evaluating the accuracy of the app prescriptions, think-aloud sessions and semi-structured interviews were carried out to explore the experiences and perceptions of OTs, and their satisfaction with the app's usability and use in practice. The findings highlighted that the app provided more accurate equipment prescriptions compared to prescribing equipment without using the app. Furthermore, these findings were then presented and mapped to 'implications to clinical practice' as a result of employing the app.

9.3 Research findings

The motivation for this research work was the lack of research effort expended on environmental assessment interventions to overcome extrinsic fall risks and encourage clinician-patient collaboration in their efforts to improve assessments of such risks that occur in the home (as discussed in the literature survey reported in section 2.8). An established clinical intervention in OT such as the EFAP was identified as a case example in which the gaps were addressed. The review of the relevant literature on the EFAP revealed how the existing tools used to visualise the measurement guidance to assess for equipment proved to be insufficient, often resulting in inaccurate measurements, rendering equipment prescriptions 'poor fit' for the patient needs. The clinicians and patients alike who participated in their research echoed these findings. Consequently, this research explored the potential impact and benefits that the alternative 3D visualisation solution could provide in enhancing current practices and tools used in the EFAP. Considerable insights were gained into the available 2D measurement guidance and prescription tools currently in use, and ways in which the proposed solution could augment the existing limitations of these EFAP tools. As such, many points for the design of an artefact were studied in collaboration with clinicians and patients alike that are linked to the objectives (outlined in Chapter 1) and are revisited in the discussions that follow, which demonstrate how these points have been addressed.

O1. Survey the fall prevention technology domain to conceptualise the state of the art systems, identify gaps, and explore the literature for a suitable approach to guide the research in the development of an artefact to address the identified gaps in the fall prevention domain. To understand the fall prevention technology area, conceptualise the various sub-domains that address the different fall risk factors and identify gaps in the field, a survey of the literature was, therefore, carried out. In that respect, Chapter 2 proposed a conceptual framework of the state of the art fall prevention technology systems developed as a result of surveying the research literature. A comprehensive survey of the research landscape was undertaken, conceptualising the studies that fall under the sub-domains in the domain and identified challenges and proposed recommendations to resolve those challenges (in section 2.8). Of the many gaps identified, a selection of those was used to frame the focus of this research, which is:

Challenge 1: *Lack of research effort focused on reducing extrinsic risk factors, which are of equally major concern for patients who exhibit intrinsic risks and live independently.*

> ***Recommendation 1:*** *Identify new opportunities and develop new technology-based applications to support patients and practitioners in their efforts to overcome extrinsic risk factors.*

Challenge 3: *Current systems do not consider or support the delivery of environmental assessment interventions to reduce fall risks.*

> ***Recommendation 3:*** *Incorporate environmental assessment interventions into Post-FPI systems*.

Challenge 4: *Existing Post-FPI systems do not enable patients and practitioners to interact and collaborate whilst fall risk assessments are carried out using Post-FPIs.*

> ***Recommendation 4:*** *Develop Post-FPIs which allow patients and practitioners to engage and collaborate with each other as part of the assessment process*.

In light of the above challenges and recommendations, there was a need for an alternative solution to address the limitations of the existing environmental assessments and possible ways in which they could be augmented to achieve better assessments for equipment. A DSR approach was, therefore, adopted which enabled the design and development of an alternative technology-based solution – the research artefact. Based on the research aim, the rationale behind the selection of DSR as an appropriate research approach to address the objectives were given along with the research process (i.e. data collection and analysis techniques) that were followed (was presented in Chapter 3). A list of methodological choices made in Chapter 3 is given below:

- **Research approach:** *DSR*
- **Use of research paradigms within the DSR cycle steps:** *interpretivism and positivism*
- **Data collection and analysis techniques:** *Mixed methods approach*
- **Software development methodology:** *RAD*

O2. Explore the challenges and opportunities of the EFAP as a case example to address the limited efforts spent on environmental assessment interventions and the existing methods used

to overcome extrinsic fall risks. The EFAP is an established intervention in the field of OT, which is carried out to reduce fall risk factors in the home where stakeholders (i.e. both clinicians and patients) are increasingly becoming equal partners in the collection of assessments for equipment prescriptions. This intervention was chosen as a case example to further investigate the abovementioned challenges that frame the research focus in this thesis. Specifically, the literature review in sections 4.1 and 5.1 discussed the EFAP in more detail and the existing 2D paper-based tools that are currently used by clinicians and patients alike to overcome extrinsic fall risk factors that occur within the home environment. Evidence from the literature revealed that using such tools has a number of drawbacks, particularly in its capability to visualise measurement guidance, which, therefore, result in the following issues:

- Insufficient visualisation of measurement guidance
- Lack of depth perception of the 2D guidance diagrams
- Paper-based recording of measurement and associated assessment data
- Heterogeneous measurement guidance tools that result in inconsistent measurement-taking techniques
- No means of enabling patient-clinician collaboration for assessments
- No efficient and readily available tool to support patients to self-assess for minor equipment

These issues were considered in the design of the artefact with the user cohorts. The proposed solution offered enhanced visualisation capabilities to better visualise the measurement guidance for the extrinsic fall-risk assessment.

O3. Design and develop an alternative approach with stakeholders to overcome visualisation limitations of existing EFAP methods currently in use. In response to the gaps identified in the literature and the selection of an appropriate approach to address the research aim, the design and development of the alternative solution was conducted in two phases with older adults and OTs in studies reported in Chapters 4 and 5. Furthermore, the challenges and benefits of employing 3D visualisation for the intended purpose were explored. To this end, highlighting the key findings of the studies linked to their aims help to demonstrate the fulfilment of this objective. The discussion that follows, therefore, focuses on the aims outlined in the first and second studies reported in Chapter 4 and Chapter 5, respectively.

> ***First aim of study 1 (Chapter 4):*** *To develop and present a bespoke 3D mobile application prototype that provides EFAP measurement guidance to OTs via the use of 3D visualisation technologies*. To achieve the first aim of the study, the developed solution was implemented by undertaking an initial user-centred conceptual design phase to ensure that the design and

functionality of the prototype would be fit for purpose, if it were to replace existing 2D measurement guidance paper-based tools. The prototype was also aligned to the needs/requirements of the patients and clinicians, as there was no evidence of this being considered previously in the literature.

Second aim of study 1 (Chapter 4): *To explore OTs perceptions of the prototype application, particularly with regard to its usability and the feasibility, challenges, and opportunities of its utilisation to support the EFAP in practice.* The main findings of the second aim of this study revealed that clinicians accepted the use of 3D visualisation technology as an effective alternative to existing approaches to better provide guidance to clinicians and patients to improve assessments. The study also revealed that clinicians found the app (Guidetomeasure-beta) functionality such as manipulating the 3D models provided a clearer visualisation of the discrete points of measurement. They were also positive about the app's usability and integration into the EFAP, and it potentially being used by other stakeholders including care givers, trainee OTs, and patients. Further, the app provided capabilities for the patients and clinicians to engage in collaborative care practice and benefits to interprofessional collaboration amongst clinicians.

Aim of study 2 (Chapter 5): *To investigate the perceptions of community dwelling older adults regarding the feasibility, benefits, and challenges of using a 3D visualisation technology application to facilitate carrying out EFAP self-assessment tasks in practice.* The perceptions of the patients were similarly explored within the same design used in study one. The findings suggest that the Guidetomeasure-beta prototype is feasible for use by older adults' subject to initial training support on how to use it. The quantitative SUS results revealed that the app may be described as 'Marginal-High' along with strong agreement with items relating to its usability and learnability. Four high-level themes emerged from think-after and focus groups: Perceived Usefulness (PU), Perceived Ease of Use (PEOU) Application Use (AU) and Self-assessment (SA), and individual SUS item discussions. Overall, the app was seen as a useful tool to promote independent living, ownership of care, reduce waiting times and an enhanced visualisation of measurement guidance to accurately interpret areas of furniture items to measure. Several design and functionality recommendations emerged from the study to further develop the app to improve upon existing functionality which includes manipulating the view and position of the 3D furniture models, clearer visual prompts and alternative keyboard interface for measurement entry.

O4. Evaluate the research artefact through user-based studies (i.e. clinicians and patients) concerning its effectiveness in enabling accurate recording of measurements, efficiency, and perceived satisfaction of its general usability, compared to the conventional 2D method counterpart. The main purpose of Chapter 7 was to demonstrate that the newly developed software artefact was successful in supporting clinicians and patients to measure furniture and self accurately and reliably. To this end, the potential of the app to enhance the visualisation of measurement guidance to enable users to take accurate measurements was formally evaluated compared with the conventional 2D booklet against the established usability metrics outlined in subsection 7.1.1 within an OT and patient user-based studies.

RQ1. Does the measurement guidance module, on average, enable more accurate recording of measurements, compared with the paper-based measurement guidance booklet? The effectiveness of 3D visualisation for the intended purpose was explored by comparing the research artefact against the conventional 2D paper-based booklet currently in use for the EFAP assessments. To this end, the two studies produced promising results, specifically enabling both user cohorts to visualise and accurately record measurements using the app resulting in more precise measurements of the furniture items in the study. The results indicated that, overall, the Guidetomeasure app seemed to enable clinicians and older adult patients to take more accurate measurements, while obtaining fewer errors than the 2D booklet.

RQ2. Does the measurement guidance module enable more consistently accurate recording of measurements, compared with the paper-based measurement guidance booklet? The evaluation results indicated that the app provided better visualisation of measurement guidance compared to its 2D equivalent which resulted in enabling more consistent accurate recording of measurements for both user cohorts. Indeed, both studies revealed that the app produced smaller median error values and significantly outperformed the booklet in most cases.

RQ3. Does the measurement guidance module enable measurements to be recorded more efficiently, compared with the paper-based measurement guidance booklet? The efficiency was evaluated by measuring the task completion time of the app compared to the 2D booklet, taking measurements of all furniture items including the popliteal height. The results produced indicated that, overall, the app seemed to enable participants to complete the measurement tasks significantly quicker compared to the booklet, efficiently localising crucial areas to measure, despite any of the participants having no previous exposure to using the app. To the best of the researcher's knowledge, there are no studies that evaluate the efficiency of measurement guidance tool in locating crucial areas to measure compared to its 2D equivalent.

RQ4. How satisfied, in terms of usability, are users of the measurement guidance module, compared with the paper-based measurement guidance booklet? This research question evaluated the participants' subjective satisfaction and comparative usability of the measurement guidance tools via the SUS questionnaire instrument. The evaluation results indicated that the app outperformed the booklet and that it is significantly more usable in terms of its capability to visualise measurement guidance and support clinicians and patients in the EFAP compared to its 2D equivalent.

RQ5. What are service users' views of the measurement guidance module, in terms of the perceived challenges, opportunities, and their intention to adopt and use this new technology in practice? The findings, in relation to this research question, showed that both user cohorts found the visual quality of the measurement guidance provided by the app to be a significant improvement to that provided by the booklet. Specifically, clinicians found that the app functionality could enable better coordination of assessments and offer enhanced functionality to help user make sense of visualising guidance of how it is perceived in reality. Although the patient's confidence in using the app to self-assess is linked to their perceived ability to physically take measurements, they would want a third party to check the accuracy of the measurements they had taken.

O5. Explore the artefact's functionality in assisting stakeholders with prescriptions of accurate equipment sizes based on a collection of assessments. The evaluation results of the recommendation module compared with conventional recommendation approaches currently in use is a strong indication of the benefits of providing prescription capabilities to hep assist clinicians with prescribing assistive equipment to patients. It is worth noting that the four research questions outlined in the introduction of study 5 was based on the usability metrics that were subsequently applied to study 3 and 4, with the exception of the efficiency measure as it was irrelevant for this present study. To this end, addressing the four research questions outlined in study 5 (reported in Chapter 8) through the evaluation results in turn fulfils the present objective. The discussion that follows, therefore, maps the findings to the respective research questions:

RQ1. Does the recommendation module, on average, provide more accurate recommendations of equipment sizes, compared with conventional methods (using no app)? This research question was examined by comparing the accuracy of recommendations generated using the app and 'no app' method for a sample of patient profiles constructed together with expert clinicians. The pilot study produced promising results with the app generating more accurate recommendations with fewer errors and capabilities to reducing human error in calculating equipment sizes, compared with the conventional methods. In particular, the app was able to provide accurate recommendations for equipment to assist patients with on/off transfers on the toilet and bed, which are located in areas where falls are highly likely to occur. It was, therefore, concluded that the app could be used by clinicians in practice to overcome extrinsic fall risk factors that would otherwise be present due to no equipment being used or abandoned.

RQ2. Does the recommendation module provide more consistently accurate recommendations, compared with providing recommendations without the use of any aid? With regards to the consistent accuracy of the app recommendations compared to the no app condition, it was found that the app significantly outperformed the no app condition in generating accurate recommendations consistently for the same patient profile with fewer errors.

RQ3. How satisfied are users with the general usability of the recommendation module and its capability to assist users with prescribing equipment? The results showed that clinicians were considerably satisfied with the general usability of the recommendation module which was evident in their responses to items relating to the app's usability and learnability. The SUS results drew attention to the app being easier to use, learning to use it was also straightforward and that it provided functionality for recommending equipment that was clear and helpful.

RQ4. What are occupational therapists' views of the recommendation module, in terms of the perceived challenges, opportunities, and their intention to adopt and use this new technology in practice? The findings suggested that clinicians were highly positive about the recommendation module and its capabilities that facilitate users with prescribing assistive equipment sizes to fit the needs of the patient and their home. Specifically, clinicians indicated promising views towards the app being a useful aid for older adults to self-assess for minor equipment and for it to be deployed in other clinical areas (i.e. disabled patients). Clinicians perceived that the app is a way of improving efficiency regarding visits to the patient's home and a means of outsourcing the assessments for minor equipment to patients or their family members, partly as a way of reducing the ever-increasing workload of OTs. Clinicians also perceived it as useful in reducing human error through calculating equipment sizes with the help of a developed prescription algorithm (see details of the algorithm in section 8.2). They also appreciated the visualisation of equipment installed within the areas of interest to the patient, as it gives instant visual feedback to the user on the provided recommendations. Furthermore, the recommendation module was reported to alleviate the heterogeneous techniques used across the NHS trusts in the UK by standardising the way in which clinicians or indeed other stakeholders prescribe equipment.

Above all, the findings of this research attained through the studies reported in Chapters 4, 5, 7 and 8 have offered significant insights regarding the clinical utility of mobile 3D visualisation technology to assist with interpreting measurement guidance and providing equipment prescriptions. Furthermore, although the results obtained indicate that 3D visualisation can contribute significantly to the EFAP, exploring its use in an uncontrolled environment dealing with unforeseen parameters must be achieved, if it is to have the level of impact in reality as seen in this research.

The results emerged from the five studies (Chapters 4, 5, 7 and 8) forms the overall findings of this research. These findings were evaluated regarding the number of contributions to the field under study, and also its practical significance. The next section addresses what has been discussed above and demonstrates how these objectives have been achieved through presenting the contributions that this research makes to the research domain.

9.4 Research contributions

To this end, the research findings are of significant value to clinicians and patients alike concerned with the provision of home-based fall prevention assessments, and more broadly to other related areas in healthcare whose assessment and treatment tools affected by the similar visual quality limitations as seen in the EFAP. Overall, the research conducted in this thesis makes three contributions to the research sphere, which is:

- A conceptual framework of the state of the art of fall prevention technology systems
- A novel mobile 3D visualisation software artefact
- Implications and recommendations for deployment in practice

Each of the contributions is now discussed in turn.

9.4.1 A conceptual framework of the state of the art of fall prevention technology systems

Many survey studies in the literature reviewed technologies applied in specific sub-domain areas of fall prevention. However, to the best of the researcher's knowledge, there were no existing surveys, which surveyed the range of fall prevention interventions and the variety of technologies employed in each sub-domain across the domain. Furthermore, there were little attempts made to conceptualise the various sub-domains that make up the fall prevention technology domain, in order to gain a holistic view of the landscape. To this end, a comprehensive review of the research literature (in Chapter 2) is conducted to understand and bridge this gap in the research domain. The review surveyed and categorised the various sub-domains to where technologies have augmented fall prevention interventions, identified gaps where opportunities for new research lies and provided a rationale for the proposed research work. A systematic approach was employed in the search through the literature in order for the searches to be reproducible. Studies in the fall prevention technology domain that satisfied the criteria set were read through with their contributions synthesized and emergent themes extracted, which exposed the gaps in the literature. A conceptual fall prevention technology framework was developed as a result of carrying out a systematic survey of the range of fall technology systems presented in the literature (see Figure 2-4). This framework provides a lens of the work proposed in the research landscape where it contains four high-level categories of fall prevention technology systems: pre-fall prevention; post-fall prevention; fall injury prevention; cross-fall prevention. Other categories of the function of fall prevention technology systems include application type, technology deployment platform, information sources, deployment environment, user interface type and collaborative function.

A detailed survey of the state of the art of fall prevention technology systems was presented as a function of the proposed conceptual framework. A number of gaps were identified in the reviewed literature sample, along with recommendations to address those gaps. Of the many gaps identified, the need for new fall prevention technology systems to incorporate environmental assessment intervention to overcome extrinsic fall risk factors was framed as the focus of this research (see section 2.8). Enabling patients and clinicians to interact and collaborate during assessments and for patients to better engage in assessments for their own care and wellbeing was also framed as the primary focus of this research. The survey and framework both contribute to the fall prevention technology domain in providing potential fruitful avenues for future research. As mentioned previously, it provides a lens through which to view the research landscape and conceptualises the categories/components and relationships amongst these within each of the sub-domain areas, which prior to this survey, did not exist in the literature. Furthermore, this also aids other researchers to understand the potential areas where new developments could be placed within the proposed framework. It also offers a point of reference in employing a methodological approach to conducting a literature survey of this nature.

9.4.2 A novel mobile 3D visualisation software artefact

This primary contribution of this research was designed, evaluated and its challenges and benefits as a viable artefact from both user cohorts explored in Chapters 4 and 5. The measurement guidance was reproduced in all its complexity within an environment that resembles how the measurements of home furniture would be perceived in reality. A final version of the app presented in Chapter 6 was empirically evaluated within a living lab setting through user-based studies (reported in Chapters 7 and 8). Guidetomeasure is a novel mobile 3D visualisation technology that assists clinicians and patients in the taking and recording of accurate measurements of home furniture and related assessment data, and to facilitate prescribing equipment sizes (based on the recorded data) as part of the EFAP. As the high levels of equipment abandonment occurring primarily as a result of the insufficient visual quality limitations, causing a collection of inaccurate measurements, this present research provides an artefact that remedies these defects and ensures that equipment prescribed is compatible to the patient's needs, by offering:

- An alternative to the 2D paper-based measurement guidance in the form of a mobile 3D visualisation application in order to better visualise crucial areas on the five key home furniture, where falls are known to occur, as it is perceived in reality *(measurement guidance module)*;
- An assistive equipment prescription algorithm, as a complementary approach, which computes the measurement and assessment data collected and provides equipment recommendations and its size that is compatible with the functional needs and fitting of the patient and their home environment *(recommendation module)*.

The *measurement guidance module* facilitates measurement-taking and recording and collection of associated assessment tasks through the use of 3D furniture items/avatar models that provide guidance via the use of arrow prompts and audio instructions. Users are able to better interpret the guidance through enhanced visualisation, navigation controls to observe the different viewpoints and arrow prompts to help localise areas that are not otherwise obvious to view in 2D illustrations. Chapter 7 reported two user cohort studies, which empirically evaluated the performance of the app, compared with existing 2D paper-based measurement guidance tools that are currently used in practice. A statistical analysis of these results revealed that app enabled users to generate more accurate measurements, consistently, and complete measurements significantly faster, resulting in fewer error values, compared with the booklet. A comparative usability evaluation of both tools showed that the two user cohorts were more satisfied with the general usability of the app.

There is, therefore, strong evidence suggesting that the app was effective and efficient in achieving its intended purpose, positively received, and was thus more preferred by clinicians and patients alike and was found to be rather easy to use and useful to guide assessments. Hence, the Guidetomeasure app is fit for purpose and more valuable to clinicians and patients alike as it can be deployed in practice to reduce the abandonment issues faced in the EFAP and provide patients with the means to assess their needs for equipment without clinical intervention (see Chapter 7). Benefits of the app over the booklet include the capacity to minimise input errors during data input, easier to administer, ease of recording measurements/assessment data and sharing of that data, and enhanced patient satisfaction. This contributes to the weave of research that exploits 3D visualisation technology to remedy visual quality issues with 2D paper-based tools that provide insufficient visualisation for the purposes of treatment and assessment of diseases and conditions in the healthcare field. Consequently, the use of 3D visualisation technology, in this present research, as an alternative approach opens up the possibility for older adult patients to become better stakeholders in the assessment of their needs for equipment. This could, therefore, have positive implications towards enhancing the provision of quality health care, contributing specifically towards the long waiting times and tackling the 'demand exceeding supply' issue by way of patient involvement in their own care, and healthcare outcomes (see subsection 9.4.3 for more details). This point is particularly valuable for patients to take their own measurements to use for prescribing minor equipment and for clinical decisions as it offers a promising approach to acquire data from patients without the need for a home visit.

The *recommendation module* provides a complete solution to facilitate the EFAP delivery identified from participants' feedback in studies 1 and 2 (Chapters 4 and 5, respectively). This module is valuable since it provides equipment size recommendations based on the stored measurements, which helps to overcome the equipment abandonment issues (i.e. poor fit of equipment to the patient and their home environment and reduce the human error to which this task could potentially be subjected). Furthermore, the app provides a 3D representation of minor equipment it prescribes superimposed by its size to allow users to visualise how the equipment installed would be perceived in reality. The extent to which accurate recommendations provided by the app were compared to recommendations that clinicians provided through the use of existing approaches currently use to prescribe equipment to patients in practice (see Chapter 8). Statistical evidence revealed that the recommendation module is more accurate and consistently accurate in recommending minor equipment sizes, compared with the conventional approaches. This was exemplified by the developed patient profiles used in the evaluation of the module in Chapter 8. Therefore, the app provides a more accurate and consistently accurate means of prescribing equipment sizes in a way that reduces the human error in calculating equipment sizes, as clinicians are likely to commit during assessments. Hence, the Guidetomeasure app is more valuable to both clinicians and patients since it prescribes accurate equipment to a wide range of patients with varying needs for equipment, whilst consistently outperforming the conventional approaches that clinicians use to prescribe equipment. This also addresses the variation of OT recommendations, as they were able to provide more consistently accurate prescriptions using the app.

The research artefact, as a complete solution, makes a contribution to the mHealth and 3D visualisation domains via the implementation and novel application of these technologies within the

Occupational Therapy setting and specifically to the EFAP. Accordingly, they benefit from this contribution by:

- Redesigning the app to fit the EFAP could improve in adapting the home environment which could lead to improvement in patient autonomy and assisted living, and more efficient approaches to fall assessments.
- Empowering patients to assess their own needs for equipment more actively, live independently and unobtrusively send data containing nuances of their lifestyle or way of living that might heighten their risk of falling to clinicians to inform personalised assessments
- Providing a collaborative tool for clinicians to prescribe equipment, without the need for a home visit, based on measurements and assessment data sourced remotely from patients to inform clinical decision making
- Having the artefact as a mobile app offers a relatively cost-effective solution that is easily accessible by stakeholders involved in the EFAP, and also complements the delivery of the EFAP
- Tackling issues with time and cost without compromising quality within healthcare (see subsection 9.4.3)
- Utilising usability metrics in order to perform the user-based evaluations of the app within a living lab environment closer to a real-life scenario

Although the developed artefact has been tailor-made to improve visualisation in the EFAP context, it provides capabilities that can be further exploited and redesigned to augment assessment practices in other neighbouring research areas that suffer from similar visual quality limitations. Furthermore, the app could be redesigned to match the assessment tools used for disabled patients, improve collaboration between clinicians and patients in diagnosing incorrect fittings in the home environment of patients (of all ages) with complex needs (discussed as future research in section 9.5).

9.4.3 Implications and recommendations for deployment in practice

The research artefact *(Guidetomeasure)* is built upon strategies clinicians use in carrying out the EFAP in practice, solutions that respond to issues at the frontier of healthcare from the perspective of clinicians and patients, not currently addressed by the existing EFAP tools. Consequently, the wide applicability of the app across the healthcare specifically for home-based fall prevention and the merit of its improvement over the 2D predecessor have led to the assumption of its practical contribution to EFAP. Moreover, insights and recommendations regarding clinicians and older patients' use of technology in practice in other healthcare contexts were gained, along with recommendations proposed in the healthcare provision based on lessons learnt and insights ascertained from findings of the five studies.

From a clinical perspective, the app could be used by clinicians across the NHS trusts and community care in the UK to remotely assess and prescribe equipment and to assist patients to engage with activities relating to their own care and wellbeing. Consequently, the app providing these capabilities could reduce healthcare costs (i.e. regarding equipment rejection and the subsequent cost of falls that would occur). Using the app could reduce effort and time spent in interpreting the guidance during a visit to the patient's home through the use of 3D visualisation furniture models. Conversely, this could also potentially result in fewer home visits as the patient would be equipped to collect data of their needs for equipment that clinicians would typically collect during a home visit. Furthermore, this could also lessen the burden of a growing ageing population has on the shortage of clinicians (that are expected to deal with this) and reduce waiting times to conduct home visits significantly by getting patients to take their own assessments without supervision. The possibility of patients collecting their own data as part of a clinical assessment may have positive consequences to the healthcare provision, as patients could become better stakeholders in their own care, and result in an increased patient satisfaction. These points are also supported by that of clinicians' feedback/input in the design and evaluation of the app described in Chapters 5, 7 and 8. This research work contributes further to the widely reported argument in the literature of clinical engagement being crucial to any effort in providing better quality care through the design and development of technology-based solutions. This research's artefact is aligned with the government mandate in encouraging NHS trusts and community-based practices to 'go paperless' by 2020 and to explore technological alternatives with the aim to improve patient satisfaction, outcomes, efficiency and experience [374, 418]. Another contribution of the artefact is its capacity to reduce possible human errors in prescribing equipment to patients, which may seem obvious at face value, but was not previously considered as it being a contributing factor to incorrect fit of equipment. This research found that reducing human errors relating to incorrect measurement input results in more accurate equipment prescriptions.

Regarding the use of the app, the possible costs of using the app could be offset by the implications and resultant costs of patients rejecting equipment and the adverse effects of this abandonment. This research contributes to enabling measurement and assessment data to be integrated/stored into the patient health records, which were not made clear or existed before the undertaking of this present research, for the simple reason that no technical infrastructure supported this previously. Furthermore, it also provided recommendations for clinicians to consider optimum ways of introducing the app to the patient and other clinicians in practice. As a result of the noteworthy contributions of the app achieving more accurate equipment prescriptions, this may also help to reduce the existing heterogeneous measurement-taking techniques in the EFAP. Furthermore, providing such a tool could help to standardise assessments and equipment recommendations and accompanies functionality that has generated accurate fit of equipment that is likely to lead to better outcomes. This research has also introduced the equipment prescription functionality as a supplementary approach to address the challenges of the EFAP, and to improve its overall assessment. The results produced in this research indicated its potential as a way of assisting clinicians with prescribing equipment sizes more accurately. Despite some concerns about some patients using the app, this could potentially be useful in supporting patients to self-assess and self-prescribe minor equipment. Clinicians could benefit further from this novel approach in practice providing its evaluation out in the field confirm what was found in study 5.

From the patients' standpoint, Guidetomeasure offers an enabling role in their own healthcare by providing a means to improve the provision of quality care and to self-assess for minor assistive equipment to help with daily living tasks around the home in their everyday life. Furthermore, enabling patients to become a better stakeholder in assessing their needs for equipment could reduce their reliance on the clinician through the app's capacity to support them in self-directed assessments. These are supported by the important implications and recommendations for patients using the app in practice in study 2 and 4. Although the app's capability to support patients with prescribing equipment has yet to be evaluated, the results produced in study 5 indicated its potential as a means for patients to self-prescribe as well as the benefit if offers to clinicians for major equipment prescriptions, if it is to be successfully adopted in practice. Providing such tool to patients increases the ease with which they record accurate and consistent assessments to enable collaboration with clinicians for monitoring and remote equipment prescription purposes. It also provides useful prompts in the form of multimodal functionality and navigation controls to reduce the effort necessary to interpret the guidance to assist with self-assessment tasks and data collection as part of the EFAP. This is an effective tool that assists patients with generating measurements more accurately compared to the booklet. Consequently, this contributes to the knowledge base in the shift of the care paradigm, enabling patients to play more of an active role in deciding and collaborating with clinicians for prescriptions that support independent living and prevention of debilitating episodes such as fall occurrences. The findings across the five study confirm the importance of patient involvement in the design of technology-assisted interventions, as they are more reliable sources to gain insights from into how other patients' in this particular user group would use the app, rather than proposing design solutions underpinned by anecdotal evidence. While there is a cost to having a mobile device, this app can be accessible/deployed on any platform, and the cost associated with the device can be offset by the cost of assessment and threat to the patient's autonomy. The artefact was delivered as a mobile solution as it mirrored the nature of the EFAP. It also provided implications for guiding assessment, treatment and diagnosis outside the clinical setting into the home, but in a way, that empowers patients to be more involved, while addressing resource limitations and waiting times for assessments due to a shortage of clinicians. This could also empower patients as a result of receiving enhanced quality of assessment for the provision of equipment and in turn improve quality of life and independence via the use of appropriate equipment prescribed through using the app. The benefits of using the app could result in a decrease of the economic and financial burden of informal care given by family members, improved patient satisfaction and outcomes related to equipment use in the home and an adapted home in line with the needs of the patient.

Although practice recommendations in the EFAP context proved valuable, there are insights that could, however, be generalised regarding clinicians and patients use of similar technologies in other healthcare contexts. This research reveals the use of effective assessment that could be transposed to assistive equipment for disabled patients. Similar to facilitating assessments in the EFAP, these findings contribute lessons learnt that could equally be applied to enable patients to visualise assessment and treatment requirements for assistive equipment in the home for a variety of disability needs. Also, facilitating the shift of healthcare for postoperative disabled patients from the hospital and into their home. This could allow disabled patients to be more in control and monitor any chronic diseases, where it might require for the home to be adapted (see section 9.5). Furthermore, the possibility of 3D visualisation for remote monitoring/home visits is an increasing trend and could be integrated into the app. Studies have been carried out recently that employed 3D visualisation technology to enable clinicians to remotely monitor patients in their home [60]. Accordingly, this functionality could be integrated into the app to allow clinicians to conduct home visits and remotely monitor equipment usage via visualisation. Considering the enhancements that the proposed app offers, the expected results of integrating such functionality into the app could be of significant value to the field in further tackling the shortage of clinicians and time and resource limitations without the presence of clinicians in the home. Upon affording clinicians' 3D exploration capabilities of the patient's home, the existing prescription module of the app could then be used for remote diagnosis for assistive equipment for different types of patients.

Findings from the **five studies** (Chapters 4, 5, 7 and 8) can be extrapolated and applied to the healthcare provision. The design of new technologies for healthcare should factor in the following points in order to deliver quality care and achieve better clinical and health outcomes.

- Mobile 3D visualisation app for improving interpretation of clinical guidance which addresses heterogeneous measurement-taking techniques used amongst clinicians in conducting assessments in the EFAP, resulting in more accurate information collected about patient.

- Patient confidence and involvement in the delivery of their care and engaging with technology-assisted interventions without clinical supervision. While there is no single solution, clinicians should assume that patients have the capacity and skills to participate in technology-assisted interventions unless their physical condition does not allow them to do so. Clinical judgement should be used when deciding whether patients should self-care independently or with assistance.
- Promote independent living and empower patients through involving them in aspects of their own care and help them to conduct skilled tasks as what clinicians would do via technology-assisted interventions. Doing this could reduce the increasing demand on clinicians and long waiting times, whilst improving healthcare outcomes and patient satisfaction.
- Consider collaborative functions in technology-assisted interventions to improve existing ways of how patients and clinicians collaborate with a focus on shared decision-making and enabling patients to self-care.
- Ensure that patients are given the appropriate/effective tools to support their role as a self-carer and to help them fulfil their new responsibilities and capabilities to facilitate self-guided tasks. Appropriate functionalities of technology-assisted intervention must suit the ability of its target patient user group, if they are effective in data collection tasks for assessments.
- Reduce heterogenous tools that are employed for homogenous clinical practices
- Clinically relevant, well-designed, usable and easy to learn technology-assisted interventions that contributes to wider clinical adoption. Access to technologies in order to perform technology-assisted interventions.
- Efficient means to collecting data from patients. Reduce technical and bureaucratic overheads, suitably replaced by fit for purpose solutions that address known issues in healthcare.
- Training and support given to clinicians to help with adopting technology in practice. Allowing real-time access to data of patients' health and lifestyle gathered from heterogeneous sources to inform diagnoses and prescriptions.
- Provide a degree of flexibility to accommodate the specific challenges that clinicians may encounter in their respective NHS trust or community-based practices, whilst still maintaining quality of care. Not assuming that 'one-size-fits-all' approach to patient care.

- Help clinicians with discharging patients and for the delivery of care to be continued outside the clinical environment in way of involving patients themselves and informal caregivers (i.e. their family members).

9.5 Research limitations and future research directions

Notwithstanding the promising and encouraging results arising from this research and the contributions they make to the wider research sphere, there are drawbacks identified along with the limitations acknowledged in each of the studies. As with any research enterprise, there are, however, limitations of this research that have to be acknowledged and which open up new directions for future research and development. It is important to note that limitations of the five studies were acknowledged (in sections 4.5.1, 5.4.1, 7.4 and 8.5.1); however, these limitations are more granular in the sense that certain aspects of the way in which the studies were conducted were highlighted. On the other hand, the limitations discussed in this section are much broader, which highlight areas for future research. Figure 9-1 presents the limitations of *this research* in relation to each of the studies reported in the previous chapters and limitations of the research as a whole, linked to *future research directions*.

9.5.1 Chapter 2: Remaining challenges

Challenges 2, 5-10 and future work: This research focused on *challenges 1, 3 and 4* which were identified in the literature survey (in Chapter 2) as gaps in the research literature. Tackling the remaining challenges was outside the scope of this research. This research addressed the prominent challenges in resolving the issues of fall prevention in the patient's home environment. However, the remaining *challenges (2 and 5-10)* and their respective recommendations provide fruitful directions for future research and development (see section 2.8 for more details). Addressing these challenges would significantly expand the knowledge base in this area and enable development of fall prevention systems to better detect fall injuries, incorporation of technologies to help with assessments beyond the clinical setting.

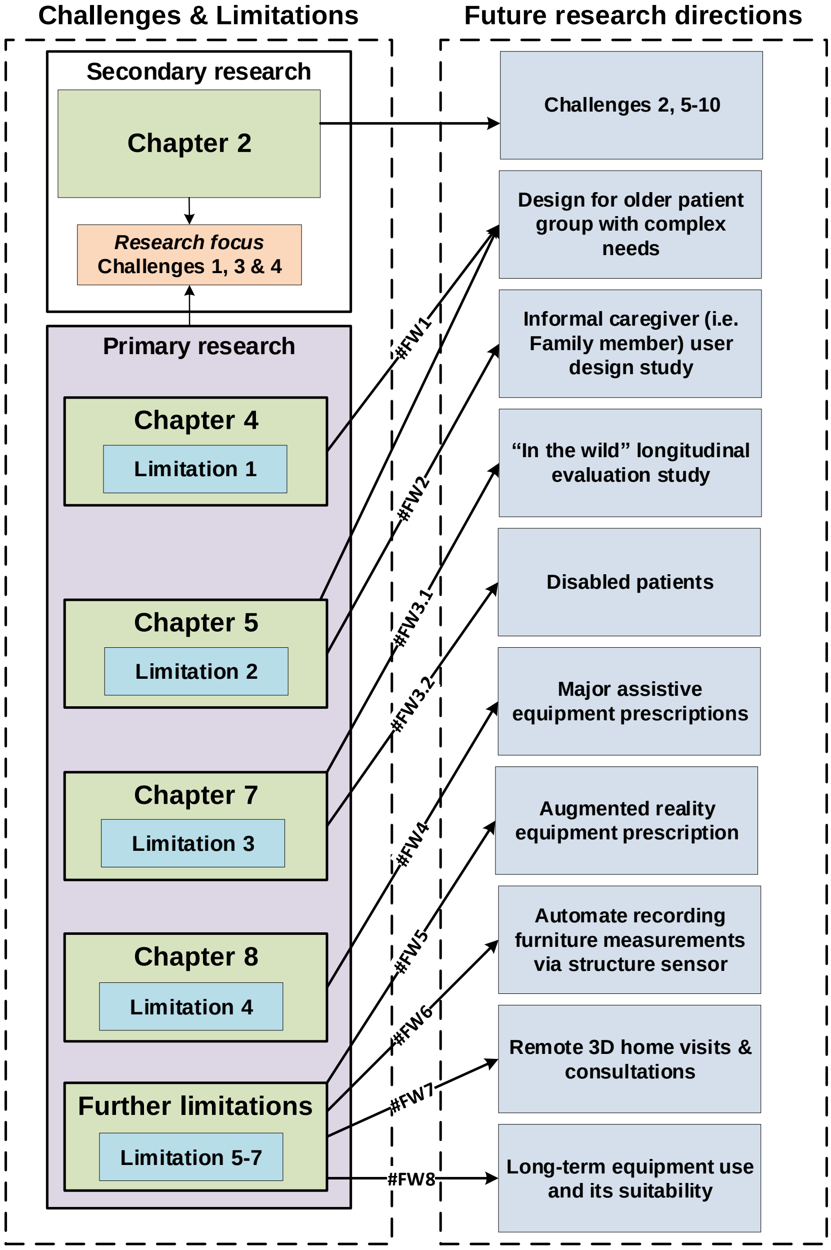


Figure 9-1: Limitations and recommendations for future research directions.

9.5.2 Chapters 4 and 5: Limitations

Limitation 1 and 2: Studies reported in *Chapters 4 and 5* focused on designing a mobile 3D application and explored its use in practice with occupational therapists and patients to enhance the visual quality of measurement guidance for better interpretation to obtain more accurate measurements. In terms of study 1, OTs was recruited from the community and hospital that see different patients with different health statuses. Including hospital-based OTs, however, may not represent the population of OTs who frequently conduct home assessment visits. Although the hospital-based OTs conducts home assessments to help with discharging patients, they do not carry out these assessments as frequently as community-based OTs. This distinction should be considered when generalising these findings to OTs using the app in the field. Nevertheless, this study is concerned with designing an app to provide enhanced visualisation of measurement guidance support equipment prescriptions rather than making generalisations as such. However, further research could explore and gain insights into the use of the app in a hospital setting and whether the app contains capabilities necessary to support clinicians with discharging patients.

Future work 1: A key limitation of *study 2 (Chapter 5)* relates to scope with regards to the lack of *designing for older patient groups with complex needs* (advance ageing conditions, i.e. visual limitations), which exemplifies the limited generalisability of the results to the broader older adult population being targeted by this research **(#FW1)**. Older adult patients who participated in this research consisted of many sub-groups suffering from different conditions, none of which affected their ability to participate in or not be considered as target users of the app. However, this study could be expanded to include those patients who are physically able to self-assess and that live independently, but exhibit conditions that the design of the app functionalities may not accommodate. Furthermore, this would consider a heterogeneous group of older patients that exists, rather than assuming that their needs and abilities are catered for by the current design of the app. Future research should, therefore, concentrate on further adapting the design and functionality of the app to accommodate the requirements of a diverse patient group who may exhibit certain advanced ageing conditions and might need support whilst using the app.

Future work 2: Another limitation of *study 2* is the lack of involvement of an *informal caregiver (i.e. family member)*, using the app to facilitate the EFAP, which was beyond the scope of this research **(#FW2)**. This research was mainly concerned with supporting and fulfilling the needs of clinicians and older adult patients as the primary stakeholders of the EFAP. As found in Chapter 7 (sections 7.2.6 and 7.3.6), that despite the improvement in performance with using the app, gaining support from clinicians and/or indeed family members in taking measurements is, therefore, needed especially in cases where patients are physically unable to do so. Further research is required to establish whether the app could be feasibly used by informal caregivers (i.e. family members) and whether it supports the need for regular care, if not then the appropriate design should be engineered to accommodate the needs for this prospective user cohort to aid them in their role.

9.5.3 Chapter 7: Limitation

Limitation 3: Chapter 7 (which contained study 3 and 4) evaluated the performance of the app regarding its effectiveness, efficiency and satisfaction in supporting users in taking accurate measurements compared with the 2D booklet tool conducted within a living laboratory setting. Despite that the app was evaluated in a living lab which included key furniture items that are typically measured in the EFAP, it not being assessed 'in the wild' is a limitation; however, this was outside the scope of this research. Interesting insights were gained from the living lab studies where specific aspects such as the interface design of the artefact, improved functionality over its counterpart and its use in a controlled environment that deliver repeatable results to be further analysed. Such studies are a precursor to a much larger trial study which may contribute to the wider adoption of the app. However, more can be understood from evaluating the app in an environment in which it is intended to be deployed, and, further, how it would be used and experienced.

Future work 3.1: This direction of enquiry could provide further insights into the clinical effectiveness of the app in term of measuring for equipment 'in the wild', how the app shapes practice and used within an uncontrolled environment in a *longitudinal study* **(#FW3.1)**. Conducting this type of study may also demonstrate the economic value of such technology in healthcare to create wider adoption.

Future work 3.2: Gaining NHS ethical clearance to evaluate the app out in the field was a barrier to it being tested in a larger-scale study **(#FW3.2)**. Specifically, it was impractical to carry out larger–scale study as it would require aspects of the clinical setting and patients home environment to be considered, something that both parties would need to consent to and would require NHS ethical clearance, a process notoriously known for being time-consuming [421]. Not suggesting this as a substitution for evaluation in the wild, the living lab ensured that the practicality and efficacy of certain aspects of the app factored in and 'in the wild' study could be a natural progression for the research problem. Through further research of this kind, unobtrusive monitoring of equipment usage in the home environment and the measurement guidance tools used that was for their prescription could also be another fruitful opportunity in this particular line of enquiry. Moreover, this type of study would require a longitudinal analysis of cases where equipment is either irregularly used or abandoned by patients. These research studies are also limited in terms of targeting *disabled patients* that could also benefit from using this app which was not the purpose of this research. However, this opens up possibilities of the app being redesigned to include assistive equipment that clinicians prescribe to disabled patients.

9.5.4 Chapter 8: Limitations

Limitation 4: The app having minor equipment prescription capabilities proved to be useful/relevant for clinicians, with some reporting its suitability for patients in study 5 (Chapter 8). The consensus of the study findings, however, indicated that there were limitations of the app in dealing with more complex cases of patients exhibiting functional ability deficits, where the prescription of minor equipment would be clinically considered unsuitable. This is viewed as a limitation in the sense that the app possesses the capabilities to support clinicians with such cases, but would have to be redesigned to include the variables involved in prescriptions that assist patients with strenuous tasks in their home. Catering for these complex cases were outside the scope of this research work.

Future work 4: In response to this limitation, one possibility is to extend the app capabilities to support *major assistive equipment prescriptions* for future research **(#FW4)**. This would further enhance the chances of clinicians using the app more frequently and long-term, resulting in more widespread clinical adoption, particularly for those that prescribes more major than minor equipment. Through further research of this type, steps could be taken to unpack the clinical reasoning that clinicians would apply in conjunction with using the app for minor equipment prescriptions. Machine learning (ML) algorithms could be integrated into the app for major equipment prescriptions to apply knowledge gained from unpacking the clinical reasoning process. An example of an ML algorithm could be applied to this problem space is for the app to predict if a patient needs a stair lift instead of a rail or a specialist chair instead of their existing chair to be raised. A classification model (a type of supervised learning) could be constructed using datasets of assessment and prescription reports from patients that clinicians have previously assessed to determine the type of prescription that the patient would need or may not need. The dataset would need to consist of patterns of data that represent cases where minor or major prescriptions were prescribed so that these scenarios are labelled/categorised, which is the purpose of classification. For example, ubiquitous data items such as demographic parameters, lifestyle details, patient records and fall occurrences could also be integrated into the classification model. The model could then enable clinicians using the app to provide major prescriptions that are more tailored to the patient needs. Additionally, investigating the relative costs and benefits of the app in practice in the same direction of applying ML for future research would also expand the knowledge base in the OT area, allowing for technology use to achieve better outcomes and improve patient satisfaction.

9.5.5 Further limitations

Limitation 5: Findings from the research studies suggested an implementation of an augmented reality solution to visualise adaptions to the home within a camera view before it is physically adapted. However, this functionality was not embedded into the app or explored as it was outside the scope of this research.

Future work 5: Implementing *augmented reality equipment prescription* solution could enable users to overlay the home environment with assistive equipment in a camera view in real-time **(#FW5)**. This could provide users with the view of their home adapted prior to equipment installations. Evidence from the literature shows that the use of augmented reality technology to support older adults with mobility and independence has shown promise [422]. This shows a trend of successfully applying such technology in this space, which highlights that there have been efforts expended on this direction of research.

Limitation 6: The taking of measurements of home furniture items using a tape measure device could be prone to human error and as a result, impact the prescribed equipment size. This point was, however, brought to light as a potential direction of enquiry and not to have been considered as it was outside the scope of this research and concerned only with improving interpretation of the measurement guidance for equipment prescriptions.

Future work 6: In the effort to further this research, one possibility is to exploit 3D-sensing capabilities to scan the patient's home environment to capture the dimensions of the key furniture items in real-time, thus automating the taking of measurements **(#FW6)**. This would provide considerable benefits to patients who may find taking measurements challenging and provide innovative applications of 3D scanning technologies in the OT field, which has not been done before and is therefore likely to significantly expand the knowledge base in this area. An example of 3D scanning technology currently used in healthcare is the *3D Structure Sensor*, developed by Occipital, which is a 3D depth scanner for mobile devices that constructs a 3D model to scale based on scanning objects in a natural environment [269]. This type of technology has been applied across the areas of orthotics and prosthetics in healthcare due to its sophisticated capabilities of constructing 3D models of the patient to scale based on using the 3D scanner.

Limitation 7: Another point of consideration is that, although the app enables clinicians to prescribe equipment based on assessment data, sourced remotely, it may not account for cases where patients or informal carers are unable to remotely send the requisite assessment data to clinicians who are unable to visit the home, for equipment prescriptions. Consequently, an attractive direction for future research would be to develop the app further to include high-fidelity 3D representations of the patient's home environment embedded with an avatar that mirrors actions performed by patients in real-time so that clinician could be provided with context to inform their clinical decision making when prescribing equipment remotely. Previous research has shown the use of taking photographs of the patient's home to provide a visual aid to support clinical decision-making/reasoning and serve as an adjunct to or substitute for the traditional home visit assessment [303, 304]. This highlights the need for visual aids of the home in which the equipment prescribed to be used, which also demonstrates the proposed direction augmenting the home to aid with equipment prescription.

Future work 7: Creating an avenue for *remote 3D home visits* would allow clinicians to inspect the patient's home remotely to inform their recommendations, collaborate with patients in a *consultative* capacity on performing daily living tasks more safely as would be done in a traditional home visit **(#FW7)**. This direction could offer significant value in providing a convenient means for both patient and clinicians and also addresses some the time and resources limitations that continue to persist in the healthcare system.

Future work 8: Longitudinal studies conducted to capture *long-term equipment use and its suitability* for the patient and their home environment could be particularly useful **(#FW8)**. Pursuing this avenue of future research could uncover insights as to whether the fit/suitability of the equipment and its long-term use is a result of using the app for equipment prescription or its paper-based equivalent. This investigation could also stimulate the need for economic evaluation of the app in terms of reduced costs, hospital admissions, home visits, number of falls and waiting times.

In summary, from the empirical investigations in this research has shown that the app significantly improves existing 2D paper-based tools currently used in practice regarding better visualisation of the measurement guidance to assess for assistive equipment as part of the EFAP. As discussed extensively, the use of mobile 3D visualisation technology provides a catalyst for which older patients can become better stakeholders in the assessment of their care and well-being in the home and for clinicians to assess more accurately on behalf of patients. It allows the measurement guidance to be visualised in a more perceivable way to the natural environment, and to facilitate the equipment size prescription and to envision its use in the context of the appropriate area within the home environment.

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Appendix A Ethics approval letter

Brunel University London

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STATEMENT OF ETHICS APPROVAL

Proposer: Julian Hamm

Title: Technology Assisted Healthcare: Exploring the use of Virtual Reality Technology to reduce fall risks in home safety assessment interventions

The Department's research ethics committee has considered the proposal recently submitted by you. Acting under delegated authority, the committee is satisfied that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that you will adhere to the terms agreed with participants and to inform the committee of any change of plans in relations to the information provided in the application form.

Yours sincerely,

Dr Malcolm Clarke
Chair of the Research Ethics Committee

Appendix B Consent form

CONSENT FORM

The purpose of this research is to explore the use and benefits of mobile 3D visualisation technology in Occupational therapy, specifically fall prevention and to ascertain the experiences of patients and OTs. This research study is performed by a researcher in the Department of Computer Science at Brunel University.

The participant should complete the whole of this sheet by themselves

Please tick the appropriate box

	YES	*NO*
Have you read the Research Participant Information Sheet?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Have you received satisfactory answers to all your questions?	☐	☐
Do you understand that you will not be referred to by name in any report concerning the study?	☐	☐
Do you understand that you are free to withdraw from the study:		
• at any time	☐	☐
• without having to give a reason for withdrawing?	☐	☐
• (remove if not relevant, adapt if necessary) without affecting your future care?	☐	☐
Do you understand that the session will be recorded on a digital voice recorder and transcribed into text format?	☐	☐
Do you understand that the transcription of the session in textual format can be provided at your request	☐	☐
Do you understand that you are free to withdraw the transcribed account of the interview if you so wish without any explanation?	☐	☐
Do you understand that any quotes used in publications that arise from your interview will be fully anonymised?	☐	☐
Do you agree to take part in this study?	☐	☐

Participant:

Name in capitals: Date: