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

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1 **Title page**

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

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23 **Abstract**

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

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

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

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

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

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52 and social burden. Deterioration of the visual system amongst other factors
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55 illuminance on stair negotiation performance in a group of older individuals
56 with visual impairment.

57 *Methods:* Eleven participants aged 60 or over with a vision of 6/18 or worse
58 ascended and descended a staircase under five lighting conditions: 50lx,
59 100lx, 200lx, in 300lx and distributed 200lx lighting. A motion capture system
60 was used to measure movements of the lower limb. Clearance, clearance
61 variability, temporal and spatial parameters and joint/segment kinematics
62 were computed.

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

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

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

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74 **Introduction**

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

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

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

94 Previous studies investigating the effects of lighting luminance levels on stair
95 negotiation have looked at effects on ground reaction forces [13], minimum
96 foot clearance and clearance variability [14, 15], temporal spatial parameters
97 [16] and centre-of-mass progression [15]. In low lighting conditions, older

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

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

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

116 **Methods**

117 *Participants*

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

121 power of 0.8 with a significance level of 0.05. The effect size was estimated to
122 be 0.25 and the correlation amongst repeated measures was estimated to be
123 0.80 based on the results obtained from a pilot study.

124 Eleven participants (seven males) with a mean age of 78 (6) years consented
125 to taking part in the study and signed a consent form. Participants were
126 included in the study if they were: 1) aged 60 or over, 2) partially sighted due
127 to macular degeneration or advanced cataract caused by old-age, all patients
128 with macular degeneration had a vision of 6/18 or worse and 3) able to
129 negotiate stairs using a step-over-step strategy. Participants were excluded if
130 they: 1) had a muscular or neurological condition or impairment that affected
131 or limited their gait or 2) had a diagnosed vestibular disorder. In addition, a
132 clinician assessed the participants' lower-limb joints (hip, knee and ankle)
133 range of motion, lower-limb muscle power and mobility and used Berg
134 Balance Score (BBS) [20], participants were excluded if they displayed
135 reduced balance caused by dizziness. The activities-specific balance
136 confidence scale (ABC) [21] and the stair self-efficacy questionnaire (SSE)
137 [22] were also completed by the participants. Participants also completed
138 questionnaires on the use of the laboratory stairs and the lighting conditions.
139 Participants were asked if they thought the stairs were poorly lit and if the
140 stairs were safe to use (see Table S1).

141 *Laboratory Setup and Lighting Configurations*

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

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

147 An array of 4x100W incandescent lamps were used on the top landing of the
148 staircase, a 200W lamp was used at the bottom landing of the stairs in
149 addition to laboratory lights and diffusers (Figure 1A). A dimmer switch control
150 was used to allow adjustment of lighting conditions and a light meter
151 (ISOTECH, England) was used to measure illuminance levels from the top
152 landing. This configuration was used to achieve five lighting conditions; low
153 illuminance 50lx, sub-optimal lighting 100lx, optimal lighting 200lx, increased
154 illuminance 300lx and distributed 200lx lighting. The poorest lighting condition
155 used in this study (50lx) was based on the findings of the study by Hill et al
156 (2000), which surveyed 150 older people's households and found that more
157 than 60% of these had lighting of 50lx or less during the day [23]. Optimal
158 lighting was defined as an illuminance of 200lx based on the
159 recommendations of Thomas Pocklington Housing Guide [24].

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

168 *Data Collection*

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

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

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

197 *Data Analysis*

198 Analysis was completed using Visual3D (C-Motion, Germantown, MD)
199 software. The hip joint centre-of-rotation was computed using regression
200 equations [26], the mid-points of the epicondyles and the malleoli markers
201 were used to define the knee and ankle joints centres-of-rotation respectively.
202 Coordinate frames for the pelvis, femurs, tibias and feet were defined and
203 joint rotations were computed using a Cardan sequence of flexion-extension,
204 abduction-adduction and internal-external rotation for the hip, knee and ankle
205 joints [25]. Gait events were identified using an algorithm [27] implemented in
206 Visual3D that makes use of kinematic data. The gait events were adjusted
207 manually when they were identified incorrectly to be in the middle of stance or
208 swing. In which case the events were visually created using the marker data
209 and when the anterior-posterior position of the foot markers indicated an initial
210 contact or a foot off. Temporal and spatial gait parameters, clearance and
211 clearance variability were also computed. Clearance was the absolute
212 minimum distance between the digitised points on the foot and the stair edge
213 [14]. This position may be different between trials and steps, however, it was
214 always one of the toe digitised positions in ascent and one of the heel
215 digitised positions in descent. Clearance variability was the standard deviation
216 between the clearance values from the three trials.

217 Analysis was completed for the right side of all participants. In ascent, the
218 right foot initiates gait from the bottom landing of the staircase and lands on
219 the 1st, 3rd, 5th and the top landing of the staircase (Figure 1A). In descent,
220 the right foot initiates gait from the top landing and lands on the 6th, 4th, 2nd
221 and bottom landing of the staircase. The first and last gait cycles were not
222 included in the analysis because the quality of the data was compromised at
223 the top and bottom of the staircase as they were at the extremes of the
224 calibrated capture volume. Table 1 shows the clearance and clearance
225 variability computed for stair ascent and descent. Note that in each gait cycle,
226 the foot clears two step edges before landing. For example, for a right foot
227 gait cycle in ascent initiated at the first step, the foot would have to clear the
228 2nd step and the 3rd step edge before landing on the 3rd step.

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

241 Results

242 *Participants*

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

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

264 *Clearance and Clearance Variability*

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

271 In ascent, the mean clearance is generally higher under 50lx lighting with
272 means of 75mm for the first cleared step and 44mm for the second cleared
273 step and lowest under 200lx distributed lighting with means of 68.5mm and
274 42.5mm. This difference in the mean values appears to be influenced by the
275 results of three participants, thus suggesting that they adopted a
276 precautionary measure when the lighting condition was poor by increasing
277 clearance. However, this trend was not seen with the other participants, thus
278 the difference was not found to be statistically significant.

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

285 *Temporal and Spatial Parameters*

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

289 parameters in ascent. In descent, differences were found in speed ($p<0.001$),
290 cadence ($p<0.001$), cycle time ($p=0.006$), stance time ($p<0.001$) and right step
291 time ($p=0.011$). The results of the posthoc statistical test showed that most of
292 the significant differences were found between 50lx and 300lx and 200lx
293 distributed lighting. Participants had lower speed, lower cadence, longer cycle
294 time and longer stance time in 50lx illuminance level compared to 300lx and
295 200lx distributed lighting. Significant differences in cadence were also found
296 between 50lx and 200lx; where participants had a lower cadence in 50lx
297 illuminance level.

298 *Kinematics*

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

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

307 **Discussion**

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

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

326 The results are largely in agreement with those of previous studies that
327 investigated stair negotiation in a group of older people [14, 15]. Hamel et al
328 (2005) and Zietz et al (2011) also found no effect of changing lighting
329 illuminance on clearance in groups of older participants.

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

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

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

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

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

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

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

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

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

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

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

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

418 **Conclusion**

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

427

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680

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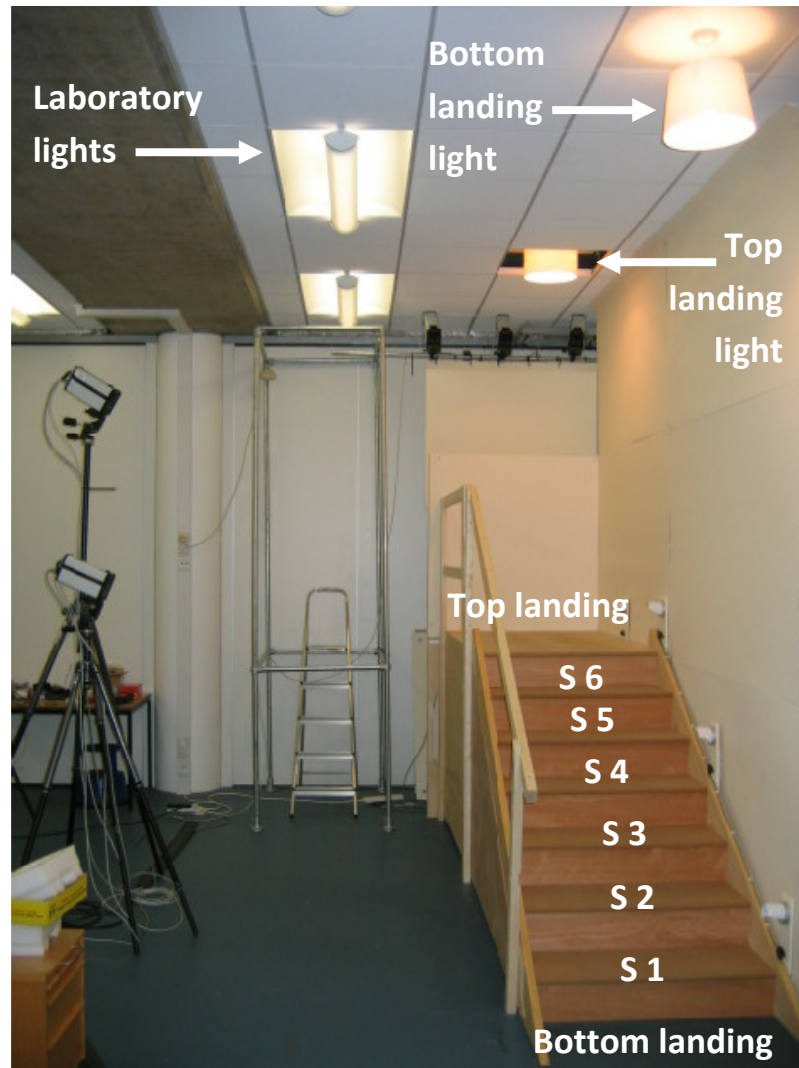
681 Figure 1: A- Showing 7-step staircase in the Movement Laboratory and the
682 lighting configuration. B – Participant with reflective markers attached to the
683 lower-limb and pelvis descending the staircase.

684

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

688

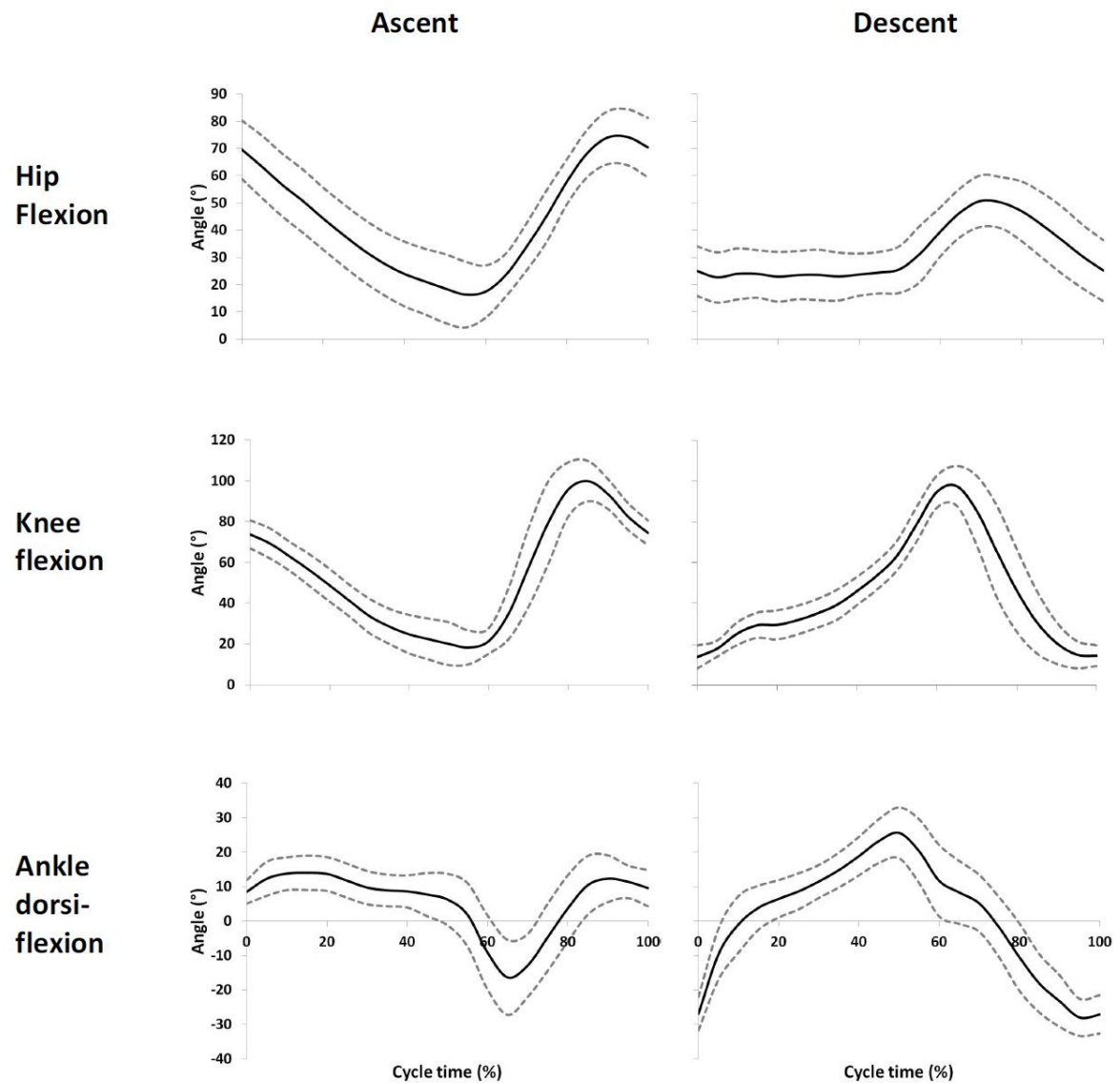
689 Figure S1: Showing the digitised positions in the heel and toe areas of the
690 shoe used in the computation of clearance. The points cover the areas of the
691 toe and heel closest to the stair edge in ascend and descend.



A



B



Showing mean values \pm 1 standard deviation

ACCV

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

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

2nd cleared step									
S5	11 (8)	9 (5)	6 (3)	9 (9)	9 (5)				
S3	9 (7)	11 (5)	5 (4)	6 (8)	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 $p=0.05$.

ASCENT							
Lighting Temporal- spatial parameters	50lx	100lx	200lx	300lx	200lx distributed	Lighting	
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	p-value	η_p^2
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

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		ASCENT					Lighting	
		50lx Mean (SD)	100lx Mean (SD)	200lx Mean (SD)	300lx Mean (SD)	200lx distributed Mean (SD)	p-value	η_p^2
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

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.

Alexandros Sourlas is a Sales Manager at Dentegris Hellas, a company working with dental equipment and dental implants. Prior to this, he spent one year in Germany as an intern working with orthopaedic prosthetics. He was employed as a research assistant at the University of Surrey when he worked on this project. He holds a BEng in Medical Engineering from Cardiff University and an MSc in Biomedical Engineering from the University of Surrey.

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.

Christopher McLean is a Consultant Ophthalmologist based at the Royal Surrey County Hospital Guildford. His primary medical degree was from Imperial College London and he is a Fellow of the Royal College of Ophthalmologists. His areas of specialism are in cataract surgery, oculoplastics and lacrimal surgery. He is a trainer in ophthalmic surgery for the Royal college of Ophthalmologists.

David Ewins is a Consultant Clinical Scientist at Queen Mary's Hospital, Roehampton, London and a Professorial Research Fellow at the University of Surrey. His clinical and research expertise is in movement analysis and functional electrical stimulation.

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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