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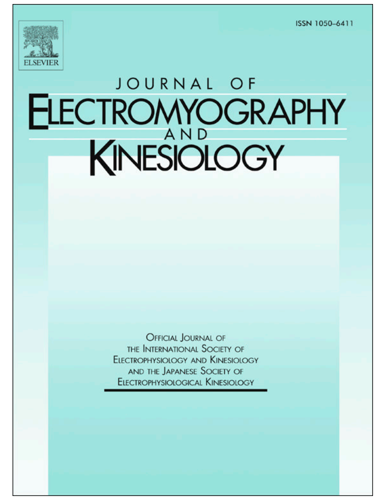

Effects of lighting illuminance levels on stair negotiation performance in individuals with visual impairment

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Title page

Effects of lighting illuminance levels on stair negotiation performance in individuals with visual impairment

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Abstract

Background: Stair-related falls of older people cause a substantial financial and social burden. Deterioration of the visual system amongst other factors put older people at a high risk of falling. Improved lighting is often recommended. The aim of this study was to investigate the effect of lighting illuminance on stair negotiation performance in older individuals with visual impairment.

Methods: Eleven participants aged 60 or over with a vision of 6/18 or worse ascended and descended a staircase under: 50lx, 100lx, 200lx, 300lx and distributed 200lx lighting. A motion capture system was used to measure movements of the lower limb. Clearance, clearance variability, temporal and spatial parameters and joint/segment kinematics were computed.

Findings: There was no effect on clearance or clearance variability. Participants had lower speed, cadence, increased cycle time and stance time in the 50lx compared to 300lx and distributed 200lx lighting in descent. The minimum hip angle in ascent was increased in the 200lx lighting. Clearance was found to be moderately correlated with balance scores.

Interpretation Individuals with visual impairment adopt precautionary gait in dim lighting conditions. This does not always result in improvements in the parameters associated with risk of falling (e.g. clearance).

Key words: lighting, vision, temporal-spatial parameters, clearance, clearance variability, kinematics, stair ascent, stair descent

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Abstract

Background: Stair-related falls of older people cause a substantial financial and social burden. Deterioration of the visual system amongst other factors put older people at a high risk of falling. Improved lighting is often recommended. The aim of this study was to investigate the effect of lighting illuminance on stair negotiation performance in a group of older individuals with visual impairment.

Methods: Eleven participants aged 60 or over with a vision of 6/18 or worse ascended and descended a staircase under five lighting conditions: 50lx, 100lx, 200lx, in 300lx and distributed 200lx lighting. A motion capture system was used to measure movements of the lower limb. Clearance, clearance variability, temporal and spatial parameters and joint/segment kinematics were computed.

Findings: There was no effect on clearance or clearance variability. Participants had lower speed, cadence, increased cycle time and stance time in dimmer lighting conditions in descent. The minimum hip angle in ascent was increased in optimal lighting conditions (200lx) compared to other lighting conditions. Clearance in this participant group was found to be moderately correlated with balance scores.

Interpretation Individuals with visual impairment adopt precautionary gait in dim lighting conditions. This does not always result in improvements in the parameters associated with risk of falling (e.g. clearance).

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Key words: lighting, kinematics, temporal-spatial parameters, clearance, vision, clearance variability

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Introduction

Falls are a common cause of morbidity, mortality and loss of function in older people [1]. Stair-related falls account for approximately one fifth to one third of accidental falls of older people at home [2, 3]. Falls on stairs is a leading cause of accidental death, accounting for 10% of fall-related mortality, approximately 80% of which are of individuals aged 65 or over [4].

The presence of age-related diseases and disabilities, as well as the physiological changes caused by ageing that affect sensory and motor functions, put older people at a higher risk of falling than their adolescent counterparts. The deterioration of the visual system is one such change that has been related to an increased risk of falls in this population. Poor vision was found to be an independent risk factor [5, 6], approximately doubling the risk of falling of older persons [6-8].

In addition to intrinsic risk factors, environmental hazards are another leading cause of falls in older people, accounting for approximately one-third of reported falls [9]. Studies assessing hazards that lead to falling in the homes of older people have identified inadequate lighting to be one of the main factors leading to a fall incidence [10-12]. Few studies have attempted to quantify the link between the deterioration of vision in older people, poor lighting and the risk of falling.

Previous studies investigating the effects of lighting luminance levels on stair negotiation have looked at effects on ground reaction forces [13], minimum foot clearance and clearance variability [14, 15], temporal spatial parameters [16] and centre-of-mass progression [15]. In low lighting conditions, older

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participants were found to have a reduced step length [15] and a decreased first peak of the vertical ground reaction force in stair descent [13], thus suggesting an adoption of safer stepping strategies in poor lighting conditions. However, other studies have not found changes in other movement parameters when lighting conditions were altered [16].

None of the previous studies included participants with known visual impairments. This is particularly important as the association of poor vision and measures of static [17, 18] and dynamic stability [19] is well-documented in the literature. The presence of this risk factor as well as inadequate lighting may result in significant changes in the biomechanical characteristics of stair negotiation, which may help explain any relationship between visual impairment, poor lighting and the increased risk of falls in this population.

The aim of this study was to investigate the effect of lighting illuminance levels on stair negotiation performance in a group of older participants with visual impairments. The study assesses biomechanical parameters associated with risk of falling during stair ascent and descent; clearance and movement variability, as well as parameters related to changes in stepping strategies; joint kinematics, temporal and spatial parameters.

Methods

Participants

The study was reviewed and granted ethical approval by Surrey Research Ethics Committee. A power analysis for a repeated-measures ANOVA design revealed that a minimum of 9 participants are needed to achieve a statistical

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power of 0.8 with a significance level of 0.05. The effect size was estimated to be 0.25 and the correlation amongst repeated measures was estimated to be 0.80 based on the results obtained from a pilot study.

Eleven participants (seven males) with a mean age of 78 (6) years consented to taking part in the study and signed a consent form. Participants were included in the study if they were: 1) aged 60 or over, 2) partially sighted due to macular degeneration or advanced cataract caused by old-age, all patients with macular degeneration had a vision of 6/18 or worse and 3) able to negotiate stairs using a step-over-step strategy. Participants were excluded if they: 1) had a muscular or neurological condition or impairment that affected or limited their gait or 2) had a diagnosed vestibular disorder. In addition, a clinician assessed the participants' lower-limb joints (hip, knee and ankle) range of motion, lower-limb muscle power and mobility and used Berg Balance Score (BBS) [20], participants were excluded if they displayed reduced balance caused by dizziness. The activities-specific balance confidence scale (ABC) [21] and the stair self-efficacy questionnaire (SSE) [22] were also completed by the participants. Participants also completed questionnaires on the use of the laboratory stairs and the lighting conditions. Participants were asked if they thought the stairs were poorly lit and if the stairs were safe to use (see Table S1).

Laboratory Setup and Lighting Configurations

A seven-step staircase (tread 300mm, rise 180mm, width 1000mm, pitch 31°) was constructed from medium density fibre board (MDF). The staircase had a top landing area of 1500x1000mm, handrails on one side and a wall on the

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other, thus simulating a domestic staircase. The walls were painted with neutral colour paint to simulate a domestic colour scheme.

An array of 4x100W incandescent lamps were used on the top landing of the staircase, a 200W lamp was used at the bottom landing of the stairs in addition to laboratory lights and diffusers (Figure 1A). A dimmer switch control was used to allow adjustment of lighting conditions and a light meter (ISOTECH, England) was used to measure illuminance levels from the top landing. This configuration was used to achieve five lighting conditions; low illuminance 50lx, sub-optimal lighting 100lx, optimal lighting 200lx, increased illuminance 300lx and distributed 200lx lighting. The poorest lighting condition used in this study (50lx) was based on the findings of the study by Hill et al (2000), which surveyed 150 older people's households and found that more than 60% of these had lighting of 50lx or less during the day [23]. Optimal lighting was defined as an illuminance of 200lx based on the recommendations of Thomas Pocklington Housing Guide [24].

The distributed 200lx lighting condition was achieved with the laboratory lights fully on, the top landing light off and the bottom landing of the stairs dimmed, this arrangement achieved illuminance level of 200lx on the top landing. Other lighting conditions were achieved using 4x100W incandescent lamps above the top landing and the dimmer switch. Lighting illuminance was measured at the top landing, the illuminance levels - with the exception of the distributed lighting condition- typically fell with the lower steps. This was believed to reflect lighting distribution on staircases in domestic environments.

Data Collection

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An 8-camera motion capture system (Qualysis, Gothenburg, Sweden) running at 100Hz was used for data capture and the 6 degree-of-freedom marker model was used [25], the model makes use of 25 retroreflective markers to track the movement of the lower-limb segments in dynamic trials. These are divided into 3 markers on the pelvis, 4 marker-clusters on the two thigh and two shank segments and 3 marker-clusters on the two foot segments. Prior to dynamic trials, a pointer was used to digitise relevant anatomical landmarks to allow definitions of segmental coordinate frames (femoral and tibial epicondyles and the 2nd metatarsal head). In addition, three points at the area of the heel and three points at the area of the toes were digitised to cover the areas of the foot likely to be closest to the stair edge (see Figure S1). The biomechanical model was used to redefine the positions of these points virtually using their relative distances to the markers on the foot segment. The minimum straight-line distance between the stair edge and any one of these points was used for foot clearance measurements [14].

Participants were allowed to ascend and descend the staircase before data collection to familiarise themselves with the laboratory set up. Following familiarisation, participants were asked to ascend and descend the staircase using a self-selected speed without the use of handrails. Participants were also instructed to initiate gait using their right foot, this was to ensure that they were clearing and landing on the same steps with their right, consequently the gait cycles of the right (and left) limbs of all trials and all participants were comparable. Three sets of ascent/descent trials were collected, each set included ascending and descending the staircase under the five lighting conditions. The order of the lighting conditions in each set was randomised

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using a 1-5 random order generator in Microsoft Excel. This gave a total of 30 motion trials to be used for analysis: 3 trials of ascent and 3 trials of descent under each lighting condition.

Data Analysis

Analysis was completed using Visual3D (C-Motion, Germantown, MD) software. The hip joint centre-of-rotation was computed using regression equations [26], the mid-points of the epidondyles and the malleoli markers were used to define the knee and ankle joints centres-of-rotation respectively. Coordinate frames for the pelvis, femurs, tibias and feet were defined and joint rotations were computed using a Cardan sequence of flexion-extension, abduction-adduction and internal-external rotation for the hip, knee and ankle joints [25]. Gait events were identified using an algorithm [27] implemented in Visual3D that makes use of kinematic data. The gait events were adjusted manually when they were identified incorrectly to be in the middle of stance or swing. In which case the events were visually created using the marker data and when the anterior-posterior position of the foot markers indicated an initial contact or a foot off. Temporal and spatial gait parameters, clearance and clearance variability were also computed. Clearance was the absolute minimum distance between the digitised points on the foot and the stair edge [14]. This position may be different between trials and steps, however, it was always one of the toe digitised positions in ascent and one of the heel digitised positions in descent. Clearance variability was the standard deviation between the clearance values from the three trials.

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Analysis was completed for the right side of all participants. In ascent, the right foot initiates gait from the bottom landing of the staircase and lands on the 1st, 3rd, 5th and the top landing of the staircase (Figure 1A). In descent, the right foot initiates gait from the top landing and lands on the 6th, 4th, 2nd and bottom landing of the staircase. The first and last gait cycles were not included in the analysis because the quality of the data was compromised at the top and bottom of the staircase as they were at the extremes of the calibrated capture volume. Table 1 shows the clearance and clearance variability computed for stair ascent and descent. Note that in each gait cycle, the foot clears two step edges before landing. For example, for a right foot gait cycle in ascent initiated at the first step, the foot would have to clear the 2nd step and the 3rd step edge before landing on the 3rd step.

The mean values obtained from the three repeat trials were used in the statistical analysis. Two-factor repeated-measures ANOVA tests were used to investigate differences in clearance and clearance variability, the two factors were the lighting condition and the cleared step number. This was completed separately for stair ascent and descent. Finally, repeated-measures ANOVA tests were also used to investigate differences in maximum, minimum and range of joint rotations and temporal and spatial parameters between the lighting conditions and the significance was set at $p=0.05$. Where significant differences were found, a posthoc test with Bonferroni correction was carried out to find where the differences lay. Because of the repeated design, partial eta squared is reported as an indication of the effect size, where 0.01, 0.06 and 0.14 indicate small, medium and large effect sizes respectively [28].

Results

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Participants

The participants had a mean score of 51 (6) on the BBS out of a maximum of 56. Participants also had a mean score of 84 (17) on the ABC scale and a mean score of 74 (18) on the SSE questionnaire; where 100 indicates complete confidence. All participants except one were able to ascend and descend the stairs without using the handrails. The participant that used the handrails was not relying on the handrails for stability and therefore was included in the analysis. All participants had a good range-of-motion and muscle power in the lower-limb (≥4/5 Oxford Scale). One participant had a reduced range-of-motion and muscle power (3/5 Oxford scale) in the eversion of the right ankle and another participant was using two sticks to balance. A table showing the patients' information, visual and balance assessments and scores in questionnaires have been included as a supplementary data file (see Table S2).

All but one of the participants agreed or strongly agreed with the statement that *the stairs were poorly lit* under the 50lx conditions whilst only one participant agreed with this statement under the 200lx distributed lighting condition. Similarly, four participants disagreed with the statement that *the stairs are safe to use* under the 50lx condition compared to a single participant under the 100lx, 200lx and 200lx distributed lighting conditions, and no participants agreed with this statement under the 300lx lighting condition. A summary of the responses to the questions is shown in Table S1.

Clearance and Clearance Variability

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Table 1 shows the mean and standard deviations for clearance and clearance variability of the first and second cleared steps in ascent and descent. The results show that there was no significant difference in clearance and clearance variability between the different lighting conditions in ascent ($p=0.129$ and $p=0.344$ respectively) and in descent ($p=0.108$ and 0.542 respectively).

In ascent, the mean clearance is generally higher under 50lx lighting with means of 75mm for the first cleared step and 44mm for the second cleared step and lowest under 200lx distributed lighting with means of 68.5mm and 42.5mm. This difference in the mean values appears to be influenced by the results of three participants, thus suggesting that they adopted a precautionary measure when the lighting condition was poor by increasing clearance. However, this trend was not seen with the other participants, thus the difference was not found to be statistically significant.

In descent, there is a trend suggesting an increase in clearance in improved lighting conditions compared to lower lighting conditions. This can be particularly seen in the steps further away from the source of light (S5 and S6), where for example, the clearance is 77mm and 50mm under 200lx distributed lighting compared to 70mm and 48mm for the 50lx. This however, did not reach statistical significance ($p=0.108$).

Temporal and Spatial Parameters

Table 2 shows the mean values for the temporal and spatial parameters in the five lighting conditions and the results of the statistical tests. The results show that there were no significant differences in any of the temporal and spatial

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parameters in ascent. In descent, differences were found in speed ($p<0.001$), cadence ($p<0.001$), cycle time ($p=0.006$), stance time ($p<0.001$) and right step time ($p=0.011$). The results of the posthoc statistical test showed that most of the significant differences were found between 50lx and 300lx and 200lx distributed lighting. Participants had lower speed, lower cadence, longer cycle time and longer stance time in 50lx illuminance level compared to 300lx and 200lx distributed lighting. Significant differences in cadence were also found between 50lx and 200lx; where participants had a lower cadence in 50lx illuminance level.

Kinematics

The mean hip, knee and ankle sagittal plane angles for ascent and descent for the 50lx lighting condition are shown in Figure 2. Table 3 shows the means and standard deviations of the maximum, minimum and range of hip, knee and ankle rotations in stair ascent and descent for all lighting conditions.

Differences were only found in the minimum hip angle in ascent ($p=0.03$). The posthoc test with Bonferroni correction revealed that the 200lx level had a significantly greater minimum hip angle compared to the 300lx during ascent ($p=0.017$).

Discussion

The study presents descriptions of the temporal-spatial parameters and lower-limb kinematics during stair ascent and descent in a group of older individuals with visual impairment under different lighting conditions. The results of the study show that lighting had an effect on the temporal parameters in stair

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descent, participants had a lower speed and cadence and an increased cycle and stance times. On the other hand, in ascent, cadence and speed were comparable across lighting conditions. Lighting had an effect on the minimum hip angle during stair ascent indicating a possible change in movement strategy under different lighting conditions. However, this change was small and did not result in statistically significant differences in clearance or clearance variability in stair ascent and descent. There was also no difference in other hip, knee and ankle kinematic parameters in ascent and descent. Previous studies investigating the effect of lighting on stair negotiation have reported the biomechanical parameters in descent only [14, 15]. Interestingly, the temporal changes seen in descent due to lighting found in this study are not seen in ascent. This is probably because ascent requires more effort than descent and participants were already negotiating the stairs in lower speeds and cadence in ascent.

The results are largely in agreement with those of previous studies that investigated stair negotiation in a group of older people [14, 15]. Hamel et al (2005) and Zietz et al (2011) also found no effect of changing lighting illuminance on clearance in groups of older participants.

Zietz et al (2011) found that different stepping strategies were used by older participants with balance problems compared to older participants with higher balance scores; older participants with compromised balance were found to have reduced clearance and to adjust to differences in stair edge contrast differently to the other older group. Since the primary focus of this study was to focus on patients with visual impairments, no attempts were made to sub-divide the participants according to their balance scores. Interestingly, the

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mean BBS and SSE scores and mean speed found in this study are closer to the scores of the group of participants with compromised balance in the study by Zietz et al (2011). However, the group in this study included a combination of participants with low and high balance scores as evidenced by the high standard deviations. This difference in participants' balance and confidence in negotiating steps could explain why only some of the participants in this study were able to adapt to the reduced lighting by increasing their clearance. In order to confirm this suggested role of balance and confidence in movement, a Pearson's correlation test was carried out between clearance in the dim lighting condition (50lx) and the BBS, SSE and ABC scores, the results reveal a moderate correlation between all three scores and minimum clearance in descent, this correlation is significant for the SSE (r=0.664,p=0.026) and ABC (r=0.620, p=0.042) scores. The results of this analysis reveals that the parameters used to assess safety when negotiating steps, such as clearance, are likely to be associated with the individual's overall ability to balance, this is also in line with the findings of Zietz et al (2011).

In addition to clearance, previous studies have found clearance variability and variability in other gait measures to be important in the assessment of the risk of falling [14, 29]. Lighting was not found to have an effect on this measure in this study.

The most evident changes to gait characteristics were those seen in temporal parameters during stair descent, where participants reduced their speed as a precautionary measure when descending in dimmer lighting conditions. These adaptations have previously been linked to fear of falling [29] and do not necessarily reduce the risk of falling. This is also evident by the absence of a

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statistically significant difference in other parameters linked with the risk of falling, such as clearance and gait variability as previously discussed.

Generally, lower-limb kinematics were not found to change with different lighting conditions. The failure to promote safe stepping by improving risk-related parameters such as clearance are probably due to the inability of the participants to control or alter their movements during ascent and descent; this may be compounded by other factors that affect motor and sensory functions in this population.

This study included patients with visual impairment due to old-age, however, it should be acknowledged that the underlying cause for visual impairment of the participants was either macular degeneration or cataract. The visual disturbances associated with these two conditions are different and therefore it may be argued that patients with these conditions adapt differently to low levels of lighting. However, the focus of this study was to include participants with severe visual impairment, and all patients included here were with severe visual impairment as assessed by the visual acquity scores. Contrast sensitivity was not assessed in this study because it was not believed to be of use in this population. This is because, contrast sensitivity becomes a less powerful measure as the vision gets weaker, especially in patients with macular degeneration. In patients with cataract, contrast sensitivity is important in performing activities of daily living in the face of an otherwise reasonable visual acuity i.e. early cataract, however, this was not the population of interest.

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The lighting conditions tested in this study covers a wide range from a typical poorly lit domestic staircase to an optimised distributed lighting condition unlikely to be available in home environments. However, one of the limitations of this study is that it does not test negotiation of steps in the dark. Previous studies indicate that a number of older people do not use lighting at night [30], the influence of this behavioural risk factor has not been assessed in this study. One reason very low lighting illuminance was not measured in this study is because the participants here had visual impairments and thus were more likely to use lighting when available. The focus of this study was therefore to assess the spectrum of different lighting conditions that are likely to be available in domestic staircases.

In addition to visual input, previous studies have identified kinaesthetic feedback as an important factor in successful negotiation of stairs [31]. The sensory function of the participants included in this study was not tested, and it may be that unidentified losses in their proprioception have also impeded them from using safer stepping strategies. Losses in other muscle strength and flexibility are also likely to play a role in movement control in this population [32].

The experimental setup adopted here could have been affected by habituation, meaning that the participants may have been habituated with the laboratory setup towards the end of the data collection session. To reduce the effect of habituation, the participants were given time to familiarise themselves with the staircase and laboratory surrounding before data collection. A randomisation process was also used to change the test condition after each ascent/descent trial as described in the methods. The study is also limited by

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the small sample size. The repeated design used here as well as the high correlation between the measurements allowed the investigation of the effect of lighting. However, the study would have benefitted from a larger sample size to confirm the results reported in this study.

Future studies should focus on testing multi-component interventions that also address losses in sensory function, muscle strength and balance with a significantly greater number of participants to avoid the limitations encountered here.

Conclusion

The results of this study show that participants with visual impairment are likely to walk more slowly in dimmer lighting conditions, suggesting an increased fear of falling. However, this precautionary behaviour does not necessarily lead to an increase in step clearance. Minimum clearance in negotiating steps in the dim lighting conditions was found to have a moderate positive correlation with the balance scores of this group, suggesting that ability to balance plays a role in negotiating steps safely and thus in the ability to adapt stepping strategies under different lighting conditions.

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ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

References

[1] NICE. Falls: assement and prevention of falls in older people. NICE Clinical Guidelines. 2013;161.

[2] Sheldon J. On the natural history of falls in old age. British Medical Journal. 1960;2:1685.

[3] Lord SR, Sherrington C, Menz HB, Close JC. Falls in older people: risk factors and strategies for prevention. Cambridge: Cambridge University Press; 2007.

[4] Startzell JK, Owens DA, Mulfinger LM, Cavanagh PR. Stair negotiation in older people: a review. Journal of the American Geriatrics Society. 2000;48:567-80.

[5] Lord SR. Visual risk factors for falls in older people. Age and Ageing. 2006;35 Suppl 2:ii42-ii5.

[6] Rubenstein LZ. Falls in older people: epidemiology, risk factors and strategies for prevention. Age and Ageing. 2006;35:ii37-ii41.

[7] Harwood RH. Visual problems and falls. Age and ageing. 2001;30:13-8.

[8] Koski K, Luukinen H, Laippala P, Kivelä S-L. Risk factors for major injurious falls among the home-dwelling elderly by functional abilities. Gerontology. 1998;44:232-8.

[9] Rubenstein LZ, Josephson KR. The epidemiology of falls and syncope. Clinics in Geriatric Medicine. 2002;18:141-58.

[10] Carter SE, Campbell EM, Sanson-Fisher RW, Redman S, Gillespie WJ. Environmental hazards in the homes of older people. Age and Ageing. 1997;26:195-202.

[11] Northridge ME, Nevitt MC, Kelsey JL, Link B. Home hazards and falls in the elderly: the role of health and functional status. American Journal of Public Health. 1995;85:509-15.

[12] Stevens M, Holman CAJ, Bennett N. Preventing falls in older people: impact of an intervention to reduce environmental hazards in the home. Journal of the American Geriatrics Society. 2001;49:1442-7.

[13] Christina KA, Cavanagh PR. Ground reaction forces and frictional demands during stair descent: effects of age and illumination. Gait & Posture. 2002;15:153-8.

[14] Hamel KA, Okita N, Higginson JS, Cavanagh PR. Foot clearance during stair descent: effects of age and illumination. Gait & Posture. 2005;21:135-40.

[15] Zietz D, Johannsen L, Hollands M. Stepping characteristics and Centre of Mass control during stair descent: Effects of age, fall risk and visual factors. Gait & Posture. 2011;34:279-84.

[16] Thies SB, Richardson JK, Ashton-Miller JA. Effects of surface irregularity and lighting on step variability during gait: a study in healthy young and older women. Gait & Posture. 2005;22:26-31.

[17] Lord SR, Clark RD, Webster I. Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age and Ageing. 1991;20:175-81.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[18] Turano K, Rubin GS, Herdman SJ, Chee E, Fried LP. Visual stabilization of posture in the elderly: fallers vs. nonfallers. Optometry & Vision Science. 1994;71:761-9.

[19] Heasley K, Buckley JG, Scally A, Twigg P, Elliott DB. Stepping up to a new level: effects of blurring vision in the elderly. Investigative Ophthalmology & Visual Science. 2004;45:2122-8.

[20] Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. Canadian Journal of Public Health. 1991;83:S7-11.

[21] Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. The Journals of Gerontology Series A, Biological Sciences and Medical Sciences. 1995;50A:M28-34.

[22] Hamel KA, Cavanagh PR. Stair performance in people aged 75 and older. Journal of the American Geriatrics Society. 2004;52:563-7.

[23] Hill L, Haslam R, Howarth PA, Brooke-Wavell KS, Sloane JE. Safety of older people on stairs: behavioural factors. Loughborough : Loughborough University. 2000.

[24] Fisk M, Raynham P. Good Practics Guide No. 5: Good housing design - lighting. A practical guide to improving lighting in existing homes. London: Thomas Pocklington Trust. 2010.

[25] Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. Gait & Posture. 2009;30:173-80.

[26] Davis Iii RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. Human Movement Science. 1991;10:575-87.

[27] Zeni J, Richards J, Higginson J. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait & Posture. 2008;27:710-4.

[28] Richardson JTE. Eta squared and partial eta squared as measures of effect size in educational research. Educational Research Review. 2011;6:135-47.

[29] Maki BE. Gait changes in older adults: predictors of falls or indicators of fear. Journal of the American Geriatrics Society. 1997;45:313-20.

[30] Haslam RA, Sloane J, Hill LD, Brooke-Wavell K, Howarth P. What do older people know about safety on stairs? Ageing and Society. 2001;21:759-76.

[31] Archea J, Collins BL, Stahl FI. Guidelines for stair safety. Washington: U.S. Department of Commerce: Natio[1] NICE. Falls: assement and prevention of falls in older people. NICE Clinical Guidelines. 2013;161.

[2] Sheldon J. On the natural history of falls in old age. British Medical Journal. 1960;2:1685.

[3] Lord SR, Sherrington C, Menz HB, Close JC. Falls in older people: risk factors and strategies for prevention. Cambridge: Cambridge University Press; 2007.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[4] Startzell JK, Owens DA, Mulfinger LM, Cavanagh PR. Stair negotiation in older people: a review. Journal of the American Geriatrics Society. 2000;48:567-80.

[5] Lord SR. Visual risk factors for falls in older people. Age and Ageing. 2006;35 Suppl 2:ii42-ii5.

[6] Rubenstein LZ. Falls in older people: epidemiology, risk factors and strategies for prevention. Age and Ageing. 2006;35:ii37-ii41.

[7] Harwood RH. Visual problems and falls. Age and ageing. 2001;30:13-8.

[8] Koski K, Luukinen H, Laippala P, Kivelä S-L. Risk factors for major injurious falls among the home-dwelling elderly by functional abilities. Gerontology. 1998;44:232-8.

[9] Rubenstein LZ, Josephson KR. The epidemiology of falls and syncope. Clinics in Geriatric Medicine. 2002;18:141-58.

[10] Carter SE, Campbell EM, Sanson-Fisher RW, Redman S, Gillespie WJ. Environmental hazards in the homes of older people. Age and Ageing. 1997;26:195-202.

[11] Northridge ME, Nevitt MC, Kelsey JL, Link B. Home hazards and falls in the elderly: the role of health and functional status. American Journal of Public Health. 1995;85:509-15.

[12] Stevens M, Holman CAJ, Bennett N. Preventing falls in older people: impact of an intervention to reduce environmental hazards in the home. Journal of the American Geriatrics Society. 2001;49:1442-7.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[13] Christina KA, Cavanagh PR. Ground reaction forces and frictional demands during stair descent: effects of age and illumination. Gait & Posture. 2002;15:153-8.

[14] Hamel KA, Okita N, Higginson JS, Cavanagh PR. Foot clearance during stair descent: effects of age and illumination. Gait & Posture. 2005;21:135-40.

[15] Zietz D, Johannsen L, Hollands M. Stepping characteristics and Centre of Mass control during stair descent: Effects of age, fall risk and visual factors. Gait & Posture. 2011;34:279-84.

[16] Thies SB, Richardson JK, Ashton-Miller JA. Effects of surface irregularity and lighting on step variability during gait: a study in healthy young and older women. Gait & Posture. 2005;22:26-31.

[17] Lord SR, Clark RD, Webster I. Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age and Ageing. 1991;20:175-81.

[18] Turano K, Rubin GS, Herdman SJ, Chee E, Fried LP. Visual stabilization of posture in the elderly: fallers vs. nonfallers. Optometry & Vision Science. 1994;71:761-9.

[19] Heasley K, Buckley JG, Scally A, Twigg P, Elliott DB. Stepping up to a new level: effects of blurring vision in the elderly. Investigative Ophthalmology & Visual Science. 2004;45:2122-8.

[20] Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. Canadian Journal of Public Health. 1991;83:S7-11.

ACCEPTED MANUSCRIPT

[21] Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. The Journals of Gerontology Series A, Biological Sciences and Medical Sciences. 1995;50A:M28-34.

[22] Hamel KA, Cavanagh PR. Stair performance in people aged 75 and older. Journal of the American Geriatrics Society. 2004;52:563-7.

[23] Hill L, Haslam R, Howarth PA, Brooke-Wavell KS, Sloane JE. Safety of older people on stairs: behavioural factors. Loughborough : Loughborough University. 2000.

[24] Fisk M, Raynham P. Good Practics Guide No. 5: Good housing design - lighting. A practical guide to improving lighting in existing homes. London: Thomas Pocklington Trust. 2010.

[25] Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. Gait & Posture. 2009;30:173-80.

[26] Davis Iii RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. Hum[1] NICE. Falls: assement and prevention of falls in older people. NICE Clinical Guidelines. 2013;161.

[2] Sheldon J. On the natural history of falls in old age. British Medical Journal. 1960;2:1685.

[3] Lord SR, Sherrington C, Menz HB, Close JC. Falls in older people: risk factors and strategies for prevention. Cambridge: Cambridge University Press; 2007.

ACCEPTED MANUSCRIPT

[4] Startzell JK, Owens DA, Mulfinger LM, Cavanagh PR. Stair negotiation in older people: a review. Journal of the American Geriatrics Society. 2000;48:567-80.

[5] Lord SR. Visual risk factors for falls in older people. Age and Ageing. 2006;35 Suppl 2:ii42-ii5.

[6] Rubenstein LZ. Falls in older people: epidemiology, risk factors and strategies for prevention. Age and Ageing. 2006;35:ii37-ii41.

[7] Harwood RH. Visual problems and falls. Age and ageing. 2001;30:13-8.

[8] Koski K, Luukinen H, Laippala P, Kivelä S-L. Risk factors for major injurious falls among the home-dwelling elderly by functional abilities. Gerontology. 1998;44:232-8.

[9] Rubenstein LZ, Josephson KR. The epidemiology of falls and syncope. Clinics in Geriatric Medicine. 2002;18:141-58.

[10] Carter SE, Campbell EM, Sanson-Fisher RW, Redman S, Gillespie WJ. Environmental hazards in the homes of older people. Age and Ageing. 1997;26:195-202.

[11] Northridge ME, Nevitt MC, Kelsey JL, Link B. Home hazards and falls in the elderly: the role of health and functional status. American Journal of Public Health. 1995;85:509-15.

[12] Stevens M, Holman CAJ, Bennett N. Preventing falls in older people: impact of an intervention to reduce environmental hazards in the home. Journal of the American Geriatrics Society. 2001;49:1442-7.

ACCEPTED MANUSCRIPT

[13] Christina KA, Cavanagh PR. Ground reaction forces and frictional demands during stair descent: effects of age and illumination. Gait & Posture. 2002;15:153-8.

[14] Hamel KA, Okita N, Higginson JS, Cavanagh PR. Foot clearance during stair descent: effects of age and illumination. Gait & Posture. 2005;21:135-40.

[15] Zietz D, Johannsen L, Hollands M. Stepping characteristics and Centre of Mass control during stair descent: Effects of age, fall risk and visual factors. Gait & Posture. 2011;34:279-84.

[16] Thies SB, Richardson JK, Ashton-Miller JA. Effects of surface irregularity and lighting on step variability during gait: a study in healthy young and older women. Gait & Posture. 2005;22:26-31.

[17] Lord SR, Clark RD, Webster I. Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age and Ageing. 1991;20:175-81.

[18] Turano K, Rubin GS, Herdman SJ, Chee E, Fried LP. Visual stabilization of posture in the elderly: fallers vs. nonfallers. Optometry & Vision Science. 1994;71:761-9.

[19] Heasley K, Buckley JG, Scally A, Twigg P, Elliott DB. Stepping up to a new level: effects of blurring vision in the elderly. Investigative Ophthalmology & Visual Science. 2004;45:2122-8.

[20] Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. Canadian Journal of Public Health. 1991;83:S7-11.

ACCEPTED MANUSCRIPT

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[21] Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. The Journals of Gerontology Series A, Biological Sciences and Medical Sciences. 1995;50A:M28-34.

[22] Hamel KA, Cavanagh PR. Stair performance in people aged 75 and older. Journal of the American Geriatrics Society. 2004;52:563-7.

[23] Hill L, Haslam R, Howarth PA, Brooke-Wavell KS, Sloane JE. Safety of older people on stairs: behavioural factors. Loughborough : Loughborough University. 2000.

[24] Fisk M, Raynham P. Good Practics Guide No. 5: Good housing design - lighting. A practical guide to improving lighting in existing homes. London: Thomas Pocklington Trust. 2010.

[25] Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. Gait & Posture. 2009;30:173-80.

[26] Davis Iii RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. Human Movement Science. 1991;10:575-87.

[27] Zeni J, Richards J, Higginson J. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait & Posture. 2008;27:710-4.

[28] Richardson JTE. Eta squared and partial eta squared as measures of effect size in educational research. Educational Research Review. 2011;6:135-47.

ACCEPTED MANUSCRIPT

[29] Maki BE. Gait changes in older adults: predictors of falls or indicators of fear. Journal of the American Geriatrics Society. 1997;45:313-20.

[30] Haslam RA, Sloane J, Hill LD, Brooke-Wavell K, Howarth P. What do older people know about safety on stairs? Ageing and Society. 2001;21:759-76.

[31] Archea J, Collins BL, Stahl FI. Guidelines for stair safety. Washington: U.S. Department of Commerce: National Bureau of Standards; 1979.

[32] Kang HG, Dingwell JB. Separating the effects of age and walking speed on gait variability. Gait & Posture. 2008;27:572-7.

an Movement Science. 1991;10:575-87.

[27] Zeni J, Richards J, Higginson J. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait & Posture. 2008;27:710-4.

[28] Richardson JTE. Eta squared and partial eta squared as measures of effect size in educational research. Educational Research Review. 2011;6:135-47.

[29] Maki BE. Gait changes in older adults: predictors of falls or indicators of fear. Journal of the American Geriatrics Society. 1997;45:313-20.

[30] Haslam RA, Sloane J, Hill LD, Brooke-Wavell K, Howarth P. What do older people know about safety on stairs? Ageing and Society. 2001;21:759-76.

ACCEPTED MANUSCRIPT

[31] Archea J, Collins BL, Stahl FI. Guidelines for stair safety. Washington: U.S. Department of Commerce: National Bureau of Standards; 1979.

[32] Kang HG, Dingwell JB. Separating the effects of age and walking speed on gait variability. Gait & Posture. 2008;27:572-7.

nal Bureau of Standards; 1979.

[32] Kang HG, Dingwell JB. Separating the effects of age and walking speed on gait variability. Gait & Posture. 2008;27:572-7.

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Figure 1: A- Showing 7-step staircase in the Movement Laboratory and the lighting configuration. B – Participant with reflective markers attached to the lower-limb and pelvis descending the staircase.

Figure 2: Rotations of the hip, knee and ankle rotation angles in the sagittal plane during one cycle of stair ascent and stair descent under the low-illuminance lighting condition (50lx).

Figure S1: Showing the digitised positions in the heel and toe areas of the shoe used in the computation of clearance. The points cover the areas of the toe and heel closest to the stair edge in ascend and descend.

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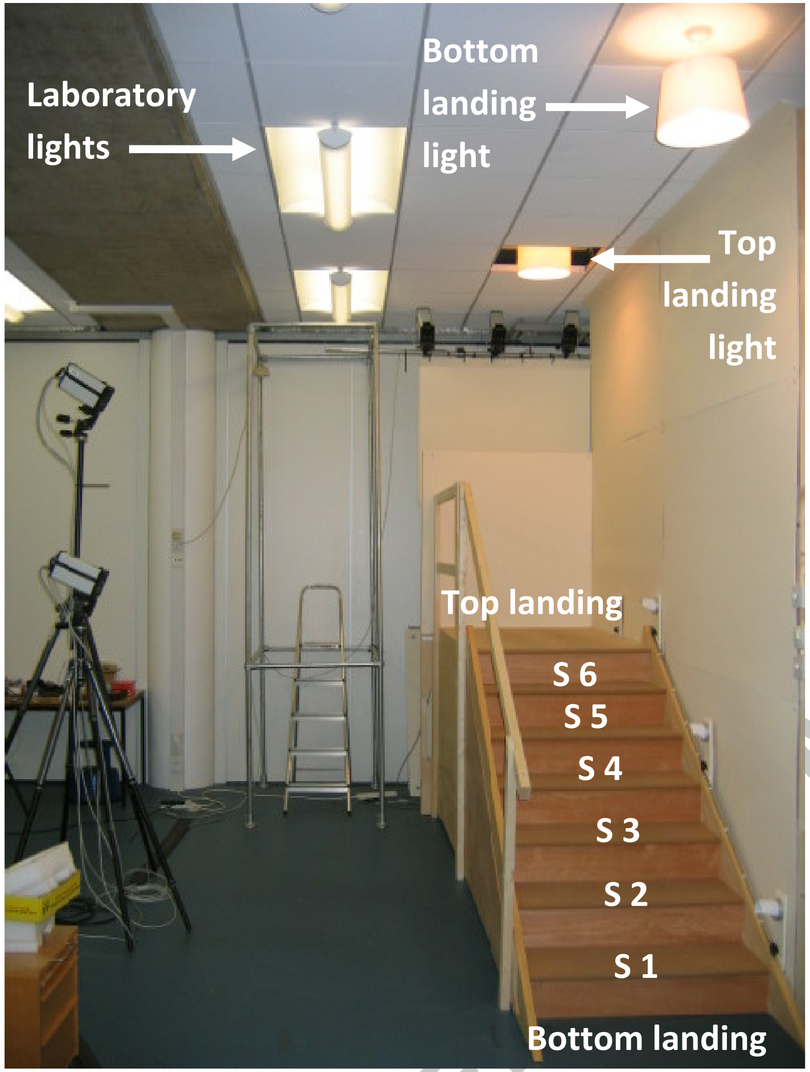
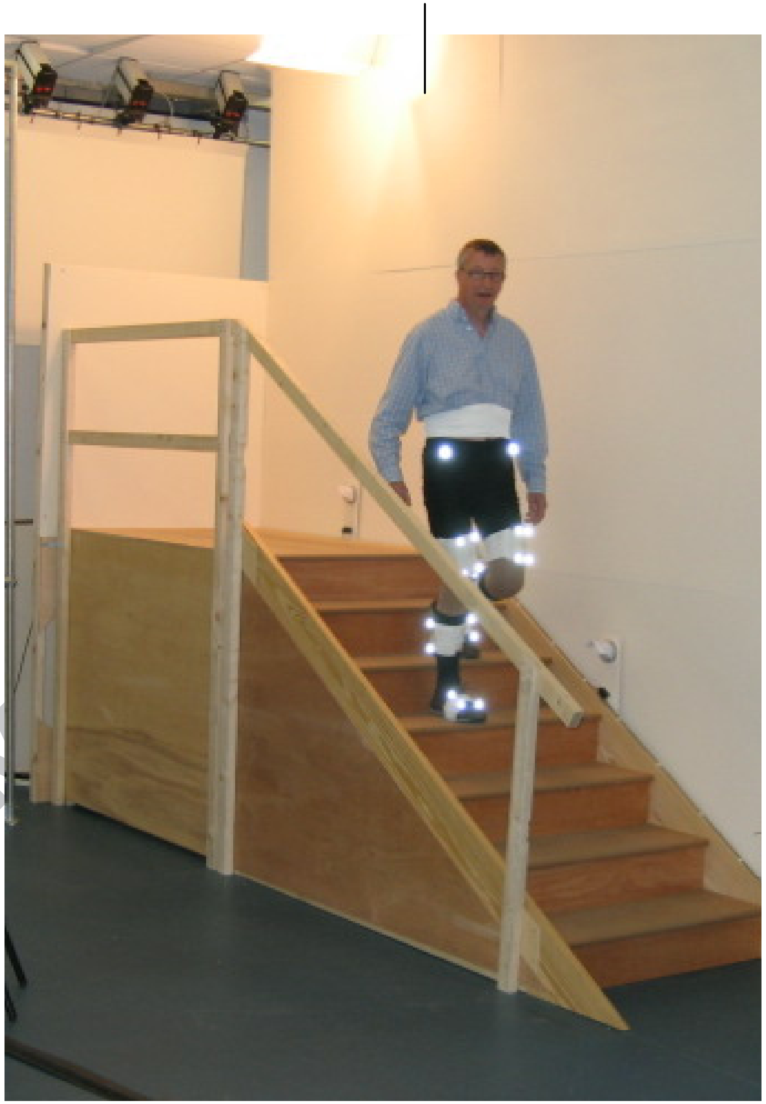


A



B

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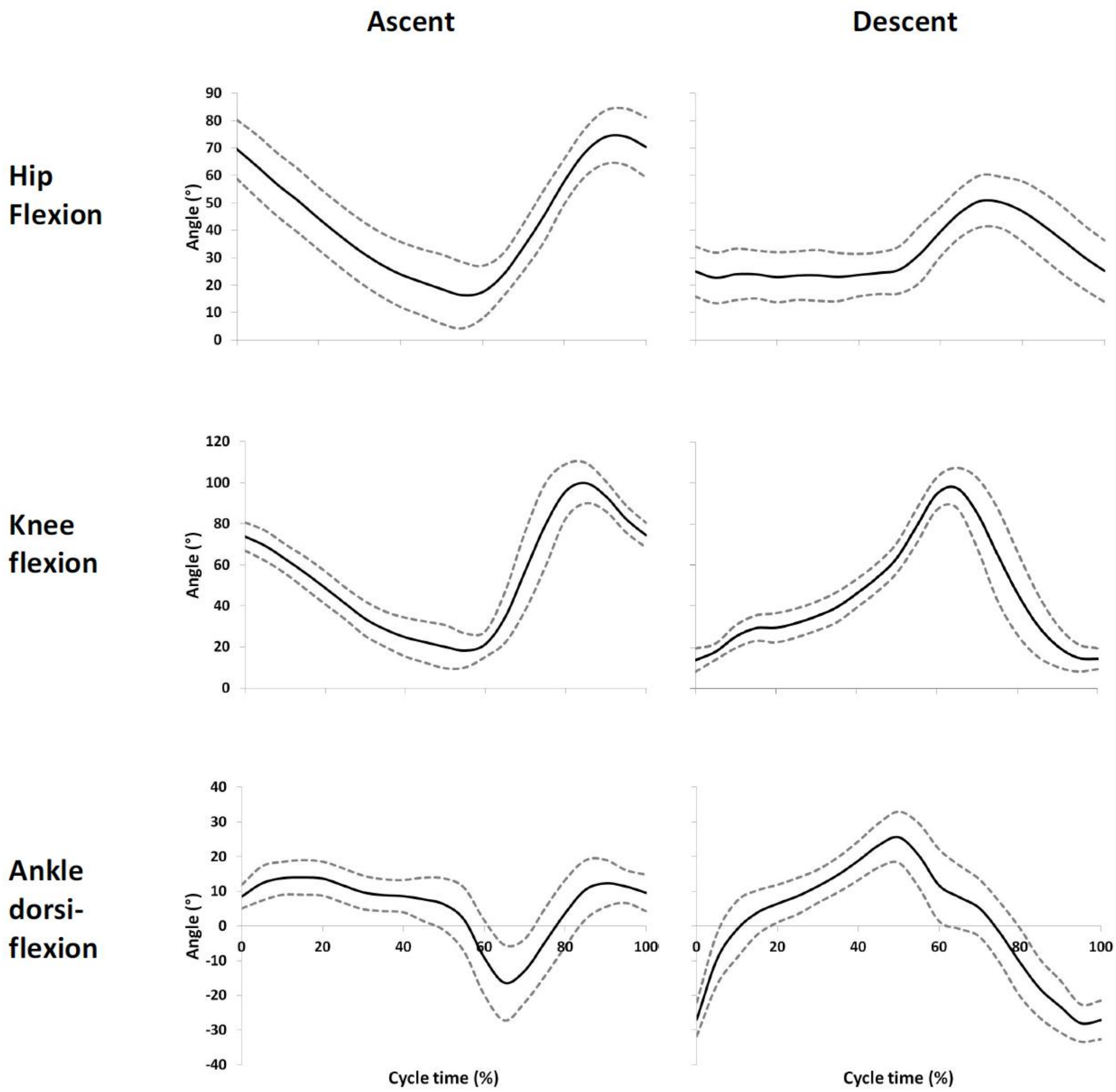

Showing mean values ± 1 standard deviation

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Table 1: Clearance and clearance variability for the cleared steps under the five lighting conditions in stair ascent and descent. The reported p-values are of the two-factor repeated ANOVA tests comparing clearance and clearance variability under the 5 lighting conditions for the 4 steps in ascent and in the 4 steps in descent, significance level is set at p=0.05.

ASCENT									
Lighting / Steps	50lx Mean (SD)	100lx Mean (SD)	200lx Mean (SD)	300lx Mean (SD)	200lx distributed Mean (SD)	Lighting		Lighting*step	
						p-value	η_p^2	p-value	η_p^2
	Clearance (mm)					0.129	0.193	0.726	0.045
1st cleared step									
S2	75 (34)	67 (26)	70 (22)	69 (20)	65 (25)				
S4	75 (29)	66 (25)	67 (20)	66 (22)	66 (21)				
2nd cleared step									
S3	45 (16)	42 (12)	43 (14)	42 (10)	38 (13)				
S5	43 (17)	39 (11)	42 (13)	38 (12)	37 (11)				
	Clearance Variability (mm)					0.344	0.093	0.533	0.068
1st cleared step									
S2	17 (22)	12 (6)	9 (4)	8 (6)	11 (6)				
S4	17 (23)	11 (4)	11 (8)	7 (5)	9 (6)				

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2nd cleared step **S3** **S5**	10 (16) 10 (12)	9 (4) 6 (5)	9 (9) 8 (8)	6 (5) 5 (5)	7 (4) 5 (2)				
DESCENT									
	Clearance (mm)					0.108	0.169	0.404	0.093
1st cleared step **S6** **S4**	70 (27) 71 (29)	73 (29) 70 (33)	74 (25) 74 (30)	75 (30) 71 (34)	77 (26) 76 (31)				
2nd cleared step **S5** **S3**	48 (28) 48 (25)	46 (26) 44 (24)	45 (22) 44 (26)	50 (22) 46 (23)	50 (19) 48 (24)				
	Clearance Variability (mm)					0.542	0.059	0.105	0.164
1st cleared step **S6** **S4**	12 (6) 9 (3)	8 (5) 8 (5)	11 (6) 9 (4)	11 (8) 8 (9)	11 (7) 7 (6)				

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2nd cleared step **S5** **S3**	11 (8) 9 (7)	9 (5) 11 (5)	6 (3) 5 (4)	9 (9) 6 (8)	9 (5) 10 (5)				

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Table 2: Temporal and spatial parameters under the five lighting conditions and the p-values of the statistical tests for stair ascent and descent, significance level is set at p=0.05.

Temporal-spatial parameters \ Lighting	50lx Mean (SD)	100lx Mean (SD)	200lx Mean (SD)	300lx Mean (SD)	200lx distributed Mean (SD)	Lighting p-value	Lighting η_p^2
ASCENT							
Speed (m/s)	0.54 (0.10)	0.54 (0.11)	0.54 (0.11)	0.54 (0.11)	0.54 (0.11)	0.807	0.039
Cadence (steps/min)	91.0 (16.0)	89.6 (15.7)	90.1 (16.5)	90.3 (16.6)	90.8 (16.9)	0.637	0.060
Cycle time (s)	1.41 (0.33)	1.41 (0.29)	1.42 (0.34)	1.41 (0.31)	1.42 (0.36)	0.959	0.004
Stance time (s)	0.90 (0.27)	0.90 (0.24)	0.90 (0.26)	0.90 (0.26)	0.92 (0.31)	0.707	0.238
Swing time (s)	0.49 (0.07)	0.49 (0.07)	0.49 (0.10)	0.49 (0.07)	0.48 (0.08)	0.698	0.052
Double support time (s)	0.41 (0.22)	0.41 (0.18)	0.41 (0.20)	0.43 (0.21)	0.43 (0.24)	0.309	0.110
Right step time (s)	0.69 (0.16)	0.70 (0.14)	0.70 (0.18)	0.70 (0.17)	0.70 (0.18)	0.767	0.027
Stride length (m)	0.73 (0.02)	0.74 (0.03)	0.74 (0.03)	0.73 (0.03)	0.73 (0.03)	0.280	0.117
Stride width (m)	0.12 (0.04)	0.12 (0.04)	0.13 (0.04)	0.13 (0.04)	0.13 (0.04)	0.492	0.066
DESCENT							
Speed (m/s)	0.54 (0.14)	0.56 (0.15)	0.56 (0.15)	0.58 (0.15)	0.57 (0.15)	**<0.001**	0.419
Cadence (steps/min)	88.6 (21.1)	92.7 (22.5)	93.4 (22.9)	97.4 (22.0)	95.4 (22.6)	**<0.001**	0.431
Cycle time (s)	1.49 (0.53)	1.45 (0.52)	1.44 (0.53)	1.37 (0.50)	1.39 (0.51)	**0.006**	0.409
Stance time (s)	0.92 (0.35)	0.90 (0.37)	0.90 (0.35)	0.85 (0.33)	0.84 (0.32)	**<0.001**	0.411
Swing time (s)	0.59 (0.21)	0.58 (0.20)	0.58 (0.22)	0.55 (0.17)	0.56 (0.18)	0.124	0.185
Double support time (s)	0.31 (0.15)	0.26 (0.12)	0.27 (0.12)	0.26 (0.11)	0.27 (0.14)	0.140	0.183
Right step time (s)	0.74 (0.25)	0.71 (0.25)	0.71 (0.27)	0.67(0.22)	0.69 (0.27)	**0.011**	0.274
Stride length (m)	0.74 (0.02)	0.74 (0.03)	0.74 (0.04)	0.74 (0.03)	0.73 (0.03)	0.822	0.037
Stride width (m)	0.14 (0.04)	0.15 (0.05)	0.15 (0.04)	0.15 (0.04)	0.15 (0.04)	0.376	0.098

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Table 3: Maximum, minimum and ranges of hip, knee and ankle rotations under the five lighting conditions and the p-values of the statistical tests for stair ascent and descent, significance level is set at p=0.05.

Joint	Lighting	50lx Mean (SD)	100lx Mean (SD)	200lx Mean (SD)	300lx Mean (SD)	200lx distributed Mean (SD)	Lighting p-value	Lighting η_p^2
ASCENT								
Hip	**Maximum (°)**	75.2 (9.9)	74.7 (10.3)	76.1 (9.8)	75.4 (10.5)	74.3 (9.6)	0.097	0.174
	Minimum (°)	13.6 (10.6)	14.8 (11.1)	15.6 (12.1)	13.1 (11.1)	13.9 (10.3)	**0.030***	0.297
	Range (°)	61.6 (5.6)	59.9 (5.0)	60.5 (5.8)	62.2 (5.4)	60.4 (5.0)	0.102	0.172
Knee	**Maximum (°)**	101.4 (9.1)	101.6 (9.1)	102.1 (8.3)	101.2 (8.9)	100.6 (10.1)	0.581	0.067
	Minimum (°)	14.3 (7.6)	14.0 (7.6)	14.7 (6.5)	14.3 (7.4)	14.6 (7.1)	0.925	0.022
	Range (°)	87.1 (5.8)	87.6 (6.3)	87.4 (6.5)	86.9 (5.1)	86.0 (7.3)	0.486	0.067
Ankle	**Maximum (°)**	17.9 (4.8)	17.8 (4.6)	17.5 (3.9)	18.0 (4.7)	18.6 (5.3)	0.663	0.057
	Minimum (°)	-21.9 (7.5)	-22.3 (8.4)	-22.8 (6.1)	-21.6 (7.0)	-22.3 (7.1)	0.543	0.073
	Range (°)	39.7 (7.0)	40.2 (6.8)	40.3 (6.5)	39.7 (6.6)	40.9 (7.9)	0.731	0.048
DESCENT								
Hip	**Maximum (°)**	52.8 (10.1)	51.4 (10.5)	52.1 (9.4)	52.3 (9.9)	51.3 (9.9)	0.087	0.180
	Minimum (°)	19.8 (9.0)	19.4 (9.4)	20.2 (9.8)	20.3 (8.7)	20.1 (9.0)	0.693	0.053
	Range (°)	32.9 (4.3)	32.0 (4.9)	31.9 (4.3)	32.0 (3.5)	31.2 (4.1)	0.290	0.116
Knee	**Maximum (°)**	101.8 (8.2)	101.2 (7.9)	101.3 (8.0)	101.1 (7.8)	101.0 (7.9)	0.670	0.056
	Minimum (°)	12.1 (6.2)	11.7 (5.5)	12.4 (4.8)	12.8 (4.6)	12.7 (5.2)	0.209	0.133
	Range (°)	89.8 (6.0)	89.5 (6.0)	88.9 (5.7)	88.3 (5.6)	88.3 (7.0)	0.317	0.109
Ankle	**Maximum (°)**	27.9 (6.5)	28.2 (6.7)	28.4 (6.3)	28.2 (6.1)	28.0 (6.5)	0.620	0.062
	Minimum (°)	-31.4 (4.4)	-21.8 (4.5)	-31.3 (4.7)	-31.8 (4.1)	-31.4 (4.9)	0.556	0.071
	Range (°)	59.2 (7.6)	59.9 (7.8)	59.7 (7.8)	60.0 (7.4)	59.4 (8.2)	0.404	0.088

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Authors Bio

Aliah F Shaheen is a Senior Lecturer in Biomechanics at Brunel University London. Prior to that, she was a Lecturer in the Centre for Biomedical Engineering at the University of Surrey where this work was conducted. Her research interests are in the areas of movement and structural variability and their role in function with applications in upper limb biomechanics, ageing and more recently, animal locomotion.

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Khim Horton is a Registered Nurse and previously a Senior Lecturer and Lead in Care of Older People at the University of Surrey. Dr Khim Horton is now an Independent Consultant and Researcher, Care of Older People. She is also an Honorary Senior Lecturer at the City University, London.

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David Gould is and has been an Electronics Technician in the Biomedical Engineering Group in the University of Surrey for twenty years following a previous period as an Aircraft Instrument Technician. He designs and builds circuits, apparatus and structures for projects within the Biomedical Engineering Group.

Salim Ghoussayni completed his MSc and PhD degrees in Biomedical Engineering at the University of Surrey. He has been involved in numerous projects focused on technologies for the measurement of human movement and interventions for neurological rehabilitation, such as functional electrical stimulation and novel applications of biofeedback and virtual reality.

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Conflict of Interest

No conflicts of interest

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