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1 **Alternate stair descent strategies for reducing joint moment demands in older individuals**

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## 22 **Abstract**

23 Descending stairs requires elevated joint moment-generating capability in the lower limbs,  
24 making it a challenging daily activity, particularly for older individuals. The aim of the study  
25 was to investigate the influence of three different strategies for descending standard and  
26 increased height stairs: step-over-step (SoS), step-by-step (SbS) and side-step (SS) on lower  
27 limb kinetics in older people. Eleven participants (mean  $\pm$  SD age: 74.8 $\pm$ 3.1 years, height:  
28 1.63 $\pm$ 0.07 m, mass: 67.7 $\pm$ 9.5 kg) descended a four-step custom built instrumented staircase at  
29 a self-selected speed, adopting each of the three strategies, at two configurations: a step-rise  
30 height of 170mm (standard; STD) and a step-rise height of 255mm (increased; INC). 3D  
31 motion capture, synchronised with embedded force plates enabled the calculation of joint  
32 kinetics of lead and trail limbs. Data were analysed using a Linear Mixed Model with gait speed  
33 selected as a covariate during weight acceptance (WA) and controlled lowering (CL) phases.  
34 A large increase in hip extensor moment in both WA and CL in the lead limb was evident  
35 during both SoS and SbS at INC step height compared to STD ( $P < .015$  for all), with no such  
36 increase in hip flexor moment evident in SS strategy ( $P = .519$ ). Lead limb knee extensor  
37 moment decreased and plantarflexor moment increased in INC SoS compared to STD SoS  
38 during CL ( $P < .001$  for both). In the trail limb, increased hip extensor and plantarflexor  
39 moments were seen in INC SS compared to STD SS ( $P < .001$  for both). The alternate strategies  
40 result in the overall task demand being split between the lead limb (weight acceptance) and  
41 trail limb (controlled lowering). Differential demand distribution patterns exist between  
42 strategies that imply targeted interventions and/or advice could be provided to older individuals  
43 in order to promote safe descent of stairs, particularly for those with specific muscle  
44 weaknesses or at high risk of falls.

## 45 **Introduction**

46 Stair descent can be a hazardous activity for those lacking the necessary musculoskeletal  
47 capacity to accomplish this demanding task. Approximately 70% of community-reported falls  
48 occur in the home, with 10% of those falls occurring on stairs (Soriano et al., 2007), which can  
49 have drastic consequences; not only on the financial burden to health services (Carey & Laffoy,  
50 2005), but also on the subsequent personal impact on quality of life and independence  
51 (Bialoszewski et al., 2008).

52

53 The demands placed on the lower limbs during stair descent are much greater than that of level  
54 gait (Hamel et al., 2005; Nadeau et al., 2003) with substantial eccentric forces generated by the  
55 ankle and knee extensor muscles of the leading limb during weight acceptance and by the knee  
56 extensor muscles of the trailing limb during controlled lowering, to control the downwards  
57 momentum of the centre of mass. Given the age-associated declines in strength and physical  
58 function (Clark et al., 2013; Guralnik et al., 1995; Hairi et al., 2010; Raj et al., 2010), it follows  
59 that older people have to work close to their maximum strength capacity at their ankles and  
60 knees when performing this task (Reeves et al., 2008a; Samuel et al., 2011). This places the  
61 older population at a much higher risk of falls, particularly when the demand of the task  
62 increases; for example when muscle strength declines further, or when the dimensions of the  
63 staircase change i.e. the height of the step increases; which has previously been shown to  
64 increase kinematic and kinetic demands in younger adults (Spanjaard et al., 2008). Given that  
65 older individual and public dwellings may not comply with post-2010 regulations governing  
66 stair design (Government, 2010) and that older individuals negotiate staircases differently to  
67 their younger counterparts (Reeves et al., 2008a), this population may require additional  
68 support, advice and/or rehabilitation in order to safely negotiate such staircases.

69

70 The effects of potential mechanisms or strategies which older people could adopt to ensure  
71 safer stair negotiation have been sparsely investigated. Reid et al., (2011) reported that centre  
72 of pressure velocity (COPv) was comparable in older and younger individuals with and without  
73 handrail use. However, older adults with a fear of falling had a reduced COPv without handrails  
74 which reduced further when handrails were used indicating the use of handrails provides  
75 additional dynamic stability. In a similar study, Reeves et al., (2008b) explored the impact of  
76 light handrail use on lower limb kinetics and kinematics and identified a redistribution of joint  
77 moment away from the knee extensors and towards the ankle plantarflexors in older  
78 individuals. Despite this increased demand on a smaller and weaker muscle group (Morse et  
79 al., 2005), the relative falls risk would be reduced by the additional points of contact (two hands  
80 in contact with the handrail) enabling a more effective dynamic balance control strategy to be  
81 adopted. Reid et al., (2007) explored the impact of an alternate stair negotiation strategy (i.e.  
82 not a traditional step-over-step manner) on knee function in young, healthy adults and revealed  
83 reductions in sagittal plane knee moments in both the trailing and leading limbs during weight  
84 acceptance and markedly reduced knee moment during controlled lowering in the leading limb.  
85 However, given that older individuals typically redistribute joint moments towards the knee in  
86 comparison to younger adults (Reeves et al, 2008a) the mechanisms by which older individuals  
87 would utilise alternate strategies is unclear.

88

89 The purpose of the study was to determine the effect of alternate stair negotiation strategies on  
90 lower-limb kinetics in older individuals and quantify how these kinetics change in response to  
91 stair negotiation at an increased step height, representing an increase in task demand. This was  
92 achieved by drawing comparisons between three stair negotiation strategies, performed at two

93 step heights, in a group of healthy older people. The three strategies investigated were a) the  
94 standard mode of descent with one foot contacting each step (Step-over-Step; SoS), b) two feet  
95 contacting each step (Step-by-Step; SbS) and c) sideways descend with two feet making contact  
96 with each step (Side-Step; SS). It was hypothesised that the alternate stair negotiation strategies  
97 would impart different musculoskeletal demands on the limbs and provide a means to alter  
98 joint loading in the face of increased step height.

99

## 100 **Methods**

### 101 *Participants*

102 All study procedures were approved by the University ethics committee (Manchester  
103 Metropolitan University) and all participants gave written informed consent to participate. A  
104 total of 11 older adults (six female and five male, mean  $\pm$  SD age:  $74.8 \pm 3.1$  years, height:  
105  $1.63 \pm 0.07$  m, mass:  $67.7 \pm 9.5$  kg) were recruited from the local and surrounding areas via  
106 advertisements placed in newspapers and through links with local community groups. Due to  
107 the potentially challenging physical tasks involved in the study, only volunteers receiving  
108 approval from their medical practitioner were accepted into the study and were included if  
109 living independently in the community and recreationally active.

110

### 111 *Staircase dimensions*

112 Data were collected on a custom-made staircase instrumented with force platforms embedded  
113 into three consecutive steps (Kistler type Z17068, Winterthur, Switzerland) and a fourth at the  
114 base of the stairs embedded into the floor (Kistler type 9253A, Winterthur, Switzerland). Force  
115 data were sampled at 1080Hz and recorded synchronously with a nine-camera optoelectronic  
116 motion analysis system sampling at 120Hz (Vicon 612 system, Vicon Motion Systems Ltd,  
117 Oxford, UK). Each step, including an independently mounted top platform, were independent  
118 structures consisting of solid steel frames bolted into the ground. This ensured a mechanically  
119 stiff construction that enabled forces to be measured independently from each platform. A  
120 handrail was also independently mounted on both sides. Two staircase configurations were  
121 utilised in the study; a standard step height (STD; riser 120mm, tread depth 280mm, step width  
122 900mm) and, in keeping with current staircase regulations (Government, 2010), an increased  
123 step height (INC; riser 220mm, tread depth 280mm and step width 900mm).

124

125 *Testing procedures*

126 All participants were asked to descend the staircase at their own self-selected speed during the  
127 three descent strategies: Step-over-Step (SoS), Step-by-Step (SbS) and Side-Step (SS) (Figure  
128 1). Handrails were present throughout testing as a safety precaution and participants were asked  
129 not to use them unless necessary, however no trials were recorded where handrails were used.  
130 For the SoS strategy the analysed portion of the descent was taken as initial contact of the left  
131 foot on the second step down until initial contact of the same foot on the floor. For the SbS and  
132 SS strategies, initial contact was taken from contact of the leading limb (i.e. the limb chosen to  
133 initiate the stepping down movement) on step two until initial contact of the same limb onto  
134 step three. These gait cycles represent steady-state gait for the leading limb. In the SS strategy,  
135 only those trials where the participant descended perpendicular to the staircase (i.e. pelvis and  
136 trunk were at an angle  $90^\circ$  relative to the direction of progression) were taken forward for  
137 further analysis. For clarity, the trailing limb for all strategies was analysed as a function of the  
138 lead limb gait cycle (i.e. graphs are plotted according to the gait cycle % of the leading limb).  
139 Due to mechanical and logistical constraints reconfiguring the staircase, full randomisation of  
140 strategy sequence was not possible and all three strategies (SoS then SbS followed by SS) were  
141 performed at the STD step height followed by all three strategies performed in the same order  
142 at the INC step height, on different days, minimising learning effects.



143 [Figure 1]

144

145 *Data analysis*

146 In order for joint kinetics to be calculated, 34 reflective markers were placed according to the  
147 Plug-in-Gait model (Bodybuilder, Plug in Gait model, Vicon Motion Systems, Oxford, UK)  
148 and filtered within Vicon using the Woltring filtering routine with a MSE of 20. For exact  
149 marker placement see (Reeves et al, 2008a). Anthropometric measurements from each  
150 participant were entered into the model and data were exported into Visual3D (C-motion,  
151 Rockville, MD, USA) whereby kinetic data were filtered using a low-pass Butterworth filter  
152 with an 8Hz cut off frequency and data were processed for further analysis. Here, gait cycles  
153 were identified for each strategy, temporal-spatial parameters (determined through individual  
154 gait cycles) were generated, and lower-limb joint moments and powers (both normalised to  
155 body mass) were calculated using inverse dynamics prior to being exporting into Microsoft  
156 Excel ®, whereby specific peak values were identified and ensemble graphs generated. For the  
157 leading limb, weight acceptance was defined as 0-25% gait cycle and controlled lowering was  
158 defined as 35-55% gait cycle (McFadyen & Winter, 1988). Controlled lowering for the trailing  
159 limb defined as 75-100% gait cycle (Figure 2). As both the SbS and SS strategies involved  
160 placing two feet on one step at the same time, force data ceased for the time phases  
161 corresponding to this double support period, and resumed at toe-off from the leading limb.

162

163

164 [Figure 2]

165 *Statistical analysis*

166 Data were exported into SPSS v21.1 (SPSS Inc., Chicago, IL, USA) for statistical analysis and  
167 examined for normality using Shapiro-Wilk's test and outliers assessed by visual inspection of  
168 box-plots. A linear mixed model was used to determine whether statistical differences existed  
169 with 'strategy' and 'step-height' considered as fixed effects and 'strategy\*step-height' also  
170 analysed to investigate whether an interaction effect existed. Due to between-strategy  
171 differences in gait speed (Table 1), joint moments and powers were analysed with gait speed  
172 as a covariate. Where a significant interaction effect was observed, a Sidak post-hoc  
173 comparison was performed with level of significance set at  $P \leq .05$ .

174

175 **Results**

176 At both STD and INC step heights, gait speed in the SoS strategy was significantly faster than  
177 both SbS and SS strategies ( $P < .001$  in all cases) (Table 1). Both INC SoS and INC SbS  
178 strategies resulted in a shorter double support phase compared to STD SoS and STD SbS,  
179 respectively (Table 1).

180

181 [Table 1]

182 **Weight Acceptance**

183 In response to increased task demand (step height) we identified; 1) a shift towards utilisation  
184 of the hip extensors in the SoS and SbS strategies 2) the demands on all lower-limb joints  
185 increased in the SbS strategy 3) the demands on the hip extensors and ankle plantarflexors, but  
186 not the knee extensors, increased in the SoS strategy 4) only power absorption in the knee  
187 extensors and ankle plantarflexors increased in the SS strategy

188

189 *Lead Limb Hip*

190 The SS strategy demonstrated a significantly greater hip flexor moment compared to SoS and  
191 SbS ( $P < .001$  for both) in the STD step height and INC step height ( $P < .001$  for both) which did  
192 not increase as step height increased ( $P = .519$ ). Interestingly, as step height increased, both SoS  
193 and SbS strategies shifted towards substantial utilisation of the hip extensors (342%,  $P < .001$   
194 and 254%,  $P = .015$  respectively) but this was not the case for the SS strategy (38%).

195

196 *Lead Limb Knee*

197 During weight acceptance, as step height increased, knee extensor moment did not increase in  
198 the SoS and SS strategies ( $P = .593$  and  $P = .199$ , respectively) but did increase in the SbS strategy  
199 (63%,  $P = .001$ ). Power absorption also increased in the SbS strategy (235%,  $P = .019$ ) as well as  
200 in the SS strategy (277%,  $P = .009$ ) at INC step height.

201

202 *Lead Limb Ankle*

203 Both SoS and SbS strategies demonstrated increased plantarflexor moment and power  
204 absorption as step height increased ( $P<.002$  for all) with plantarflexor moment at INC step  
205 height also significantly greater than the SS strategy (34%,  $P=.018$  and 30%  $P=.001$ ,  
206 respectively). Power absorption increased significantly with increased step height in the SS  
207 strategy (242%,  $P<.001$ ).

208

209 [Table 2]

210

### 211 **Controlled lowering**

212 In response to increased task demand (step height) we identified; 1) greater demands were  
213 placed on the lead limb hip extensors and knee extensors in the SbS strategy at STD step height  
214 2) demands on the hip extensors increased in all strategies in the trail limb but only in the SoS  
215 strategy in the lead limb 3) demand on the knee extensors reduced and demand on the ankle  
216 plantarflexors increased in both lead and trail limbs in the SoS strategy 3) demands on the knee  
217 extensors were reduced in the SS strategy at STD step height in the lead limb however,  
218 demands were increased in the trailing limb at INC step height.

219

#### 220 *Lead Limb Hip*

221 During controlled lowering, similar patterns existed as seen during weight acceptance. The SbS  
222 strategy demonstrated a reduced hip flexor/shift towards hip extensor moment compared to  
223 both SoS and SS at the STD step height ( $P<.001$  for both). The shift towards hip extensor  
224 moment at INC step height compared to STD was apparent in the SoS strategy ( $P=<.001$ ) and

225 was significantly larger than both SbS and SS at INC step height ( $P=.037$  and  $P<.001$ ,  
226 respectively).

227

#### 228 *Trail Limb Hip*

229 During controlled lowering, hip extensor moment increased significantly in all three strategies  
230 at INC step height compared to STD (SoS; 391%, SbS; 492% and SS; 162%,  $P<.001$  in all  
231 cases).

232

#### 233 *Lead Limb Knee*

234 During controlled lowering, knee extensor moment and power absorption were greater in the  
235 SoS strategy at STD step height compared to SbS and SS ( $P<.001$  for all) however, there was  
236 a reduction in knee extensor moment and power absorption at INC step height compared to  
237 STD step height for the SoS strategy (23%,  $P<.001$  and 29%  $P=.004$ , respectively) which was  
238 not evident in either SbS or SS strategies ( $P=>.232$  for all).

239

#### 240 *Trail Limb Knee*

241 During controlled lowering, both SoS and SbS strategies demonstrated reduced knee extensor  
242 moment at INC step height compared to STD (31%,  $P=.039$  and 26%,  $P=.013$ , respectively),  
243 both of which were also reduced compared to INC SS (41%,  $P=.003$  and 36%,  $P=.070$ ,  
244 respectively) with power absorption also less than INC SS ( $P=.003$  and  $P=.000$ , respectively).  
245 Compared to STD step height, INC SbS demonstrated reduced power absorption (28%,  
246  $P=.009$ ) and INC SS demonstrated increased power absorption (37%,  $P<.001$ ).

247

248 *Lead Limb Ankle*

249 During controlled lowering, at both STD and INC step heights, plantarflexor moment and  
250 power generation was significantly greater in the SoS strategy compared to SbS and SS (range;  
251 47-215%,  $P < .001$  for all). Plantarflexor moment and power generation significantly increased  
252 in SoS INC step height compared to STD (32%,  $P < .001$  and 57%,  $P = .023$ ) whilst plantarflexor  
253 moment significantly reduced in SS strategy at INC step height (37%,  $P < .001$ ).

254

255 *Trail Limb Ankle*

256 During controlled lowering, plantarflexor moment and power absorption increased in INC SoS  
257 compared to STD SoS (38%,  $P = .042$  and 127%,  $P < .001$ , respectively) with only plantarflexor  
258 moment increasing at INC step height in the SbS strategy (54%,  $P < .001$ ). Power absorption  
259 was significantly greater in the SoS strategy compared to SbS and SS at both STD and INC  
260 step heights ( $P < .001$  in all cases).

261

262 [Table 3]

263

264 [Figure 3]

265 **Discussion**

266 This novel study on the impact of different stair negotiation strategies on the sagittal plane joint  
267 loading patterns in older people during two staircase configurations has revealed interesting  
268 and functionally important mechanisms. First, by the very nature of the Step-by-Step (SbS) and  
269 Side-Step (SS) strategies, two feet are placed on the same step at the same time which creates  
270 a ‘pause’ in the gait cycle which in itself, is a means to reduce gait speed without prolonging  
271 single-limb support. These strategies also negate the need for a second instance of joint  
272 moments in the lead limb typically seen in the controlled lowering phase of the cyclic Step-  
273 over-Step (SoS) strategy. Instead, the trailing limb performs the controlled lowering to the next  
274 step, therefore the musculoskeletal demands placed on the limbs during weight acceptance and  
275 controlled lowering are split between the leading and trailing limbs, respectively. This means  
276 that one leg can solely lead or trail in SbS and SS strategies, whereas both legs do both tasks  
277 in SoS, which could have specific implications for rehabilitation practice in those with  
278 unilateral pain or weakness. Second, in response to the increased task demand (increased step  
279 height), the demand on the plantarflexors and hip extensors of the leading limb increase  
280 substantially in the SoS strategy. The SS strategy seems effective at minimising the  
281 contribution of the ankle plantarflexors and hip extensors to the task with no increase in joint  
282 moments in the leading limb during weight acceptance observed at the increased step height.  
283 These findings may be of particular benefit to those frequently encountering non-conforming  
284 staircases or those with impaired strength capacities, principally those with joint specific  
285 muscle weakness and at risk of falls.

286

287 *Effect of stair negotiation strategy*

288 Not only is the overall task demand divided between the two limbs with the alternate strategies  
289 of SbS and SS, but there are further distributions between the joints, particularly in the SS  
290 strategy. Previous work has demonstrated that older individuals redistribute the demands of  
291 stair descent away from the ankle and towards the knee during the typical SoS strategy (Reeves  
292 et al, 2008a). Our data reveals that the demands on the ankle plantarflexors are further reduced  
293 in the SS strategy with both moment and power reduced during controlled lowering in the  
294 trailing limb and power absorption also reduced in the SbS strategy (Table 3). Cluff &  
295 Robertson (2011) identified a positive correlation between demands on the plantarflexors and  
296 stair descent progression velocity over four consecutive gait cycles, with no such correlation  
297 evident with the demands on the knee extensors or hip flexors. This suggests that individuals  
298 with unilateral weakness, musculoskeletal impairments or pain in the plantarflexors, should  
299 adopt the SS strategy and use the affected limb as the trailing limb as a means to reduce  
300 plantarflexor demand.

301

302 Few studies have investigated alternate stair negotiation strategies during stair descent. A  
303 previous study compared the traditional SoS strategy to the SbS strategy on knee mechanics in  
304 younger adults (Reid et al, 2007). Gait speed was slower in the SbS strategy, internal knee  
305 extensor moment was reduced during the weight acceptance phase in the leading limb but  
306 maintained in the trailing limb to ensure adequate controlled lowering. In contrast, the present  
307 study observed comparable knee moments during weight acceptance across all strategies,  
308 which is likely due to the absence of statistical control of gait speed by Reid et al, (2007). The  
309 non-significant 20 and 35% reductions in joint moments seen in the SbS and SS strategies  
310 (Table 2) and the findings by Reid et al., (2007) likely reflect the slower gait speed, and not a  
311 true effect of an alternate strategy.



312

313 The absence of a controlled lowering moment in the leading limb observed in the present study  
314 is consistent with the findings by Reid et al., (2007) and reflects the shift in joint demands to  
315 the trailing limb (Table 3, Figure 3). Given the previously reported age-related declines in  
316 muscle strength (Hairi et al, 2010; Raj et al, 2010) and associated age-related adaptations to  
317 stair negotiation in response to such changes (Reeves et al, 2008a), these data demonstrate that  
318 alternate strategies offer a means to share the task demand *between* limbs instead of the cyclic  
319 interchange between weight acceptance *and* controlled lowering performed by the same limb  
320 in SoS. The between-limb sharing of the task demand is evident within current amputee  
321 rehabilitation practice with instruction to descend stairs adopting a SbS strategy and leading  
322 with their prosthetic (Ainslie, 2012) as a means to avoid potential instability on the prosthetic  
323 limb during controlled lowering. Our findings support the rationale for this rehabilitation  
324 practice and offer promising and cost-effective avenues to prevent falls in older individuals,  
325 particularly in those with unilateral pain, weakness or dysfunction as well as those with  
326 impaired postural stability. It is imperative that future research explores the impact of adopting  
327 such alternative strategies to assess their effectiveness in the prevention of falls.

328

### 329 *Response to increased step height*

330 As the overall demand of the task increased, surprising joint moment profiles were revealed in  
331 the SoS strategy. A clear and consistent shift towards utilising the hip extensors to a greater  
332 extent in both the leading and trailing limbs were seen in weight acceptance and controlled  
333 lowering (Tables 2 and 3, Figure 3). This mechanism has previously been observed in  
334 claudicants with peripheral arterial disease, and was postulated as being a means to reduce the  
335 demands on potentially weak knee extensors (King et al., 2018). The present study also found

336 that knee extensor moment was unchanged during weight acceptance and, surprisingly,  
337 decreased during controlled lowering in SoS (Table 3, Figure 2), in contrast to previous  
338 research on young males descending a staircase at progressively greater step heights (Spanjaard  
339 et al, 2008). Furthermore, plantarflexor moment increased in both weight acceptance and  
340 controlled lowering phases with SoS strategy (Table 3, Figure 2). Similar mechanisms are  
341 evident in the SbS strategy with increased hip extensor moment during weight acceptance and  
342 a substantial increase in plantarflexor moment during controlled lowering of the trailing limb  
343 (Figure 3). These findings indicate that in scenarios where the task demand is high, either  
344 through reductions in strength due to ageing or alterations to staircase dimensions, the demand  
345 is redistributed away from the knee extensors and towards the hip extensors and ankle  
346 plantarflexors. This may mean that older individuals are approaching the limits of (or  
347 potentially exceeding) their strength capabilities, particularly at the ankles as Reeves et al.,  
348 (2008a) identified that they typically redistribute moments *away* from the plantarflexors at a  
349 standard step height in order to operate within safer limits of their maximum strength. The  
350 reasons for these shifts in joint moments are unclear at this stage however, there may be two  
351 possible explanations. First, the increased hip extensor moment in the leading limb may reflect  
352 a more upright body posture, shifting the centre of mass (CoM) more posteriorly and thereby  
353 altering the application of the ground reaction force relative to both the knee and hip joint  
354 centres. This suggestion supports previous work identifying a preference in older individuals  
355 to utilise the trailing limb more to control the downwards acceleration of the CoM (Buckley et  
356 al., 2013). Second, it may be that the strength reserve previously identified in the knee extensors  
357 that allow joint moment redistribution to occur (Reeves et al, 2008a), is incapable of  
358 compensating for further increases in task demand. These findings reinforce the importance of  
359 maintaining lower-limb muscle strength with advancing age in order to safely accomplish stair  
360 descent at an increased step height. Furthermore, the identified shift back towards utilisation

361 of smaller and weaker ankle plantarflexors may be a mechanism of falls in older individuals.  
362 Further investigations on the contributions of each muscle group, relative to their maximum  
363 strength, in comparison to strategies adopted by younger counterparts are essential to explore  
364 the reasons for these mechanisms and to identify joint-specific limitations for targeted exercise  
365 interventions. Interestingly, the potential manipulation of the CoM as a means to increase  
366 stability in the SoS strategy only, corresponds to previous research whereby the control of the  
367 CoM or CoP in those with a fear of falls (Reid et al., 2011) or those with a high risk of falls  
368 (Zietz et al., 2011) was achieved with handrail use. In environments where handrails may not  
369 be present to utilise this external support to assist in CoM/CoP control, adopting an alternate  
370 strategy to the traditional SoS may provide those at risk of falls the control required to maintain  
371 safe negotiation. More explicit investigation on dynamic stability during these strategies is  
372 warranted, particularly in those at risk of falls.

373

374 Interestingly, in the SS strategy, the plantarflexor moment did not increase during weight  
375 acceptance in the leading limb ( $P=.723$ ). A small, but likely clinically insignificant, trend  
376 towards an increase was observed in the trailing limb during controlled lowering (9% increase,  
377  $P=.073$  (Table 3)) however, this was significantly less than both SoS and SbS (Table 3). There  
378 was also no further increase in hip extensor moment in the leading limb during weight  
379 acceptance, that was observed in both SoS and SbS strategies (Table 2). Instead, the stair  
380 descent task was predominantly achieved by the trailing limb hip extensors, which  
381 demonstrated a significant increase compared to the standard step height, and trailing limb knee  
382 extensors, with significant increases seen compared to SoS and SbS (Table 3). The dimensions  
383 of the staircase at increased step height in the present study possessed a riser height at the  
384 maximum height recommended for *new* private staircase designs (Government, 2010). Hence,  
385 the likelihood of an older individual encountering a staircase possessing such a riser height in

386 older private or public dwellings is high. This SS strategy offers a means to descend such a  
387 staircase, or high step, by progressively loading the hip and knee extensors of the trailing limb  
388 to control the lowering of the centre of mass (Figure 3) and avoiding additional undue loading  
389 of the plantarflexors of either limb. Adopting such a SS strategy may be a means to reduce risk  
390 of falls in a home-setting and should be a focus for future investigation.

391

## 392 **Conclusions**

393 This novel study explored the effect of adopting alternate stair descent strategies on lower-limb  
394 joint kinetics at two different step configurations. In both the typical step-over-step strategy  
395 and step-by-step strategy, as the task demand increased, the knee extensors were unloaded and  
396 the task demand redistributed to the hip extensors and ankle plantarflexors in both the leading  
397 and trailing limbs. Adopting the side-step strategy seems to avoid increased loading of the  
398 ankle plantarflexors at both standard and increased step heights, and may be an appropriate  
399 strategy for an individual with impairments in the plantarflexors to employ. Further research  
400 into alternate strategies is needed, however these promising findings could have substantial  
401 effects on rehabilitation interventions and home-based advice for older individuals with joint  
402 specific muscle weaknesses and those at risk for falls. Advocating such strategies, particularly  
403 for those at risk of falling, may reduce the prevalence of falls and subsequent costs to health  
404 services.

405

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409

410 **Conflict of Interest**

411 There are no known conflicts of interests.

412

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499 **Table 1.** Group mean (SD) temporal-spatial parameters for each strategy at both step heights.  
 500 Differences between strategy and height are represented by superscript numbers  
 501 corresponding to each strategy. Significance differences are represented by \* (P<.05). STD =  
 502 standard step height, INC = increased step height, SoS = step-over-step strategy, SBS = step-  
 503 by-step strategy, SS = side-step strategy

504 <sup>1</sup> = STD SoS, <sup>2</sup> = STD SbS, <sup>3</sup> = STD SS, <sup>4</sup> = INC SoS, <sup>5</sup> = INC SbS, <sup>6</sup> = INC SS

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<b>Strategy</b>	<b>STD SoS<sup>1</sup></b>	<b>STD SbS<sup>2</sup></b>	<b>STD SS<sup>3</sup></b>	<b>INC SoS<sup>4</sup></b>	<b>INC SbS<sup>5</sup></b>	<b>INC SS<sup>6</sup></b>
<b>Gait speed (m/s)</b>	0.49 (0.05) <sup>2,3*</sup>	0.26 (0.04)	0.24 (0.02)	0.49 (0.07) <sup>5,6*</sup>	0.28 (0.03)	0.25 (0.04)
<b>Stance phase (%)</b>	60.4 (3.2)	60.3 (2.5)	65.9 (4.2)	59.4 (4.0)	60.3 (4.0)	66.8 (4.7)
<b>Double Support (%)</b>	24.0 (2.9) <sup>4*</sup>	27.7 (3.0) <sup>5*</sup>	28.6 (6.6)	17.2 (4.0)	21.2 (4.3)	29.8 (7.4)

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515 **Table 2.** Group mean (SD) joint moments and powers during the weight acceptance (WA)  
516 phase for lead limb. All units are Nm/Kg unless otherwise stated and positive values indicate  
517 internal hip extensor, knee extensor and ankle plantarflexor moments, and power generation.  
518 Between strategy and height differences are represented by superscript numbers corresponding  
519 to each strategy. Significance differences are represented by \* (P<.05). Trends towards  
520 significance (P<.10) are represented by ^. STD = standard step height, INC = increased step  
521 height, SoS = step-over-step strategy, SBS = step-by-step strategy, SS = side-step strategy

Strategy	STD SoS <sup>1</sup>	STD Sbs <sup>2</sup>	STD SS <sup>3</sup>	INC SoS <sup>4</sup>	INC Sbs <sup>5</sup>	INC SS <sup>6</sup>
<b>Hip</b>						
Lead Limb moment during WA	0.12 (0.14) <sup>3*,4*</sup>	0.13 (0.19) <sup>3*,5*</sup>	-0.24 (0.09)	0.53 (0.23) <sup>5*,6*</sup>	0.46 (0.47) <sup>6*</sup>	-0.33 (0.11)
<b>Knee</b>						
Lead Limb moment during WA	0.77 (0.18)	0.62 (0.40) <sup>5*</sup>	0.50 (0.22)	0.80 (0.32)	1.01 (0.39)	0.66 (0.35)
Lead Limb Power during WA (W/Kg)	-0.86 (0.53) <sup>3*</sup>	-0.55 (0.67) <sup>5*</sup>	-0.30 (0.32) <sup>6*</sup>	-1.40 (1.50)	-1.84 (1.35)	-1.13 (0.78)
<b>Ankle</b>						
Lead Limb moment during WA	1.03 (0.23) <sup>4*</sup>	0.93 (0.22) <sup>5*</sup>	1.07 (0.36)	1.55 (0.46) <sup>6*</sup>	1.46 (0.36) <sup>6*</sup>	1.02 (0.08)
Lead Limb Power during WA (W/Kg)	-2.82 (1.22) <sup>4*</sup>	-2.49 (0.77) <sup>5*</sup>	-2.88 (1.06) <sup>6*</sup>	-5.66 (1.96)	-6.00 (2.18)	-4.09 (0.42)

522 <sup>1</sup> = STD SoS, <sup>2</sup> = STD Sbs, <sup>3</sup> = STD SS, <sup>4</sup> = INC SoS, <sup>5</sup> = INC Sbs, <sup>6</sup> = INC SS

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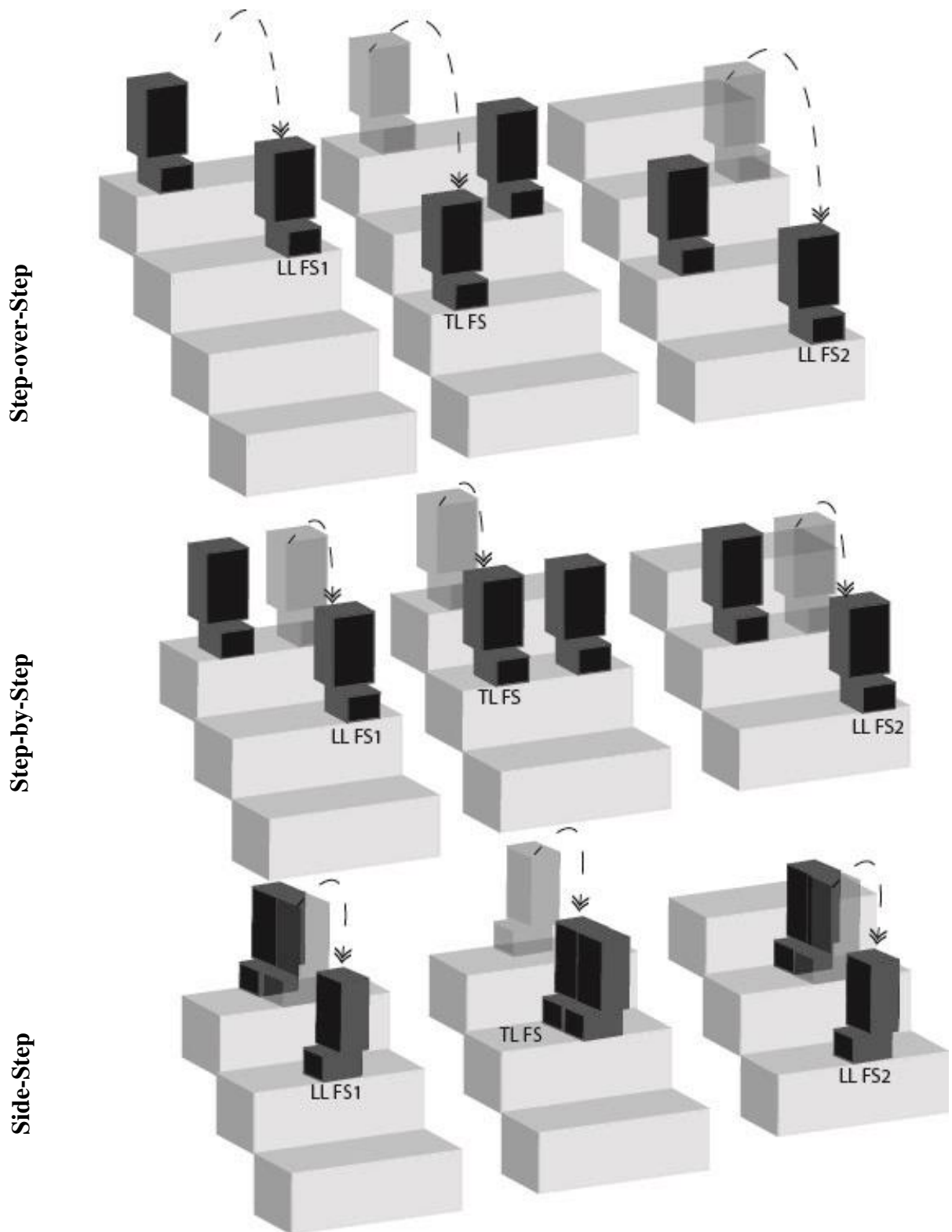
525 **Table 3.** Group mean (SD) joint moments and powers during the controlled lowering (CL)  
526 phase for both lead and trail limbs. All units are Nm/Kg unless otherwise stated and positive  
527 values indicate internal hip extensor, knee extensor and ankle plantarflexor moments, and  
528 power generation. Between strategy and height differences are represented by superscript  
529 numbers corresponding to each strategy. Significant differences are represented by \* (P<.05).  
530 Trends towards significance (P<.10) are represented by ^. STD = standard step height, INC =  
531 increased step height, SoS = step-over-step strategy, SBS = step-by-step strategy, SS = side-  
532 step strategy

Strategy	STD SoS <sup>1</sup>	STD Sbs <sup>2</sup>	STD SS <sup>3</sup>	INC SoS <sup>4</sup>	INC Sbs <sup>5</sup>	INC SS <sup>6</sup>
<b>Hip</b>						
Lead Limb moment during CL	-0.08 (0.11) <sup>2*,4*</sup>	0.08 (0.11) <sup>3*</sup>	-0.19 (0.12)	0.39 (0.20) <sup>5*,6*</sup>	0.19 (0.22) <sup>6*</sup>	-0.25 (0.08)
Trail Limb moment during CL	0.11 (0.18) <sup>4*</sup>	0.12 (0.14) <sup>5*</sup>	0.13 (0.11) <sup>6*</sup>	0.54 (0.33)	0.71 (0.18)	0.34 (0.26)
<b>Knee</b>						
Lead Limb moment during CL	0.88 (0.19) <sup>2*,3*,4*</sup>	0.32 (0.19)	0.26 (0.23) <sup>6*</sup>	0.68 (0.18) <sup>5^</sup>	0.45 (0.34) <sup>6*</sup>	0.38 (0.24)
Lead Limb Power during CL (W/Kg)	-2.43 (0.54) <sup>2*,3*,4*</sup>	-0.25 (0.37)	-0.06 (0.12) <sup>6*</sup>	-1.73 (0.67) <sup>5*,6*</sup>	-0.21 (0.21)	-0.10 (0.14)
Trail Limb moment during CL	0.93 (0.27) <sup>4*</sup>	0.94 (0.20) <sup>5*</sup>	1.08 (0.30)	0.64 (0.32) <sup>6*</sup>	0.70 (0.33) <sup>6^</sup>	1.09 (0.25)
Trail Limb Power during CL (W/Kg)	-2.10 (0.49)	-2.16 (0.59) <sup>5*</sup>	-2.44 (0.38) <sup>6*</sup>	-1.92 (0.94) <sup>6*</sup>	-1.55 (0.46) <sup>6*</sup>	-3.34 (0.49)
<b>Ankle</b>						
Lead Limb moment during CL	1.10 (0.08) <sup>2*,3*,4*</sup>	0.66 (0.13)	0.75 (0.25) <sup>6*</sup>	1.45 (0.09) <sup>5*,6*</sup>	0.73 (0.25) <sup>6*</sup>	0.46 (0.12)
Lead Limb Power during CL (W/Kg)	1.30 (0.33) <sup>2*,3*,4*</sup>	-0.31 (0.16)	-0.19 (0.13) <sup>6^</sup>	2.01 (0.65) <sup>5*,6*</sup>	-0.85 (1.43)	-0.21 (0.27)
Trail Limb moment during CL	1.17 (0.14) <sup>3*,4*</sup>	0.94 (0.18) <sup>5*</sup>	0.82 (0.09) <sup>6^</sup>	1.61 (0.64) <sup>6*</sup>	1.45 (0.13) <sup>6*</sup>	0.90 (0.11)
Trail Limb Power during CL (W/Kg)	-2.71 (1.05) <sup>2*,3*,4*</sup>	-1.20 (0.36) <sup>3*</sup>	-0.85 (0.23)	-6.15 (3.41) <sup>5*,6*</sup>	-1.44 (0.48) <sup>6*</sup>	-0.71 (0.17)

533 <sup>1</sup> = STD SoS, <sup>2</sup> = STD Sbs, <sup>3</sup> = STD SS, <sup>4</sup> = INC SoS, <sup>5</sup> = INC Sbs, <sup>6</sup> = INC

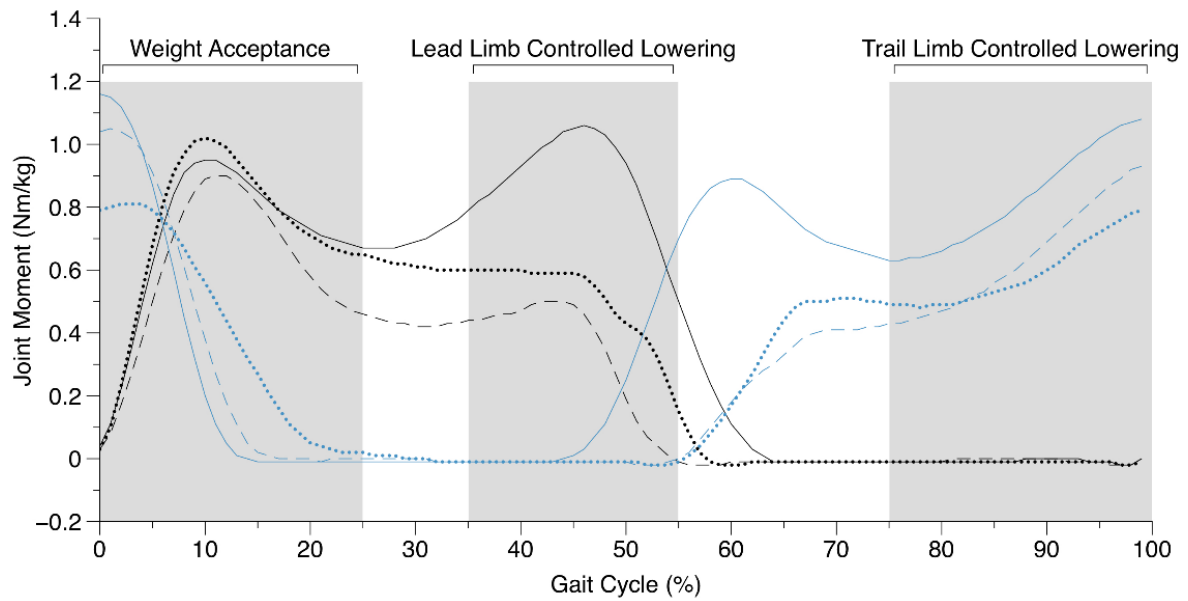
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536 **Figure 1.** Stair negotiation strategies for Step-over-Step, Step-by-Step and Side-Step. One gait  
 537 cycle was defined from LL FS1 to LL FS2 for all strategies. LL = Lead Limb, TL = Trail Limb,  
 538 FS = Foot strike

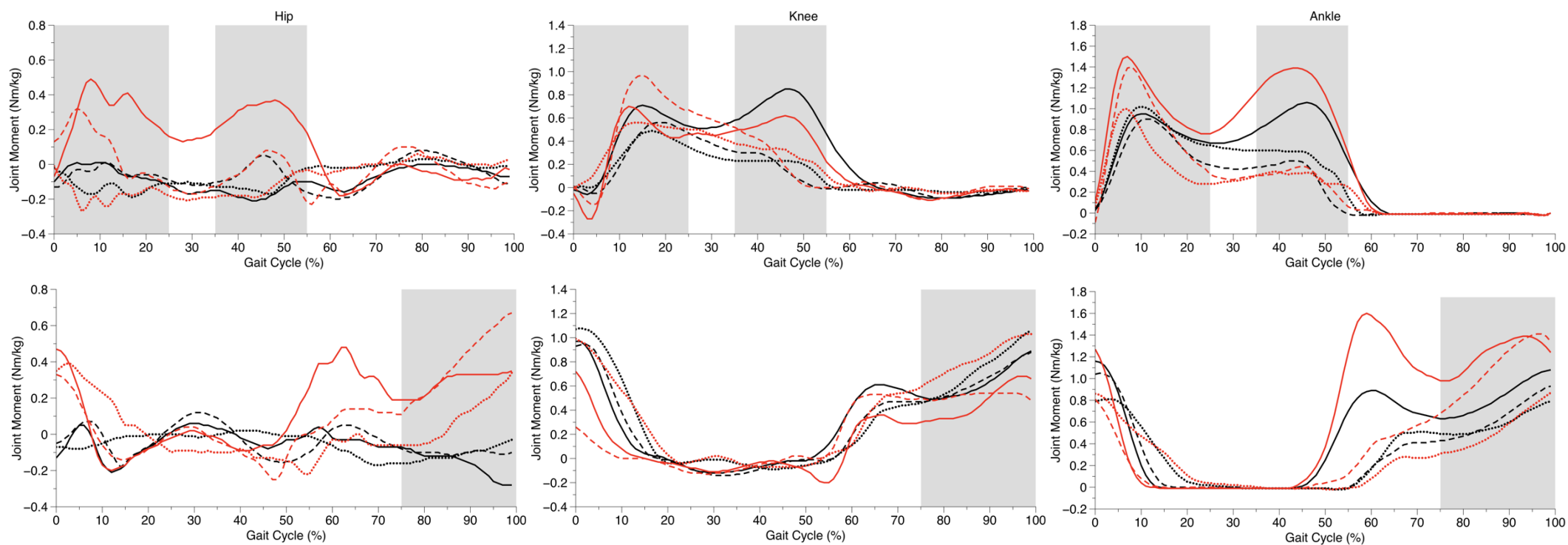
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541 **Figure 2.** Example joint moment profile for the lead limb (black) and trail limb (blue) plotted  
 542 on one graph across a full gait cycle of the leading. Shaded areas represent the phases used for  
 543 data extraction and further analysis for all three negotiation strategies. Solid line represents  
 544 SoS strategy, dashed line represents SbS strategy, dotted line represents SS strategy; black  
 545 represents STD step height and blue represents INC step height.

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548 **Figure 3.** Group mean joint moments for the leading limb (top row) and trailing limb (bottom row) across a full lead limb gait cycle from foot contact  
 549 to subsequent ipsilateral foot contact for the hip, knee and ankle. Positive values indicate hip and knee extensor moment and plantarflexor moment.  
 550 STD = standard step height (black line), INC = increased step height (red line), SoS = step-over-step strategy (solid), SbS = step-by-step strategy  
 551 (dashed), SS = side-step strategy (dotted). Shaded areas indicate regions for data extraction and analysis.