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Enabling older adults to carry out paperless falls-risk self-assessments using guidetomeasure-3D: A mixed methods study

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ABSTRACT

Background: The home environment falls-risk assessment process (HEFAP) is a widely used falls prevention intervention strategy which involves a clinician using paper-based measurement guidance to ensure that appropriate information and measurements are taken and recorded accurately. Despite the current use of paper-based guidance, over 30% of all assistive devices installed within the home are abandoned by patients. This is in part due to poor fit between the device, the patient, and the environment in which it is installed. Currently HEFAP is a clinician-led process, however, older adult patients are increasingly being expected to collect HEFAP measurements themselves as part of the personalisation agenda. Without appropriate patient-centred guidance, levels of device abandonment to are likely to rise to unprecedented levels. This study presents guidetomeasure-3D, a mobile 3D measurement guidance application designed to support patients in carrying out HEFAP self-assessments.

Aim: The aim of this study is to present guidetomeasure-3D, a web-enabled 3D mobile application that enables older-adult patients to carry out self-assessment measurement tasks, and to carry out a mixed-methods evaluation of its performance, and associated user perceptions of the application, compared with a 2D paper-based equivalent.

Methods: Thirty-four older adult participants took part in a mixed-methods within-subjects repeated measures study set within a living lab. A series of HEFAP self-assessment tasks were carried out according to two treatment conditions: (1) using the 3D guidetomeasure-3D application; (2) using a 2D paper-based guide. SUS questionnaires and semi-structured interviews were completed at the end of the task. A comparative statistical analysis explored performance with regards to measurement accuracy, accuracy consistency, task efficiency, and system usability. Interview transcripts were analysed using inductive and deductive thematic analysis (informed by UTAUT).

Results: The guidetomeasure-3D application outperformed the 2D paper-based guidance in terms of accuracy (smaller mean error difference in 11 out of 12 items), accuracy consistency ($p < 0.05$, for 6 out of 12 items), task efficiency ($p = 0.003$), system usability ($p < 0.00625$, for two out of 10 SUS items), and clarity of guidance ($p < 0.0125$, for three out of four items). Three high-level themes emerged from interviews: Performance Expectancy, Effort Expectancy, and Social Influence. Participants reported that guidetomeasure-3D provided improved visual quality, clarity, and more precise guidance overall. Real-time audio instruction was reported as being particularly useful, as was the use of the object rotation and zoom functions which were associated with improving user confidence particularly when carrying out more challenging tasks.

Conclusions: This study reveals that older adults using guidetomeasure-3D achieved improved levels of accuracy and efficiency along with improved satisfaction and increased levels of confidence compared with the 2D paper-based equivalent. These results are significant and promising for overcoming HEFAP equipment abandonment issue. Furthermore they constitute an important step towards overcoming challenges associated with older adult patients, the digitisation of healthcare, and realising the enablement of patient self-care and management via the innovative use of mobile technologies. Numerous opportunities for the generalisability and transferability of the findings of this research are also proposed. Future research will explore the extent to which mobile 3D visualisation technologies may be utilised to optimise the clinical utility of HEFAP when deployed by clinicians.

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1. Introduction

The world population is ageing, between 2015 and 2030 the number of people aged 60 and over will have increased by 56 percent from 901 million to 1.4 billion [1]. This poses a significant challenge to health and social care providers with falls incidents being one of the most prominent problems to be tackled [1,2]. The number of falls related injuries has increased in recent years, in part as a result of an ageing population [3]. On average each year, 37.3 million falls of varying degrees of severity are recorded around the world resulting in an estimated 646,000 premature deaths [4]. In the UK alone, the annual cost of falls to the National Health Service (NHS) is estimated as being in excess of £2.3 billion and it is anticipated that this figure will continue to rise [5]. Approximately 30% of older adults over the age of 65 years and 50% of adults over 80, who live independently, fall each year [3]. Fall related incidents can cause a wide range of ensuing problems such as immediate physical injuries, decreased independence when carrying out activities of daily living (ADLs), disabilities, and negative psychological impacts including fear or loss of confidence and isolation [6]. In the United Kingdom, there are over 300,000 fall patients hospitalised each year and this number could be significantly higher if the unreported cases were accounted for [7]. The result is an expanding and burdening demand on health and social care services and resources [8,9]. This issue highlights the necessity for implementation of evidence-based, innovative approaches that empower service users and carers to support a continuum of health provision and care; and at the same time, relieve the ever-increasing pressure on respective governmental bodies to provide fall prevention intervention services in more cost-efficient ways [5]. Such a sustainable health system can only be realised by the empowerment of service users to utilise research-evidenced Information and Communication Technology (ICT) interventions to self-assess, self-manage, and provide self-care thus reducing the demand for clinicians in the delivery of such health interventions [10,11]. Additional benefits of effective and innovative ICT interventions in healthcare include the potential increase in service user engagement and adherence to prescribed services which may subsequently result in higher levels of overall service user satisfaction as well as an overall improvement in quality of life [5]. However, despite the wide range of anticipated benefits of deploying innovative ICT interventions, it is important to be mindful of the range of unintended, and potentially undesirable, consequences of deploying such interventions [12,13]. Nevertheless, the proliferation of such interventions to a commercially-ready level continues to be desirable on a global scale which is evident by the strategic research agendas and calls for action issued by international research frameworks, for example, from USA and European Research Councils [14]. There are already a number of documented initiatives and provision models that support the enablement of the service user as the owner of their own healthcare, and to take responsibility for self-assessments and the management of their health conditions [15,16]. Indeed, there has already been some change in focus, away from the more paternalistic models of care, towards more patient-centred models that pass more responsibility on to the patient to become more involved in their own care [17]. This change has partly started to emerge from the notion of the 'expert patient', who is expected to proactively seek out important information, use self-testing and management devices effectively, and independently make informed decisions about their own care [18,19]. However, a true shift towards patient-centred self-care can only be realised by the design, development and deployment of new innovative, enabling, and usable ICT solutions. One of the key fall prevention interventions used to reduce the risk of falling within the home setting is the prescription of assistive devices (ADs) such as stair handrails, toilet raisers, chair raisers, bath boards, and bathroom grab rails. ADs are growing in importance for falls prevention interventions, as they are believed to reduce the risk of falling [20,21], promote functional independence [22], and increase self-efficacy [23] and quality of life [24,25]. The devices market was valued at USD 12.37 billion in 2012 and is expected to reach an estimated value of USD 19.68 billion by 2019 [26]. This is perhaps not surprising given that the risk of falls and the need for ADs increases with age [27]. There is also evidence that indicates, assuming the correct prescription of ADs, that substantial cost savings for healthcare providers can be made by promoting the use of such devices [28,29]. Despite the apparent benefits, there appear to be a number of barriers to ensure that ADs are successfully adopted and used. These barriers can include lack of knowledge about the device, lack of patient involvement in the process of selecting it, attitude towards the use of such devices, and lack of fit between service users, the ADs, and their home environment [30,31].

1.1. Prescribing assistive devices for falls prevention

The primary procedure for prescribing ADs to patients within the home, with a view to promoting independent living and overcoming the risk of falls, requires a clinician (typically an occupational therapist) to engage in the home environment falls-risk assessment process (HEFAP). This involves the clinician visiting the patient's home to carry out a falls risk assessment. However, largely as a result of time and resource limitations, an emerging expectation is for family members or service users to carry out HEFAP self-assessments, hence recording measurements of key items independently on behalf of therapists [21,32]. The key steps involved in HEFAP include (1) gathering information about the patient's functional abilities, (2) taking patient measurements (typically popliteal height) and measurements of fittings and key items of furniture, and (3) prescribing ADs to be installed within the home based on the information and measurements gathered. The patient information and measurements gathered as part of HEFAP directly inform the precise type, size, and nature of the ADs that are prescribed and therefore play a vital role in ensuring the successful fit between the prescribed assistive devices and the person using it [33,34]. Currently paper-based assessment guidance forms are used to assist in HEFAP, with a view to ensuring the correct measurements are recorded and the necessary associated patient data is collected. These forms include measurement guidance which is presented in the form of 2D illustrations indicating the key items of home furniture, fittings, and the patient that must be measured. The paper-based two-dimensional (2D) illustrations are typically annotated with measurement arrows that serve as prompts to indicate the precise points in three-dimensional (3D) space that must be accurately identified and measured in order to gather the necessary data to formulate an assessment and to accurately prescribe the necessary ADs [35]. A recent study funded by the UK Occupational Therapy Research Foundation has developed and published a 2D paper-based measurement guidance tool which has been specifically designed to enhance and standardise the quality of paper-based guidance and improve the accuracy of AD self-assessment measurements recorded by patients and practitioners [36,37]. The 2D paper-based guidance was developed via a five-stage user-centred study and represents the current state-of-the-art in 2D paper-based clinical measurement guidance in the field. It offers measurement guidance for the five items of furniture (bed, bath, toilet, chair, and stairs) that are most frequently associated with falls within the home and hence are most commonly measured as part of HEFAP [38,39]. Fig. 1 presents some example content from the 2D paper-based measurement guidance.

Although the use of standardised 2D paper-based measurement guidance is becoming increasingly prominent in light of the important role that accurate measurements have on optimum AD prescription, approximately 30% of ADs that are prescribed are abandoned by service users within the first year [30,37]. This is a large figure, which may be attributed to a failure on the part of the health service that has prescribed the equipment and has direct and significant consequences on potential levels of patient independence and overall quality of life [40]. Furthermore, this negatively impacts on patient health outcomes,

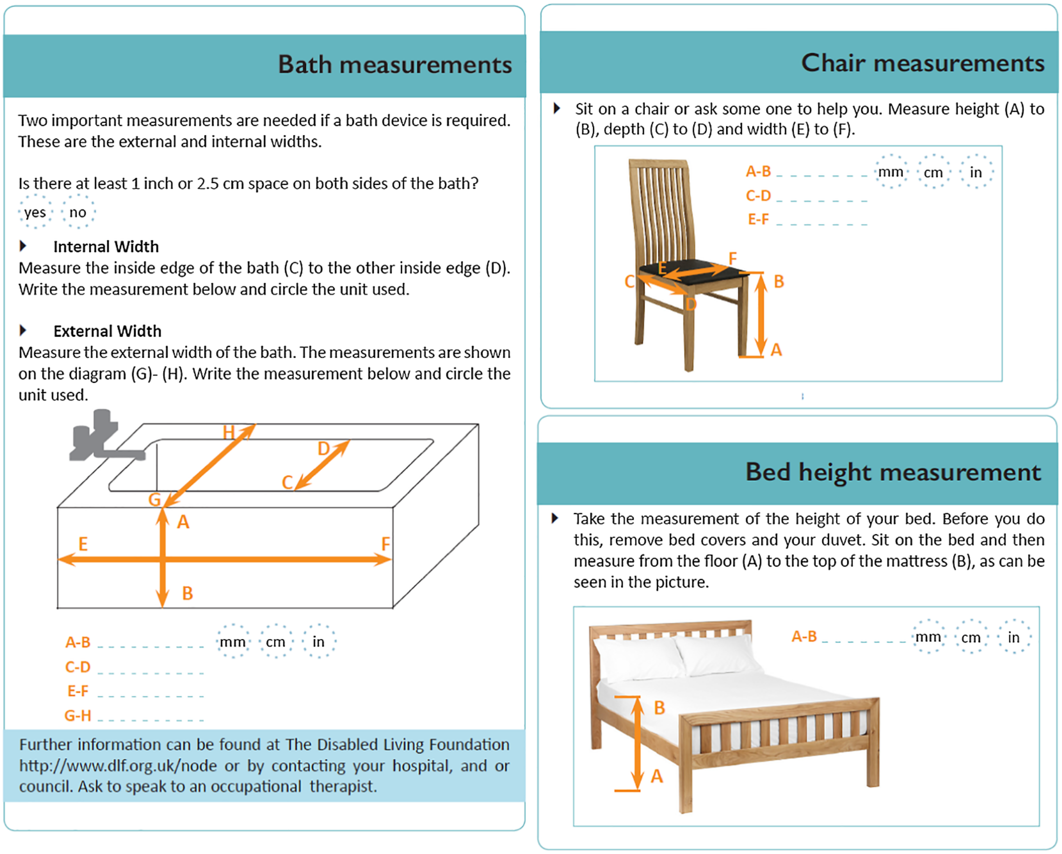

Fig. 1. Example content from 2D paper-based measurement guidance tool.

accelerates functional decline, increases overall exposure to fall risks in the home, whilst also unnecessarily depleting already scarce and valuable healthcare resources [40,41]. One of the key reasons for equipment abandonment is a result of ‘poor fit’ between ADs and the person using them [30,31]. To compound this issue, it is anticipated that due to time and healthcare resource limitations, the responsibility of taking and recording measurements will soon become that of the service user and/or their respective carers and family members [32]. Given the issue of ‘poor fit’ that already arises as a result of trained occupational therapists typically carrying out these tasks, it is likely that this will remain a significant issue particularly if patients and carers are being given the responsibility of carrying out these skilled tasks themselves [42]. Moreover, given that almost a third (30%) of all ADs are abandoned by patients within the first year in part due to issue of poor fit, there is a need to explore whether new and innovative technology-based tools can provide clearer and more effective HEFAP assessment guidance and support, to facilitate more accurate and reliable recording of home assessment measurements and associated information.

1.2. Enhanced self-assessment via simulated 3D visualisation

Simulated 3D visualisation technologies are concerned with the use of computer graphics software applications that exploit inherent aspects of human perception to display images that simulate three spatial dimensions within 2D space. Typically, users are able to visualise, control and interact with objects displayed within a 3D space. There are some examples of existing research that suggest the potential added value that 3D visualisations can bring to healthcare practice. For example, in recent years, the fall prevention research domain has explored the value of applying 3D visualisations to improve uptake and adherence to home-based falls prevention exercise programmes by replacing traditional paper-based 2D illustrated exercises with equivalent interactive 3D visualisations of these programmes [43,44]. Another recent study has developed a robotic system to automatically model patients’ home environments in 3D space to assist clinicians in identifying the precise location and nature of extrinsic fall hazards [45]. In terms of using 3D visualisation technologies to improve patient self-assessment, Spyridonis et al. [46] developed a mobile application that enables patients to rotate, manipulate, and report the precise location of back pain by using a 3D representation of the human body. The study reported that patients found the application more intuitive than an equivalent 2D paper-based assessment guide which is typically used in practice. It was also found that patients were able to more accurately report the location of their back pain. Other studies have found similar benefits in utilising 3D visualisations to communicate other forms of pain to clinicians, such as enabling patients to express and communicate their symptoms of pain to clinicians by annotating specific regions on a simulated 3D representation of the human body using free-hand drawing [47]. Benefits of 3D visualisations have also been reported in the context of pre-operative breast augmentation using 2D digital photographs of the patient’s torso which are reconstructed into 3D models [48]. This system helps clinicians perform more detailed pre-operative assessments than would be possible in the absence of the simulated 3D visual representations. In the field of occupational therapy, a 3D interior design application has been found to have perceived value in facilitating patient-practitioner joint decision making in the pre-discharge home adaptation process [49,50]. However, it is important to note that existing research has found that digital applications used to facilitate patient-practitioner interactions have a significant influence on the information that is recorded about the patient during these interactions and may lead to a loss of important patient information. Hence, care should be taken when designing such systems to ensure that important patient information is not lost [51,52]. Furthermore, a pilot study of older adult perceptions of using 3D visualisation technologies for self-assessment measurement tasks indicates positive service user attitudes towards their use in practice [53]. No existing research, however, explores the clinical utility of such technologies in terms of its effectiveness, efficiency, or whether 3D visualisation measurement guidance enables the recording of more accurate HEFAP measurements compared with the existing state of the art 2D paper-based guidance.

In summary, it is a necessity and an expectation that new mobile technology-based tools will play a key enabling role in the delivery of future healthcare delivery paradigms [54]. Such tools will help transform current paternalistic models of care into more patient-centred models that make patient self-care, self-assessment and self-management a reality. The falls prevention domain is no exception to this. Considering that patients will soon be responsible for carrying out self-assessments for the prescription of ADs coupled with the high level of equipment abandonment occurring despite the use of 2D paper-based measurement guidance, there is an urgent need to develop new technology-based solutions that support the self-assessment tasks required for accurate AD prescription. More specifically, given that 3D visualisation technologies have achieved promising results in other patient self-assessment oriented tasks, there is a need to explore the value of applying such technologies in the context of HEFAP and particularly with older adult patients.

1.3. Research aims

The aims of this study are two-fold. First, to present the guidetomeasure-3D application, a web-enabled 3D mobile application which provides older adult service users with interactive 3D measurement guidance for carrying out self-assessment measurement tasks. Second, to evaluate the performance of the guidetomeasure-3D application compared with existing 2D paper-based measurement guidance tools that are currently used in practice. This is a mixed methods study which 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 this study:

(RQ1): Does the guidetomeasure-3D application, on average, enable more accurate recording of measurements, compared with the paper-based measurement guidance booklet?
(RQ2): Does the guidetomeasure-3D application enable more consistently accurate recording of measurements, compared with the paper-based measurement guidance booklet?
(RQ3): Does the guidetomeasure-3D 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 guidetomeasure-3D application, compared with the paper-based measurement guidance booklet?
(RQ5): What are service users' views of the guidetomeasure-3D application, in terms of the perceived challenges, opportunities, and their intention to adopt and use this new technology in practice?

Section 2 presents the guidetomeasure-3D system architecture and application walkthrough. In Section 3, the methods used for the empirical evaluation of the application are presented, followed by the results in Section 4 and a discussion of the results in Section 5. Conclusions are drawn in Section 6.

2. The guidetomeasure-3D application walkthrough

2.1. System architecture

The application was developed using the Unity3D game engine which supports multi-platform deployment including Android, IOS, desktop and the Web. Unity3D was chosen as a development tool as it possesses capabilities to render 3D models on any supported mobile device seamlessly and provides native support for the device on which the application is deployed. In order to accommodate emerging initiatives of patient involvement in their own care, patient-clinician collaboration and nuanced 'ways of working' in a healthcare context, the back-end has been converted into a microservice-based architecture and is Web API-enabled which exposes an endpoint (for each service user) that allows clinicians' internal systems to fetch assessment data from the guidetomeasure-3D database and manage user's assessments. Furthermore, this provides clinicians with reliable and fast access to service user assessment data. The core functionalities are constructed as microservices to ease the manageability and scaling of the application, furthermore, individual services are able to communicate directly with each other through HTTP without the need of an infrastructure to facilitate such transmission. The component microservices also have the benefit of reducing dependencies and hence provide more flexibility and interoperability to work with existing systems that clinicians may already be using in their respective roles and clinical settings. Decoupling the clinically-focused functionality into microservices enhances the potential for scalability. For example, functionality that provides better delivery of assessments can more easily be operationalised in other neighbouring areas of healthcare that may require similar functionality. Therefore, employing such an architectural design could generalise soundly to other settings as it reduces environmental dependencies, running completely independently from the setting in which it is deployed and has the potential of being used beyond the environment investigated in this study. This also enables integration into other environments that may be more accustomed to delivering assessment in a non-technically focused manner. Fig. 2 shows the underlying system architecture including the discreet microservice components that are responsible for building the individual furniture scenes, rendering the 3D models for the application, storing assessment data, and enabling clinicians to retrieve service user assessments through API calls.

The *unity3D engine* is responsible for rendering the furniture scenes which contains objects such as the *avatar model*, *3D furniture models* and *arrow prompts* of the application. There are in total five furniture scenes and an "about you" scene which prompts users to record their popliteal height dimensions. Each functionality and model in the scene is represented as a *GameObject*, their respective behaviours have been scripted in C# programming language. Measurements and assessment data stored in the *local SQLite* database on the device is simultaneously synchronised to the centralised remote server via HTTPS. Data stored on the remote server is purely for backup purposes and is only accessible by clinicians via a secure web-based application. Recorded measurements are merged with the corresponding patient record which is stored on a *MySQL database* housed on the centralised *remote server*. Any supporting pictures taken of the patients' home furniture is stored in the *image repository* to be viewed by clinicians who have access via an API call. The *built-in web API* exposes a GET endpoint, which enables clinicians to retrieve and manage service user assessments. The endpoints are the service user ID (that is in the form of a 128-bit globally unique identifier number), which is concatenated on to the base address of the built-in API. These endpoints require special permissions to access them via the use of token based authentication. In accordance with RESTful API principles, once clinicians make an API call using the GET method, a metadata JSON string object of the service user profile and the corresponding measurement data is returned from the guidetomeasure-3D local DB which could subsequently be used for equipment prescription purposes. The publicly interfacing API makes a GET request to the persistent storage service and serialises the data into JSON format and provides the transformed dataset for it to be consumed via another GET request. The raw JSON string is then extracted and assembled as assessment data for it to be sent as an email over SFTP and/or ingested using an in-house web-enabled app, maintained by the respective

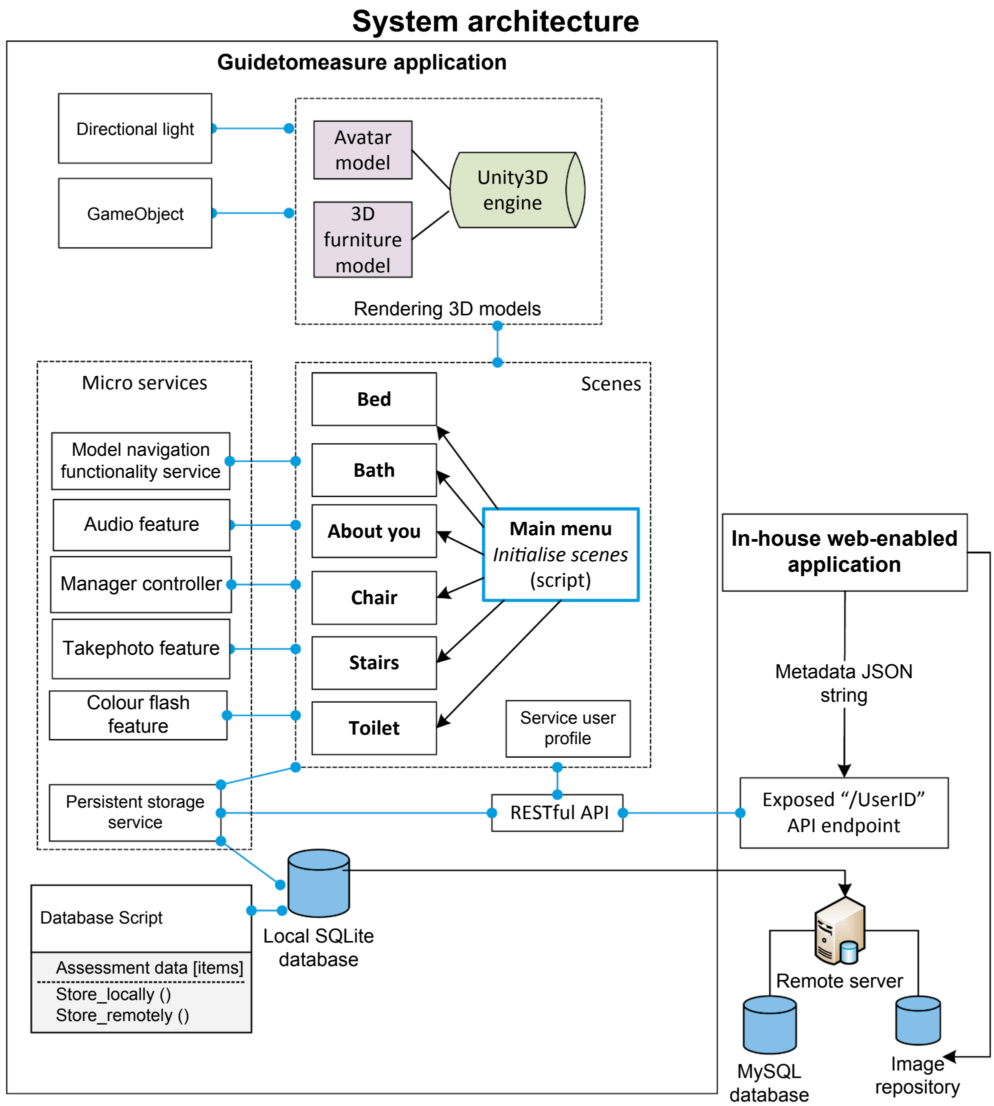

Fig. 2. guidetomeasure-3D system architecture.

clinical practice/hospital. Having such an architecture configured in this way provides the opportunity to allow API calls to be made from third parties in a straightforward and scalable way, which for example would be a useful feature for 3rd party assistive equipment manufacturers. Further research could explore the use of an electronic tape measure, utilising laser-based depth sensor enabled tablet devices such as Project Tango [55], to automate the manual task of taking measurements and to send the measurements by superimposing it onto the 3D models and storing it in a central DB. This data could be accessed and retrieved using a similar architecture to the one presented here. However, the accuracy, versatility, and robustness of tablet integrated mobile depth sensing devices for indoor measurement is an area which still faces significant technical research challenges before it can become a realistic and reliable alternative to conventional measurement practice [56]. It is worthy to note that this setup is decoupled from any in-house system that clinicians use. The next sub-section provides a detailed walkthrough of the application.

2.2. Application walkthrough

This section provides a walkthrough of guidetomeasure-3D. In addition, the 3D measurement guidance is showcased as a side-by-side comparison with the items included in the current state-of-the-art 2D evidence-based measurement guidance booklet, which is currently used by patients and clinicians as part of the HEFAP process [36].

2.2.1. Launch screen and main menu

The first screen that users are presented with is the launch screen. They receive brief audio instructions, welcoming them to the application and are prompted to touch the image in the centre of the screen to proceed, which takes them to the main menu. Audio instructions prompt the user to select the item that they would like to measure. Fig. 3 presents both the launch screen and the main menu screen as it appears to the user.

2.2.2. Measurement recording and guidance

The main menu presents the five home furniture items and an 'About you' option which relates specifically to the patient user interacting with the application. Each of the six options can be accessed by touching the appropriate representative icon displayed on the main menu screen. Once an option is selected, the application displays a 3D model of the item to be measured, complete with measurement guidance. Fig. 4 shows the toilet model that is presented after selecting this item on the main menu.

The 3D furniture model presented in this scene includes arrow prompts which visually indicate where the measurements should be

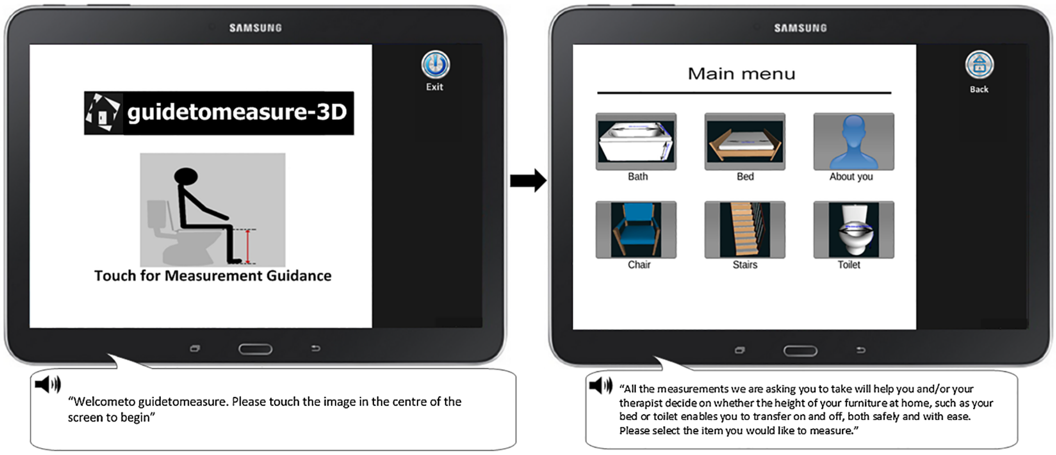

Fig. 3. Launch screen (Left), and Main Menu (Right).

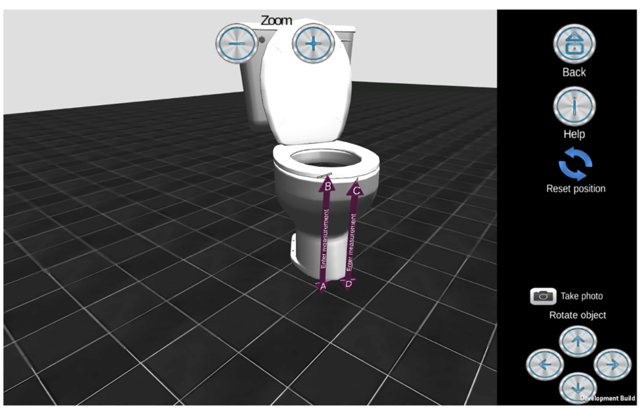

Fig. 4. Measurement guidance screen for toilet.

taken from and to. As can be seen, there are two pairs of measurements that must be taken and recorded on this screen, those relating to points A to B and points C to D. These arrow prompts are carefully positioned so that they mirror the necessary measurement points indicated for this item in the state-of-the-art 2D measurement guidance booklet [36]. The arrow prompts are embedded with flashing colour animation (pulsating through the full RGB colour spectrum with a few milliseconds transition between each colour) to indicate to the user that the arrow is awaiting selection. The arrow prompts contain an error handling mechanism and will only stop the pulsating colour transition once a numeric measurement value has been provided. Once a measurement is recorded, the arrow prompts return to a static colour state and the measurement entered is displayed on the respective arrow. On selection of an arrow, a voice prompt provides instructions specific to the arrow which has been selected and a numeric virtual keyboard is presented to the user to insert the measurement value. On selecting an item of furniture for the first time during the session, the system prompts the user to set their preferred unit of measurement for the remainder of that session (MM, CM, Inches) before continuing on to present the item of furniture that has been selected. The use of the numeric keyboard is in line with the recommendations of existing healthcare studies which suggest that the keyboard interface and keying of numbers could be made easier by tailoring the type of keyboard to show only the numbers or characters that are typically used for the intended task [57]. In this case, users are only required to input numeric values, hence a numeric keyboard is presented as opposed to a standard alpha-numeric keyboard. Fig. 5 presents an annotated toilet model, showcasing the range of functionality offered.

2.2.3. Interaction mechanisms and additional features

The control panel on the right hand side of the screen provides a range of functionality, including a 'Back' button which returns the user to the main menu, and a 'Help' button which provides additional audio based instruction for the task at hand. A 'Reset position' button allows the user to reset the orientation of the 3D model back to its original position. The 'Take photo' button takes the user to the camera view and enables them to take a picture of the item they are measuring. This function provides the user with an opportunity to visually capture an image of the actual item being measured and the surrounding environment/context in which it is situated, which may be used along with the recorded measurements when making associated prescription decisions. In particular, providing a function that enables the recording of this additional level of contextual detail about the home environment provides an important form of evidence capture that helps facilitate and substantiate clinical decisions made in relation to equipment prescriptions. Furthermore, the captured photographic record may enable more complex configurations of patient living arrangements to be considered, and help identify scenarios that may require less conventional AD prescriptions. Existing evidence has shown that visual aids (particularly in the form of photographs) have been used effectively to capture important detail about the home environment that contributes to improved assessment decisions [58]. This technique has not only proven to be satisfactory with regards to evaluating the feasibility of assessments in the home with patients who are prone to falling, it has also be found to help reduce the cognitive load in comprehending information as part of a shared-decision making process for home assessments [59]. Exocentric rotation of the 3D model is made possible via two interaction mechanisms: (1) via the directional arrows positioned on the bottom left of the control pane; (2) by performing the swipe gesture which involves moving a finger across the touchscreen to orbit the view perspective of the 3D model. Fig. 6 shows both of the rotation mechanisms within the context of the bath measurement guidance screen.

There are also two interaction mechanisms for zooming in and out of the target. This can be done either by touching the 'Zoom +' (zoom in) or 'Zoom −' (zoom out) buttons positioned centrally at the top of the screen, or by using pinch gestures. Fig. 7 showcases the zoom in function via the 'pinch out' gesture (applying two fingers on the screen and gradually moving them apart) and by touching the 'Zoom +' button.

Conversely, Fig. 8 showcases the zoom out function within the context of the chair measurement guidance screen.

2.2.4. Measurement guidance alongside 2D paper-based booklet

This section delivers a side-by-side presentation of the 2D measurement guidance provided by the evidence-based booklet versus the equivalent guidetomeasure-3D measurement guidance. Figures

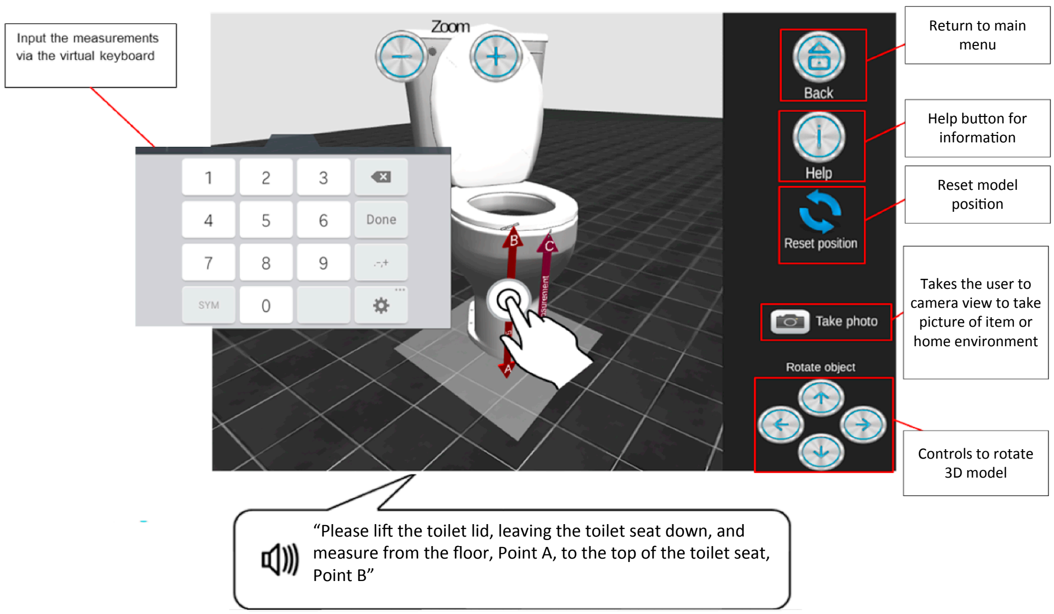

Fig. 5. Annotated measurement guidance screen.

Figs. 9–14 present the bath, bed, chair, stairs, toilet, and 'About you' measurement guidance screens and booklet pages respectively.

2.2.5. Additional 'About you' information

Once the patient has entered their popliteal height, they are then presented with an assessment questionnaire related to their demographics, activities of daily living, functional ability to use equipment, and the furniture to which it is attached. The user is prompted to enter answers to the questions through free text fields, multiple choice items, and binary options (yes or no) answers. After the assessment data and notes have been entered, the user can click on the Save button and the data is then stored in the local database and as a text file in the device storage.

3. Methods

This section provides details of the mixed methods data collection and analysis protocol used to address the specific research aims of this study. Fig. 15 provides an overview of the protocol.

3.1. Participants

Thirty-four participants were recruited to the study 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 carers 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) for a 2-tailed hypothesis, was calculated as $N = 34$ participants. The inclusion criteria were as follows: (1) aged 55 and over; (2) familiar with using smartphones/tablets computers; (3) considered to be active with no restrictions that prohibit their ability to measure key items of home furniture; (4) good understanding the English language. In total, 34 participants were recruited, nineteen of which were female and 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.

3.2. Protocol and instrumentation

This mixed methods study adopted a counterbalanced within-subjects design to verify the accuracy and consistency of measurements

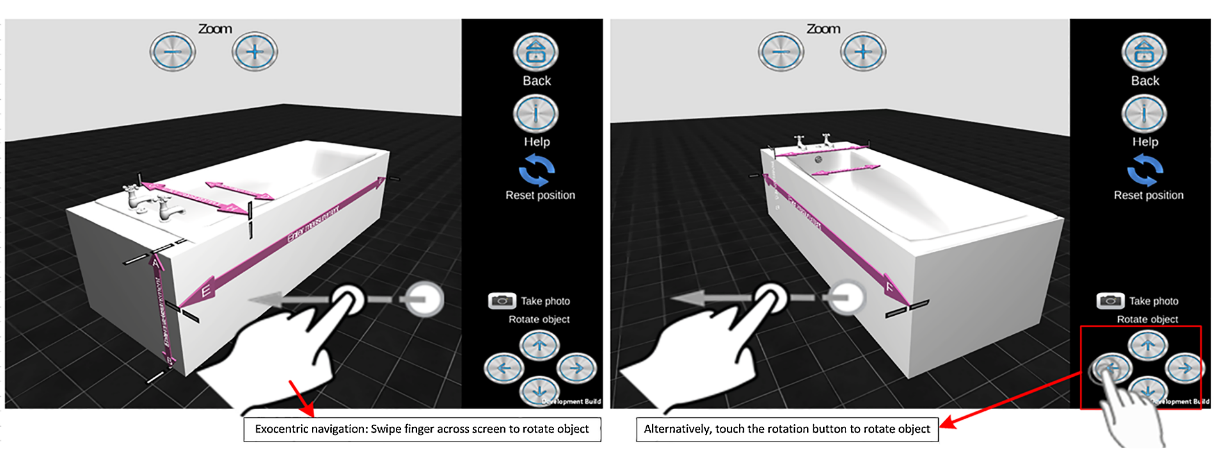

Fig. 6. Exocentric navigation (using the drag touch gesture) and rotation buttons.

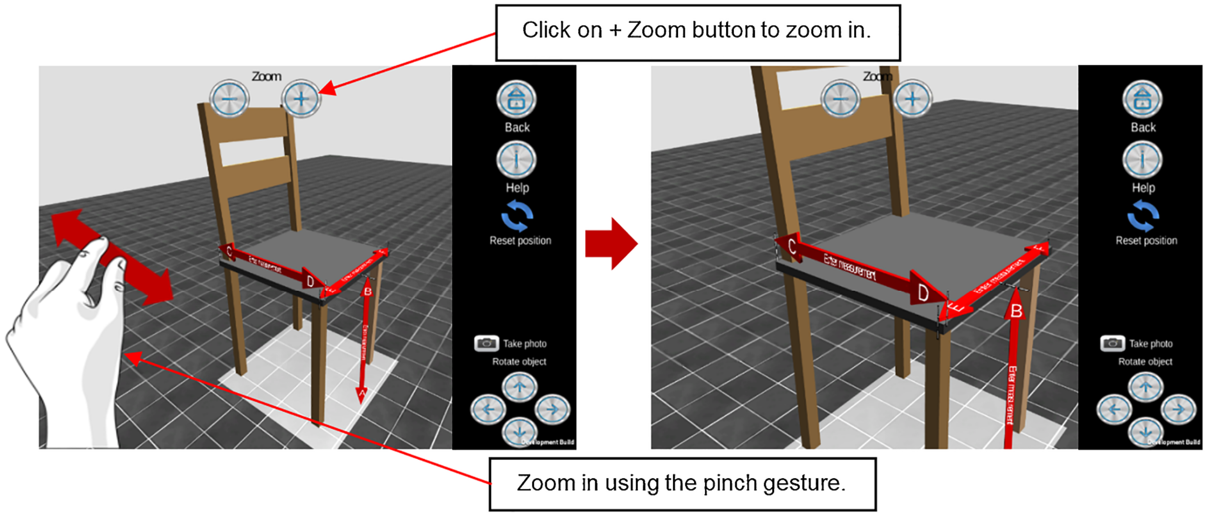

Fig. 7. Chair measurement screen demonstrating Zoom in function.

recorded using the guidetomeasure-3D application compared with paper-based booklet measurement guidance. 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 a full-length of 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 present 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 from each participant at the start of each session. Initially, participants were given a brief demonstration of the two measurement guidance tools (i.e. guidetomeasure-3D and booklet) and were given a tour of the living lab environment. They were then issued with one of the measurement guidance tools and asked to record the measurements of items as directed by the measurement guidance tool. The total amount of time taken was noted on completion of the measurement task. Participants were then asked to complete an adapted Systems Usability Scale (SUS) questionnaire [60] which included the 10 standard SUS statements and four additional bespoke statements specifically about the clarity of guidance provided 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. by alternating the order in which the 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 to explore the perceived challenges and opportunities of using these in practice. All interviews were recorded and transcribed verbatim.

3.3. Data analysis

3.3.1. Quantitative data analysis

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. 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

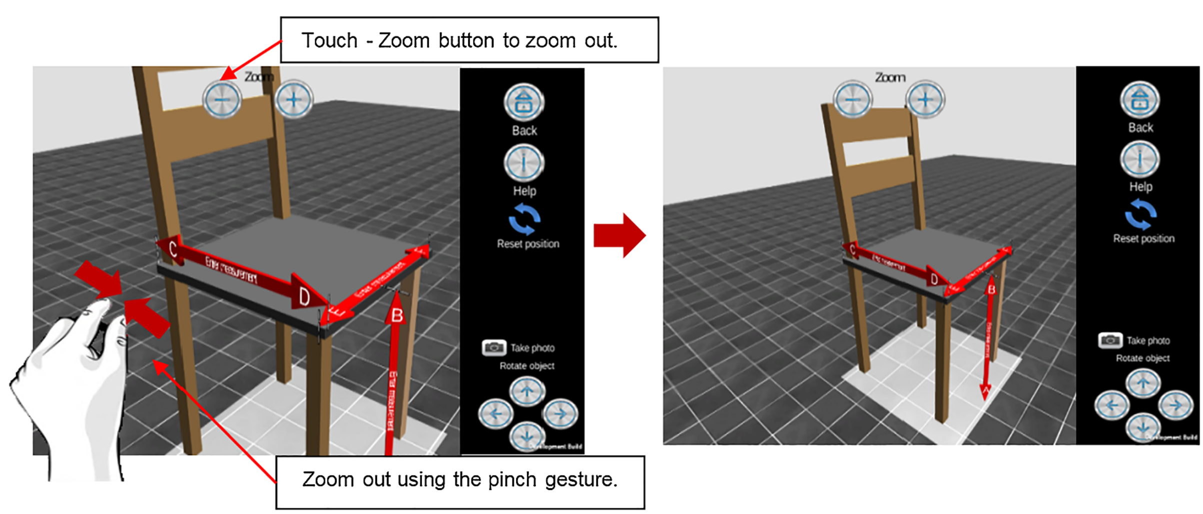

Fig. 8. Chair measurement screen Zoom out feature.

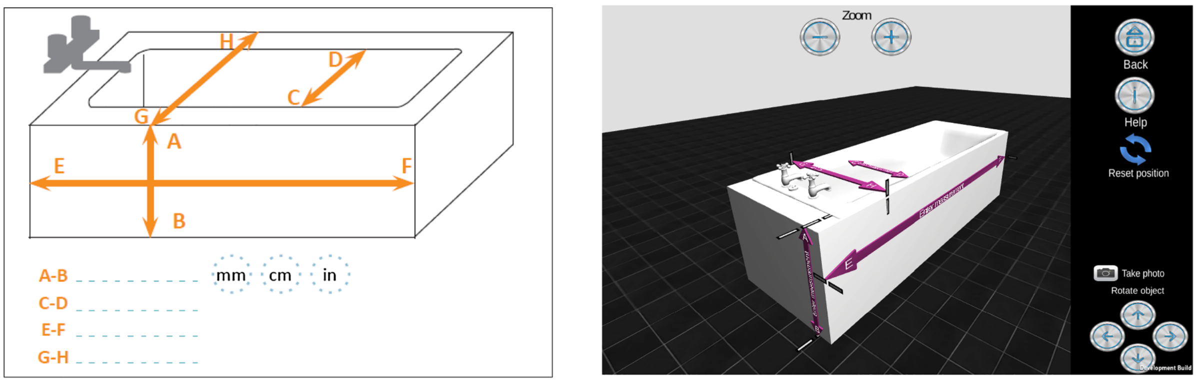

Fig. 9. Booklet bath guidance (Left) vs. bath guidance for guidetomeasure-3D (Right).

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. 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 [61,62] i.e. Usability (SUS items 1–3 & 5–9) and Learnability (SUS items 4 & 10). The significance threshold used to establish statistical significance for individual SUS item comparisons was adjusted using the Bonferroni correction for contrasts method [63] to account for the exploratory nature of this comparison, and to adjust for the potential inflated alpha effect of comparing a family of items individually. Significance thresholds used for statistical paired comparisons of measurement accuracy and consistency (RQ1 & RQ2) were not adjusted using a correction for contrasts method, as the rationale for these comparisons were not exploratory in nature. These counterbalanced paired comparisons were carried out in direct response to the main hypotheses of the study, i.e. to establish the extent to which guidetomeasure-3D outperforms the paper-based measurement guidance for each individual item of furniture, and for each of their respective unique measurements. Furthermore, overall SUS scores were calculated and interpreted according to the acceptability range, and the adjective and school grading scales [60]. 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 [64].

3.3.2. Qualitative data analysis

Thematic template analysis [65] was used to analyse interview transcripts (RQ5). This analysis was deductive [66], where analysis was driven by a pre-defined template (a priori) of themes based on a theoretical framework and/or the analytical interest of the researchers [67]. 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 [68,69]. 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; Effort Expectancy; Social Influence. The entire corpus was perused and coded; identifying specific extracts from the data that related to the three UTAUT themes. The corpus was then perused iteratively through several stages of splicing, linking, deleting and reassigning sub-themes within the context of the three 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 are dependent on the context in which data was collected and analysed [70].

4. Results

4.1. Measurement accuracy

The first research question was to compare the relative accuracy of measurements recorded using guidetomeasure-3D and the booklet measurement guidance tool. The results of the comparison between the guidetomeasure-3D app. and the booklet, and the extent to which the respective recorded measurements are significantly different from the true mean values are presented in Table 1.

Comparing the measurement guidance tool results, in all cases, with

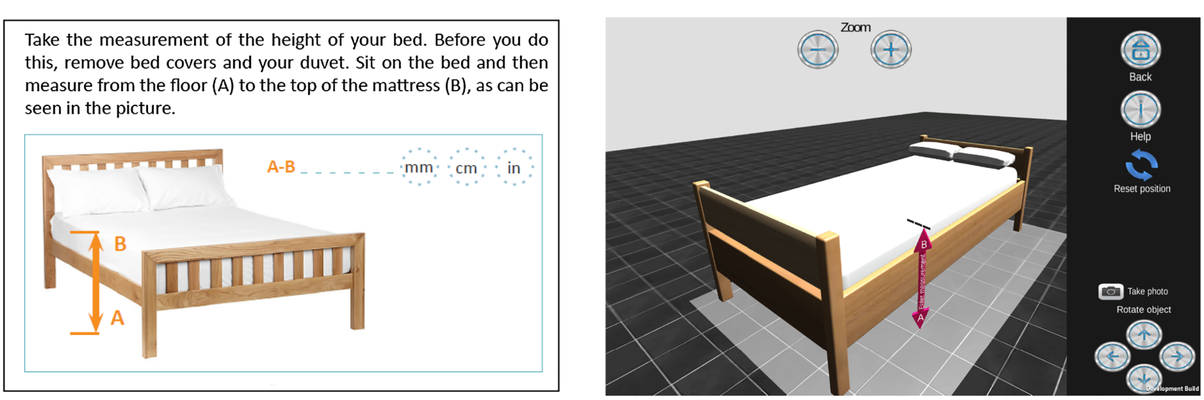

Fig. 10. Booklet bed guidance (Left) vs. bed guidance for guidetomeasure-3D (Right).

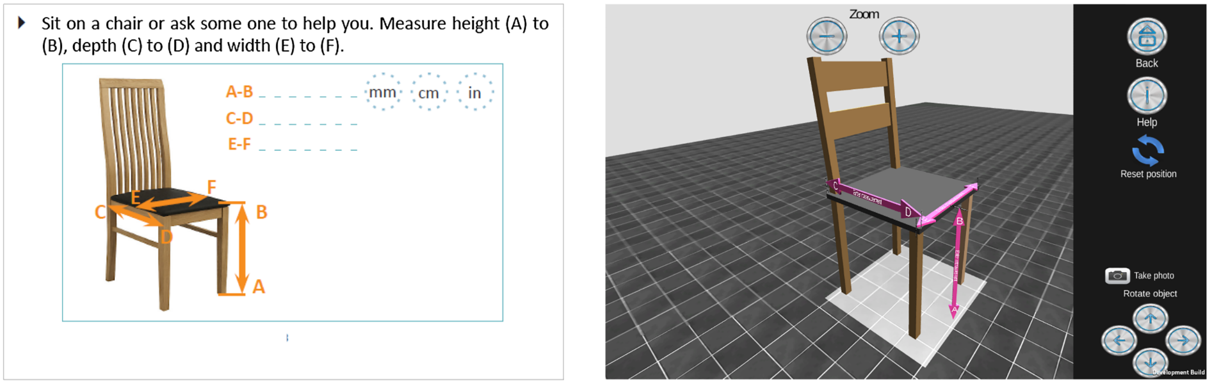

Fig. 11. Booklet chair guidance (Left) vs. chair guidance for guidetomeasure-3D (Right).

the exception of bath-external width, standard deviation values for guidetomeasure-3D were smaller than that of the booklet. Therefore, as an initial observation, this indicates that guidetomeasure-3D 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 guidetomeasure-3D and 0.17 for the booklet. This indicates that in absolute terms, guidetomeasure-3D generated more accurate measurements compared with the booklet for 11 of the 12 measurements.

The one sampled comparison of the guidetomeasure-3D 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 ($p = 0.157$). Hence, indicating that in these cases there is no evidence that guidetomeasure-3D produced 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, guidetomeasure-3D produced inaccurate measurements at the 0.05 level.

The one sampled comparison of the booklet mean error differences against 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 guidetomeasure-3D and the 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. Therefore, 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 guidetomeasure-3D 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 ($p = 0.076$).

4.2. Measurement accuracy consistency

The second research question was to compare the accuracy consistency of measurements recorded using the two respective measurement guidance tools. The results of this analysis are presented in Table 2.

When considering the median error differences between the two measurement guidance tools, in eight 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: ($Md = -0.12$); bath-height ($Md = -0.12$); chair-height ($Md = -1.56$); chair-width ($Md = -2.25$); chair-depth ($Md = -6.26$); toilet-height B ($Md = 0.01$); bed-height ($Md = -3.00$); patient-popliteal ($Md = -0.60$). In one case, the median error for guidetomeasure-3D 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 guidetomeasure-3D and the booklet. This indicates that the mid-point error values tended to be lower for guidetomeasure-3D compared with the booklet.

The Wilcoxon signed-rank test comparing the absolute error differences of guidetomeasure-3D and the booklet measurements, reveals

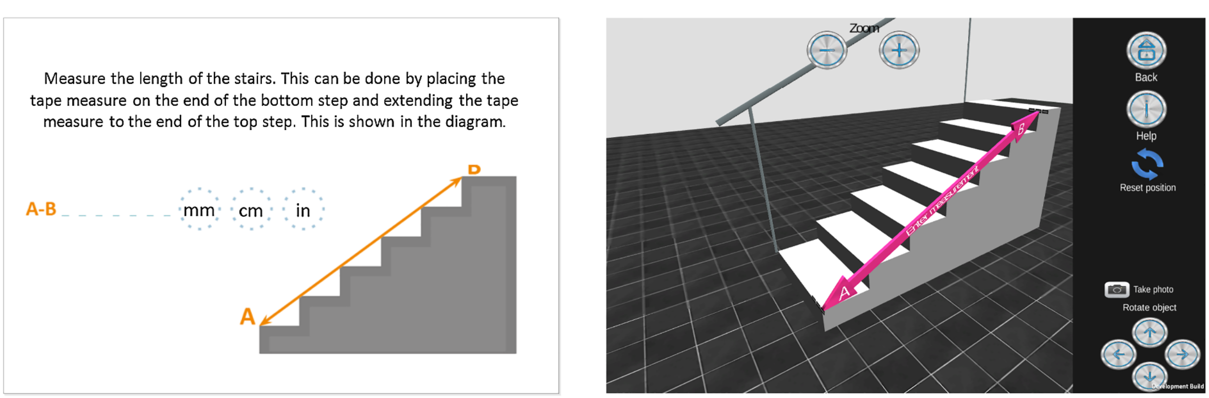

Fig. 12. Booklet stairs guidance (Left) vs. stairs guidance for guidetomeasure-3D (Right).

Fig. 13. Booklet toilet guidance (Left) vs. toilet guidance for guidetomeasure-3D (Right).

that in half of the cases (six out of the 12), guidetomeasure-3D 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 guidetomeasure-3D consistently produced more accurate measurements (i.e. lower measurement error differences) compared with the booklet.

Overall, comparing the performance of guidetomeasure-3D and the booklet in terms of accuracy consistency, guidetomeasure-3D outperformed the booklet in six of the 12 cases, generating significantly more consistently accurate measurements than the booklet. In five of the remaining six cases, the differences were not significantly different, however, guidetomeasure-3D tended to generate smaller error differences compared with 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.

4.3. 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. The results of this analysis are presented in Table 3.

The result of the paired samples t-test comparing task completion times for guidetomeasure-3D and the booklet measurement guidance tool reveals that participants required significantly less time when using guidetomeasure-3D ($M = 572.67$, 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 the 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.

4.4. Satisfaction and overall usability

The fourth research question was to evaluate the usability of guidetomeasure-3D compared with the booklet. The overall SUS score for guidetomeasure-3D was 81.1 out of 100 ($SD = 12.4$), which, according to the evaluation criteria for SUS [64], 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 'Good', 'acceptable', and 'Grade C' levels of usability. Fig. 16 presents the SUS rating scale with the overall SUS scores for guidetomeasure-3D and the booklet.

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. To account for the potential inflated alpha problem, the critical t value and subsequent p value significance threshold was adjusted to reflect the actual number of comparisons within each family of items on the SUS instrument, using the Bonferroni corrections for contrasts method [63]. Therefore,

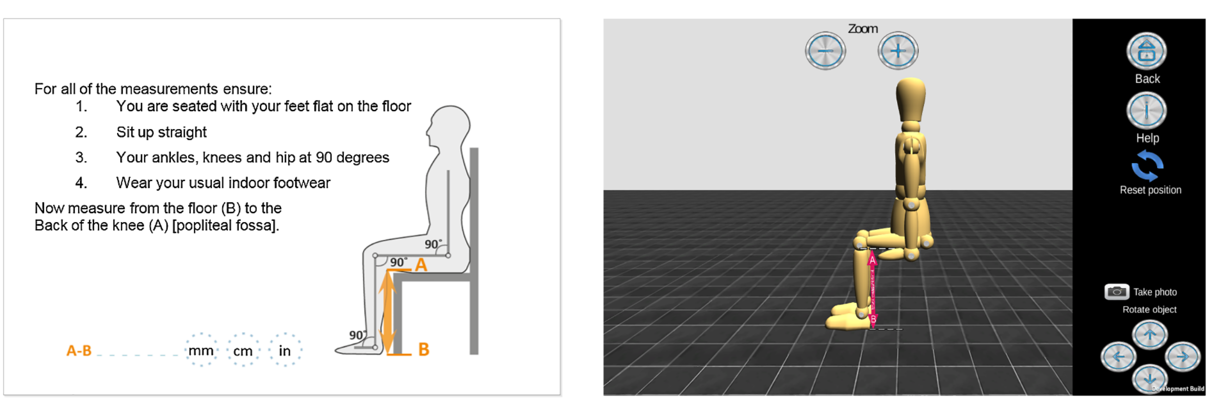

Fig. 14. Booklet 'About you' guidance (Left) vs. 'About you' guidance for guidetomeasure-3D (Right).

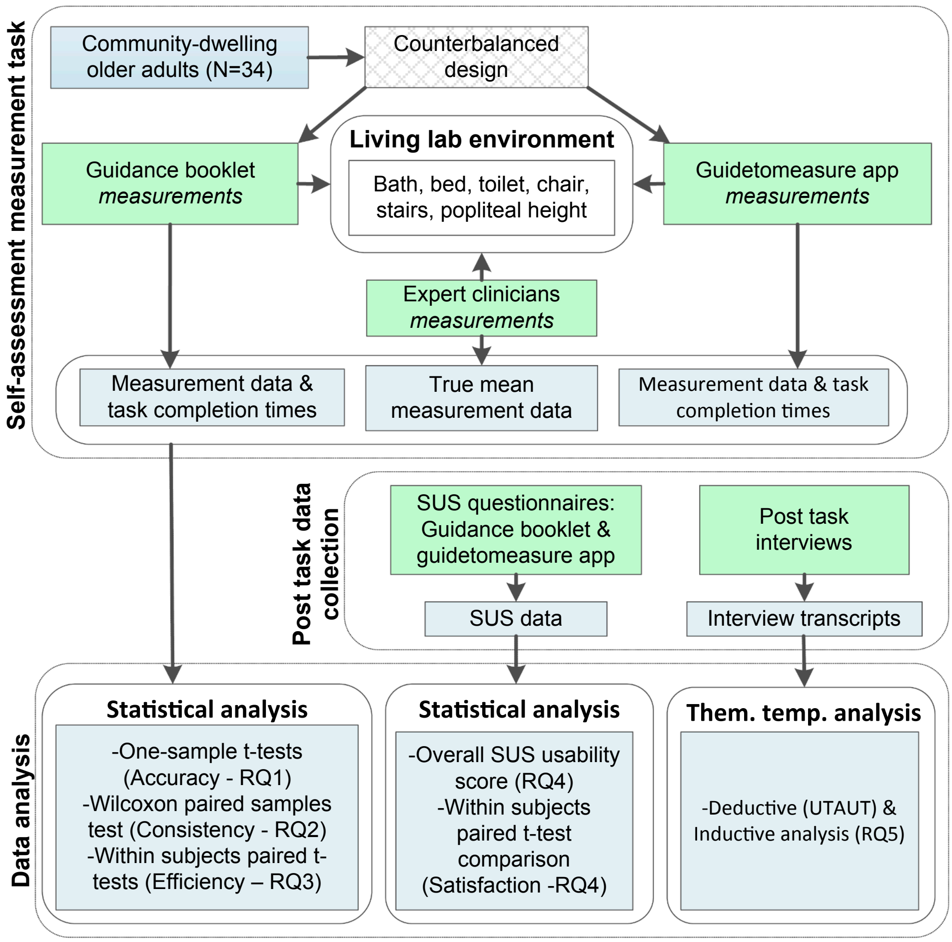

Fig. 15. Mixed methods data collection and analysis procedure.

Table 1
Measurement accuracy for the guidetomeasure-3D app. and booklet guidance.

		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.

Table 2
Accuracy consistency for the guidetomeasure-3D app. and booklet guidance.

	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.
[*] Statitisically significant at < 0.05 level.

SUS items 1–3 and 5–9 (eight items in total) are considered to belong to the Usability construct, hence the critical t value was adjusted to $t \geq 2.757$ and $p < 0.00625$. For SUS items 4 and 10, which belong to the Learnability family (two items in total) the critical t value was adjusted to $t \geq 2.035$ and $p < 0.025$ and for Items A1–A4 (four items) the critical t was adjusted to $t \geq 2.462$ and $p < 0.0125$. Table 4 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. for SUS items and clarity of guidance items, guidetomeasure-3D 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 to require technical support (S4) and may require less of a 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 ($p = 0.296$). Two of the ten SUS items (S2, S3) were significantly different, and in both cases, guidetomeasure-3D significantly outperformed the booklet. For the clarity of guidance items, three of the four items (A2–A4) were significantly higher for guidetomeasure-3D compared with the booklet.

Results for item S2, reveal that participants tended to be more positive about guidetomeasure-3D and that it was significantly less unnecessarily complex than the booklet ($p = 0.001$). For S3, participants found guidetomeasure-3D significantly easier to use compared to the booklet ($p = 0.002$). Item A2, indicates that guidetomeasure-3D improves the way participants measure home furniture, more so than the booklet ($p = 0.000$). Results for item A3, reveal that guidetomeasure-3D provides more clear and helpful instructions compared with the booklet ($p = 0.000$), and that guidetomeasure-3D more clearly illustrated where measurement points on the items were, compared with the booklet ($p = 0.000$).

With regards to the paired samples t-tests comparing the 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 [71]. However, the Cronbach's alpha score for Learnability was below the threshold and therefore will not be considered further. Table 5 presents the results of the comparison of these respective constructs.

Guidetomeasure-3D achieved a significantly higher Usability score ($M = 4.10$, $SD = 1.13$) compared with the booklet ($M = 3.67$, SD 1.11), t (34) = 4.350, $p = 0.000$. For clarity of guidance, guidetomeasure-3D 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, guidetomeasure-3D was considered to be significantly more usable and provided better clarity of guidance compared with the booklet.

4.5. Perceived challenges, opportunities, adoption and use

The fifth research question was to explore users' views about the perceived challenges and opportunities of using guidetomeasure-3D as a measurement guide and attitudes towards adopting this tool in practice. Three high-level themes emerged from the thematic template analysis: Performance Expectancy; Effort Expectancy; Social Influence. The information in parentheses, appended to each quote in this section,

Table 3
Task completion time for guidetomeasure-3D app. and booklet guidance.

	App.		Booklet		Piared differences			
	Mean (s)	St. Dev.	Mean (s)	St. Dev.	Mean diff. (s)	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.

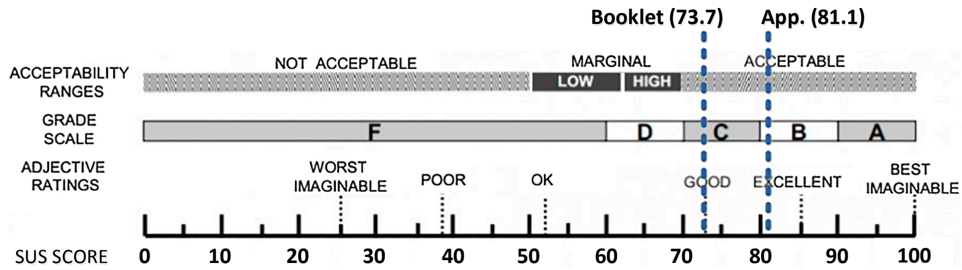

Fig. 16. SUS rating scale results for guidetomeasure-3D app and the booklet.

Table 4
Guidetomeasure-3D app. and booklet comparison of SUS scores.

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.
Items 4 & 10 to $p < 0.025$; Items A1–A4 to $p < 0.0125$.
[a] Responses of negative items reversed to align with positive items, higher scores indicate positive responses.
* Statistically significant at equivalent of < 0.05 level: Items 1–3 & 5–9 adjusted to $p < 0.00625$.

presents additional information about the participant that provided the quote, i.e. a unique participant ID, gender, age.

4.5.1. Performance expectancy

Participants reported that the *visual quality* of the guidance provided by guidetomeasure-3D was particularly useful and was a noticable 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 guidetomeasure-3D 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 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 guidetomeasure-3D 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

Table 5
Comparison of SUS constructs.

Construct	Items	Cronbach's alpha		App. Mean	Booklet Mean	Gap score (App. – Booklet)	Sig. (2-tail)
		App	Booklet				
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.

guidetomeasure-3D as they offered them a 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)*

4.5.2. Effort expectancy

In terms of the effort required to utilise the measurement guidance tools, participants considered both guidetomeasure-3D and the booklet 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 guidetomeasure-3D for the chair needed to be more clearly presented. Indeed, overall participants noted that the chair was the item that posed the greatest challenge in the measurement task, i.e. for both guidetomeasure-3D and the booklet.

> *"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, 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. Several references were made to guidetomeasure-3D offering more of an *improved visualisation* of the measurement guidance compared with the booklet. For example, participants commented on the bath being the clearest guidance provided by the application, as the quality of models and their 3D representation struck more of a realistic resemblance with the instruction that would be provided by a clinician in a real-life setting. There were, however, some participants who expressed that for some items and individual measurements, guidetomeasure-3D had no real benefit over the booklet. It was, however, noted that this was not in all cases, and that in others guidetomeasure-3D 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)*

4.5.3. 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 in the measurement guidance, both with guidetomeasure-3D 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 some additional input to provide a second opinion about the recorded measurements, as they felt this would increase the likelihood of obtaining more accurate results and would 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 it's 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 was seen as a potentially challenging, and 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)*

5. Discussion

This study presented guidetomeasure-3D, a 3D mobile application which provides interactive guidance to enable service users to carry out self-assessment measurement tasks as part of the HEFAP. The application architecture and Web API is designed to enable integration directly into existing clinical pathways and to enable service users to report recorded self-assessment measurements directly to clinicians. In order to evaluate the performance of this application, a user-based study involving 34 older adult participants was conducted within a living lab environment to investigate the extent to which guidetomeasure-3D enabled participants to effectively (accuracy, and accuracy consistency) and efficiently (task completion time) record measurements using the 3D app compared with an equivalent 2D paper-based measurement guide booklet 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 intentions to adopt the new application in practice.

5.1. Research question 1

The first research question explored the relative accuracy of measurements and the extent to which each measurement guidance tool generated measurements that were not significantly different from the true mean. The results of this study are promising, revealing that in the majority of cases, guidetomeasure-3D 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 smaller 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 guidetomeasure-3D and the booklet. Both measurement guides performed equally well for the same five out of 12 measurements. However, guidetomeasure-3D outperformed the booklet on two additional measurements, both of which were chair measurements (chair width and depth). Therefore, guidetomeasure-3D generated accurate measurements for two of the three chair measurements, compared with the booklet, which generated no accurate chair measurements 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 guidetomeasure-3D and the booklet, it seems that the guidance provided by guidetomeasure-3D was more effective in enabling participants to overcome some of these challenges and take more accurate measurements of this item. Existing research suggests that some of the most important measurements, in terms of reducing the risk of falls, are those related to the chair. Chair measurements are particularly important as they impact the patient's ability to rise to stand from the chair and require significant trunk flexion and fast movements for chair transfers [72,73]. More generally, enabling improvements in measurement accuracy, particularly for patient self-assessments, is an important positive outcome because it equips the patient with the necessary expertise to carry out a clinical assessment tasks more effectively, hence improving the potential for them to be involved in clinical decision making, and ultimately moving them closer towards becoming an expert patient. This indeed is very much in line with the vision of delivering patient-centred, re-abling and personalised care [10,11].

5.2. Research question 2

The second research question compared the relative accuracy consistency of the two measurement guidance tools. The results were very promising and revealed that there were no cases in which the booklet outperformed guidetomeasure-3D in terms of accuracy consistency. In all cases that there was a median error difference, guidetomeasure-3D produced smaller median error values. This further supports the findings from the first research question, that guidetomeasure-3D generated smaller measurement errors compared with the booklet. When comparing the statistical significance of differences in terms of consistency of measurement accuracy between guidetomeasure-3D and the booklet, the result was that guidetomeasure-3D 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 anthropometric measurement. Overall, in all cases that there were differences in performance, this could be explained by guidetomeasure-3D 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 guidetomeasure-3D for all three chair measurements. Given the important and prevalent role that appropriate chair height plays in the context of fall prevention interventions [21,74], this finding supports the notion that there may be significant practical value in replacing existing paper-based measurement guidance with 3D measurement guidance. The medium - large effect size achieved for the bed and anthropometric measurements (popliteal height) adds further support to this notion. Indeed, accurate bed height adaptation is considered key for preventing a range of extrinsic fall risk factors [8,75] and popliteal height is a particularly crucial measure which is required in order to calculate adapted chair height, bed height, and toilet height [38]. 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, which is a positive outcome when considering the added value that this application is delivering. 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. [76] 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 of 31 articles comparing relative task performance using 2D and 3D visualisations [77]. The improved accuracy consistency achieved by guidetomeasure-3D is an important outcome because inaccurate measurements could lead to equipment abandonment and an overall reduction in quality of life as a result of being unable to engage safely in occupations of daily living [37,78].

5.3. Research question 3

The third research question compared the task completion time for guidetomeasure-3D with the booklet. The results revealed that guidetomeasure-3D 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 [79–81]. Making self-assessment tasks more efficient for patients is an important finding and has benefits to patients who are increasingly being given the responsibility to deliver self-care and self-assessments [32]. More generally, there are also clear benefits for health and social care services as home visits are perceived as being time consuming and resource intensive exercises which some consider impacts negatively upon wider occupational therapy practice [82].

5.4. Research question 4

The fourth research question evaluated the comparative usability of the measurement guidance tools via the SUS questionnaire. The results revealed that guidetomeasure-3D outperformed the booklet in terms of the overall SUS score: app − 81.1 versus booklet 73.7. This resulted in the guidetomeasure-3D application achieving 'Excellent' and 'Acceptable' levels of usability at 'Grade B' (school grading scale), versus 'Good' and 'Acceptable' levels of usability at 'Grade 'C' (school grading scale) for the booklet. The individual SUS item results revealed that there was a significant positive preference in terms of guidetomeasure-3D being reported as significantly less complex (S2), and easier to use (S3). The booklet did not significantly outperform guidetomeasure-3D on any individual SUS item. In terms of SUS sub-scales, guidetomeasure-3D 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 [83,84]. The finding that 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 [84], especially as older adults are believed to be more familiar with 2D paper-based forms that are typically used for self-care and assessment tasks [35]. It should be noted, that one of the inclusion criteria for this study was that participants were already familiar with mobile touch screen devices, which may have 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 in years to come [85]. The finding that guidetomeasure-3D was assessed as being a more usable self-assessment tool than the booklet which is currently used in practice, is an important finding. Furthermore, it is important to be mindful when developing novel technology-based healthcare applications for clinicians and patient users, that user needs are identified and met by the application, as patients 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 [86,87]. Furthermore, producing more usable self-assessment tools can decrease cognitive load on the patient, promote continuous engagement in healthcare interventions, and improve health outcomes overall, but only if every effort is made to ensure these applications are usable [88].

5.5. Research question 5

The fifth research question aimed to explore users' views of guidetomeasure-3D 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 the measurement guidance provided by guidetomeasure-3D was a welcomed improvement to that provided by the booklet. Annotations in situ with the 3D models were seen to offer more precise indications of the points to be measured, as was on-arrow annotation of measurements, which provided useful data recording support. Real-time audio instructions were also seen as a 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 [62,89]. The finding that users generally perceived that guidetomeasure-3D 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 [84]. 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. However, it was also noted that the additional functionality was not entirely necessary for the less challenging measurements. 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 [90–92] and wound care [93]. The issue of user confidence in carrying out this task featured strongly when considering user perceptions relating to the 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 healthcare 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 [94]. 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 take on these new responsibilities [37].

5.6. Generalisability and transferability

5.6.1. Accuracy, accuracy consistency, and efficiency of self-assessment and data capture tasks

In terms of the wider generalisability of these findings to healthcare practice, HEFAP is not just practiced in the UK and Europe, but is a process that is carried out by health services across the world [95]. Hence, with regards to improved measurement accuracy, there is significant potential to realise measurement accuracy gains on a global scale, i.e. by utilising such an approach more widely for home assessment tasks. One of the barriers to wider adoption in practice is making the availability of such software applications available to potential users. With a view to overcoming this barrier, an early beta prototype version of the guidetomeasure-3D application is already freely available for patients and practitioners to download and install on android devices [96]. Updated alpha versions of the application will continue to be made freely available to potential users as this research progresses. Furthermore, there are numerous other areas of clinical practice, such as cosmetic surgery [97], wound care management [98], and physiotherapy [99], which rely on clinicians and patients to take and record accurate manual measurements as part of their roles. The findings in this study, that have shown a significant improvement in manual measurement accuracy via the use of mobile 3D visualisation technologies, presents important new opportunities that may be applied to improve manual measurement practice that occurs across a broad range of fields of healthcare practice.

These study findings also deliver numerous contributions to the wider research field of ICT applications for health more generally. For example, the finding that accuracy consistency is significantly improved using 3D mobile visualisation technologies for this patient-led self-assessment task, serves as a valuable case example that may be used to justify the exploration of utilising similar technologies for any health self-assessment and data capture settings that involve an element of 3D spatial information comprehension and/or measurement. Furthermore, the finding that this mobile 3D tool consistently improves the ability of older adult patients to carry out self-assessments more accurately provides important evidence that the vision of enabling and empowering patients to be able to independently deliver effective, reliable, and accurate self-care has significant potential of being realised via the development of innovative patient-centred technological applications. The vast range of existing paper-based patient assessment and information leaflets, which is the standard format in which patient information and self-care guidance is provided across all areas of healthcare [100,101], often results in this information not being readily accessible or comprehensible to the patient [102]. The findings of this study therefore present significant positive implications and opportunities for the field of health and biomedical informatics more generally, as it provides case evidence that there are significant performance and accuracy benefits to be realised via the digitisation of current paper-based information sources that currently permeate all areas of healthcare delivery. It is important to note, however, that digitisation and adoption of health information technologies in practice is not necessarily unproblematic in its own right, and has the potential to cause a range of issues including increases in medical errors and decreased clinician performance [103]. Nevertheless, the results of this study make an important contribution to knowledge in the field of biomedical informatics, by adding to the growing, but still incomplete, taxonomy of benefits that may be realised from the deployment of 3D mobile technologies within healthcare delivery settings.

In addition to accuracy and consistency, efficiency gains were also delivered by guidetomeasure-3D in terms of the amount of time taken to complete the measurement tasks. This is an important finding, particularly in light of there being a range of concerns around lowered levels of efficiency as a consequence of adopting new health information technologies in practice [103]. These concerns may well still remain and may depend on, for example, the specifics of the proposed technological innovation, the context in which it is deployed, the required training overhead for a specific application, and its interoperability with existing systems. Nevertheless, the findings of this study reveal that in-task efficiency gains are achievable by utilising 3D visualisation technology, which are encouraging results, and represents new opportunities to explore, more generally, the benefits of incorporating such technologies into health assessment guidance and data capture tasks that involve an element of manual measurement and/or the communicating of 3D spatial information from and to patients and practitioners.

5.6.2. Usability and adoption of technology in practice

These findings have important future reaching and generalisable implications for the digitisation of healthcare systems and their deployment on mobile touchscreen devices, particularly given that a positive usability outcome has been achieved with an older adult sample population that is familiar with using smartphone/touchscreen technologies. This population represents the more technologically aware older adult cohorts of the future. These results therefore support the notion that well-developed user-centred mobile 3D touchscreen applications have the promising potential of delivering more usable alternatives to traditional paper-based guidance tools in the future. Moreover, the results are also particularly important as they provide a novel example that indicates that older adult patients view mobile touch-screen technology as being a preferable medium, over paper-based methods, for patient-led data capture tasks and the delivery of self-care guidance. This is of importance as it could have widespread positive influence on future research initiatives, given that there is a clear and present need for new opportunities and associated case examples that demonstrate how mobile technology solutions can be deployed to help alleviate the increasing burden on health resources, and enable older-adult patients in particular to embrace the delivery of more efficient and effective self-care interventions [104]. Existing research has already found promising results, for example, from developing a mobile touchscreen application that enables the capture of resuscitation data, which was preferred by physicians and nurses over its paper-based equivalent, achieving improved task completion rates and delivering improved levels of usability [105]. The finding in this study, that older adult patient users also found a mobile touchscreen-based application more usable compared with the paper-based equivalent, adds support to the notion that there are significant gains for clinicians, and patients, to be realised by investing further development effort and resources into digitising existing paper-based data capture and self-care guidance tools. Moreover, the fact that there is now evidence that both practitioners *and patients* see benefits from digitisation of previously paper-based resources, provides valuable support for investing further effort into digitisation of previously paper-based health resources, and across a wider range of healthcare settings. However, in doing so, it is crucial that designers and developers remain mindful of the potential undesirable and unintended consequences that may result as a consequence of such digitisation [12]. According to some participants in this study, guidetomeasure-3D enhanced their level of confidence in the task, and hence the guidetomeasure-3D application presented here serves as a valuable case example for the fields of health and biomedical informatics. The application demonstrates a range of interactive digital application features, which together, enable older adults to feel higher levels of confidence when carrying out self-assessment tasks, compared with the traditional paper-based equivalent. There is therefore an opportunity for future studies to emulate the application features presented here and apply them to new areas of clinical practice. However, it is important to note that guidetomeasure-3D does not eliminate entirely the issue of lack of confidence when carrying out self-assessments. Indeed, some users reported that they would not feel confident using either paper-based or digitised versions of the measurement guidance tool.

5.6.3. Advancing methods and applications

The research presented in this study adds to the growing body of evidence that demonstrates the role that electronic applications have in advancing effectiveness, quality, and safety in health and social care. Primarily, the research focus of the work presented here adheres to the three guiding principles of delivering digital healthcare, as outlined in the recently published Topol Review [106], namely that new technology should be evidence based, the technology should empower users, and where possible should allow more time for direct patient care and provision. Healthcare provision is in the midst of a transition away from primarily focusing on the treatment of disease, towards recognising the value of health promotion and the enablement of patients to play an active role as experts in maintaining and managing their own health [107]. Novel applications of technology are seen as playing a key role in making this transition possible for both patients and practitioners, and hence it is crucial that appropriate human-factors engineering methods are used in the process of implementing these systems, if they are to deliver their full enabling potential to their users [103]. Despite this ongoing and increasing need to transition towards a healthcare model that primarily seeks to empower the patient and deliver technology enabled self-care efficiencies, a recent comprehensive survey of the state of the art in falls prevention technologies found that the majority of falls prevention technology research still maintains a focus on delivering applications that perpetuate the delivery of traditional disease prevention focused models of care [44]. There is a need for future research to invest more effort into developing novel applications that seek to support and enable the transition towards empowering the patient. We therefore believe that the research and the application presented here, and the human-factors engineering methods used, serves as an important, if not comparatively rare, case example of research that seeks to progress the field of biomedical informatics in a direction that enables older adult patients to be expert and more independent partners in the delivery of their own care.

The methods employed in this study contribute to the field of biomedical informatics by presenting an important example of a pluralistic methodological approach towards developing and evaluating a novel application, whilst positioning the user at the centre of its focus. A systematic, yet pluralistic methodological approach, as is taken here, is already recognised as being necessary and of significant value in other fields of study such as clinical decision making [108], and therefore this study provides an important point of reference for the development of future applications that seek to digitise previously paper-based self-assessment guidance within the field of biomedical informatics. Particularly, from a system development and evaluation perspective, in terms of accuracy, accuracy consistency, efficiency, and usability, the study design and quantitative data analysis approach, which includes counterbalanced paired comparisons of performance across all of these measures, delivers a transparent evidence base on which to evaluate the relative performance of the new innovation compared with the traditional equivalent. The qualitative data analysis of user perspectives, partly informed by the UTAUT model to explore the perceived challenges, opportunities, and intentions to adopt the technology in practice, provide a valuable additional level of insight which helps to triangulate and contextualise the findings. We therefore believe that the comprehensive and systematic user-centred mixed-methods approach presented here will serve as a benchmark for similar future studies that aim to develop and evaluate software applications that replace traditional systems.

5.6.4. Interoperability and technical deployment opportunities

The guidetomeasure-3D application has been architecturally designed to be interoperable and integrated into existing and future clinical settings, and can also be expanded upon via additional microservices which may be utilised in different care pathways as the need arises. Moreover, a number of considerations have been factored in to maximise the generalisability of the software artefact presented in this study. These are as follows:

- There are multiple data points (in various formats) that are pulled from heterogeneous data sources that this app deals with. For assessments to be conducted, these data points, consisting of key-value pairs, are serialised into a common data structure/format, i.e. JSON format to be consumed by a front-end layer. Providing a data transformation mechanism to serialise data originating from heterogeneous sources in multiple data formats, offers opportunities for wide-ranging use, and maps particularly well to domains such as healthcare where the varied range of assessments and associated tasks conducted across practices tend to be non-monolithic in nature. The transformed data can then be consumed via an API call to a front-end UI which can be designed specifically for the needs of the consumer independently of the underlying system architecture. Given the heterogeneous nature of the way in which HEFAP is utilised, the functionality that the app provides is decomposed into microservices to cater for this heterogeneity. Leveraging API endpoints through asynchronous requests allows for the data to be presented and manipulated through custom or existing in-house front-end UIs according to the needs of the user or service.
- One of the benefits of RESTful services is that the transformed assessment data could be requested from persistent storage to be used by in-house systems of healthcare practices in which the app is deployed, i.e. to integrate the data to patient records directly or to compose and send emails to other clinicians for handovers and follow-up assessments. Requests could also be made to third parties that are involved in healthcare assessments.
- As data is requested from multiple heterogeneous sources, this provides a means of integrating devices, as part of a network, used for optimising/automating data collection activities relating to assessments that are otherwise not currently used, hence, data could be retrieved and transformed in a way that is understood by the app. In the context of this research, this eliminates the need for manual recording of measurements to be taken as part of the assessment process. In general, this also provides further/future capabilities of interfacing with devices relevant to the context for which the app has been redeveloped.
- In terms of interoperability, the backend of guidetomeasure-3D contains a collection of clinically-focused functionality as services that are made use of by the requesting interfaces (in this particular case, a 3D visualisation of the state-of-the-art measurement guidance). As the underlying architectural design is context independent, as the UI presents the data to the end-users specific to a particular context/need, there is scope for delivering similar types of state-of-the-art guidance in other healthcare areas, and to other stakeholders such as clinicians, patients, carers, and multidisciplinary care teams that may have similar or related task requirements.

As mentioned previously, the architectural design, assessment data transformation, e.g. into JSON, format and the RESTful API component all enable the proposed application to be integrated into other healthcare contexts and environments. While guidetomeasure-3D is designed to address a specific problem within healthcare, the underlying technology may provide a 'blueprint' for similar touchscreen-based apps in other areas in healthcare that have similar needs to digitise previously paper-based data capture and assessment tasks.

6. Conclusions

An interactive mobile 3D measurement guide, and associated system architecture, for HEFAP self-assessments has been presented in this study. An empirical mixed methods evaluation of the performance of the guidetomeasure-3D application revealed that in terms of accuracy, accuracy consistency, task completion time, and usability, there were significant performance gains achieved over the current state of the art paper-based 2D measurement guide equivalent. The development of a mobile 3D application that achieves significant improvements in measurement accuracy and usability for older adult patients is an important finding, particularly given the high levels of equipment abandonment and the growing expectation that patients and carers carry out HEFAP assessments themselves. In line with the personalisation agenda, patient self-assessment has been suggested as the future of healthcare provision, and in the case of HEFAP, giving users control over the assessment process recognises users as experts and as having the skills necessary to take control over their own health [109]. However, self-assessment can only work successfully if users are given effective and high-quality guidance and can use and understand the information provided [110]. Our research makes a considerable contribution, as it demonstrates how novel mobile 3D technologies may be used to empower older adult users to carry out assessments more effectively, efficiently, and with enhanced levels of confidence and improved levels of service user autonomy, hence enabling the provision of more personalised care. This in turn, could improve overall patient satisfaction, quality of life, and ultimately, the level of engagement with assistive equipment for falls prevention [23]. We have also comprehensively explored and discussed the generalisability and transferability of this work and how it may influence and contribute to healthcare practice more generally. Increased older adult patient autonomy promises to deliver crucial efficiencies which are much needed, given the growing demands on clinicians' time and the increasing strain on public resources. Future research will focus on exploring the development of an automated assistive equipment recommendation function. The microservices architectural designed and deployed for the guidetomeasure-3D application also enables us to explore the feasibility of integrating depth-sensing technologies into this application with a view to automating the manual measurement process, which is another future area that this research will focus on. If implemented effectively, this could help to further reduce the burden on OTs by automatically capturing measurements of home furniture items and prescribing home adaptations based on the information collected during a HEFAP self-assessment, hence moving HEFAP closer towards becoming a task that is fully administered by the patient.

Conflict of interest

The authors declared that there is no conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbi.2019.103135.

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