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

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Abstract

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

Introduction

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

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

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

The purpose of the study was to determine the effect of alternate stair negotiation strategies on lower-limb kinetics in older individuals and quantify how these kinetics change in response to stair negotiation at an increased step height, representing an increase in task demand. This was achieved by drawing comparisons between three stair negotiation strategies, performed at two step heights, in a group of healthy older people. The three strategies investigated were a) the standard mode of descent with one foot contacting each step (Step-over-Step; SoS), b) two feet contacting each step (Step-by-Step; SbS) and c) sideways descend with two feet making contact with each step (Side-Step; SS). It was hypothesised that the alternate stair negotiation strategies would impart different musculoskeletal demands on the limbs and provide a means to alter joint loading in the face of increased step height.

Methods

Participants

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

Staircase dimensions

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

Testing procedures

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

[Figure 1]

Data analysis

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

[Figure 2]

Statistical analysis

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

Results

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

[Table 1]

Weight Acceptance

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

Lead Limb Hip

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

Lead Limb Knee

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

Lead Limb Ankle

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

[Table 2]

Controlled lowering

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

Lead Limb Hip

During controlled lowering, similar patterns existed as seen during weight acceptance. The SbS strategy demonstrated a reduced hip flexor/shift towards hip extensor moment compared to both SoS and SS at the STD step height (P<.001 for both). The shift towards hip extensor moment at INC step height compared to STD was apparent in the SoS strategy (P=<001) and was significantly larger than both SbS and SS at INC step height (P=.037 and P=<001, respectively).

Trail Limb Hip

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

Lead Limb Knee

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

Trail Limb Knee

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

Lead Limb Ankle

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

Trail Limb Ankle

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

[Table 3]

[Figure 3]

Discussion

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

Effect of stair negotiation strategy

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

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

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

Response to increased step height

As the overall demand of the task increased, surprising joint moment profiles were revealed in the SoS strategy. A clear and consistent shift towards utilising the hip extensors to a greater extent in both the leading and trailing limbs were seen in weight acceptance and controlled lowering (Tables 2 and 3, Figure 3). This mechanism has previously been observed in claudicants with peripheral arterial disease, and was postulated as being a means to reduce the demands on potentially weak knee extensors (King et al., 2018). The present study also found that knee extensor moment was unchanged during weight acceptance and, surprisingly, decreased during controlled lowering in SoS (Table 3, Figure 2), in contrast to previous research on young males descending a staircase at progressively greater step heights (Spanjaard et al, 2008). Furthermore, plantarflexor moment increased in both weight acceptance and controlled lowering phases with SoS strategy (Table 3, Figure 2). Similar mechanisms are evident in the SbS strategy with increased hip extensor moment during weight acceptance and a substantial increase in plantarflexor moment during controlled lowering of the trailing limb (Figure 3). These findings indicate that in scenarios where the task demand is high, either through reductions in strength due to ageing or alterations to staircase dimensions, the demand is redistributed away from the knee extensors and towards the hip extensors and ankle plantarflexors. This may mean that older individuals are approaching the limits of (or potentially exceeding) their strength capabilities, particularly at the ankles as Reeves et al., (2008a) identified that they typically redistribute moments *away* from the plantarflexors at a standard step height in order to operate within safer limits of their maximum strength. The reasons for these shifts in joint moments are unclear at this stage however, there may be two possible explanations. First, the increased hip extensor moment in the leading limb may reflect a more upright body posture, shifting the centre of mass (CoM) more posteriorly and thereby altering the application of the ground reaction force relative to both the knee and hip joint centres. This suggestion supports previous work identifying a preference in older individuals to utilise the trailing limb more to control the downwards acceleration of the CoM (Buckley et al., 2013). Second, it may be that the strength reserve previously identified in the knee extensors that allow joint moment redistribution to occur (Reeves et al, 2008a), is incapable of compensating for further increases in task demand. These findings reinforce the importance of maintaining lower-limb muscle strength with advancing age in order to safely accomplish stair descent at an increased step height. Furthermore, the identified shift back towards utilisation of smaller and weaker ankle plantarflexors may be a mechanism of falls in older individuals. Further investigations on the contributions of each muscle group, relative to their maximum strength, in comparison to strategies adopted by younger counterparts are essential to explore the reasons for these mechanisms and to identify joint-specific limitations for targeted exercise interventions. Interestingly, the potential manipulation of the CoM as a means to increase stability in the SoS strategy only, corresponds to previous research whereby the control of the CoM or CoP in those with a fear of falls (Reid et al., 2011) or those with a high risk of falls (Zietz et al., 2011) was achieved with handrail use. In environments where handrails may not be present to utilise this external support to assist in CoM/CoP control, adopting an alternate strategy to the traditional SoS may provide those at risk of falls the control required to maintain safe negotiation. More explicit investigation on dynamic stability during these strategies is warranted, particularly in those at risk of falls.

Interestingly, in the SS strategy, the plantarflexor moment did not increase during weight acceptance in the leading limb (P=.723). A small, but likely clinically insignificant, trend towards an increase was observed in the trailing limb during controlled lowering (9% increase, P=.073 (Table 3)) however, this was significantly less than both SoS and SbS (Table 3). There was also no further increase in hip extensor moment in the leading limb during weight acceptance, that was observed in both SoS and SbS strategies (Table 2). Instead, the stair descent task was predominantly achieved by the trailing limb hip extensors, which demonstrated a significant increase compared to the standard step height, and trailing limb knee extensors, with significant increases seen compared to SoS and SbS (Table 3). The dimensions of the staircase at increased step height in the present study possessed a riser height at the maximum height recommended for *new* private staircase designs (Government, 2010). Hence, the likelihood of an older individual encountering a staircase possessing such a riser height in older private or public dwellings is high. This SS strategy offers a means to descend such a staircase, or high step, by progressively loading the hip and knee extensors of the trailing limb to control the lowering of the centre of mass (Figure 3) and avoiding additional undue loading of the plantarflexors of either limb. Adopting such a SS strategy may be a means to reduce risk of falls in a home-setting and should be a focus for future investigation.

Conclusions

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

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Conflict of Interest

There are no known conflicts of interests.

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

[1] = STD SoS, [2] = STD SbS, [3] = STD SS, [4] = INC SoS, [5] = INC SbS, [6] = INC SS

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

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

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

[1] = STD SoS, [2] = STD SbS, [3] = STD SS, [4] = INC SoS, [5] = INC SbS, [6] = INC SS

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

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

^{1} = STD SoS, ^{2} = STD SbS, ^{3} = STD SS, ^{4} = INC SoS, ^{5} = INC SbS, ^{6} = INC

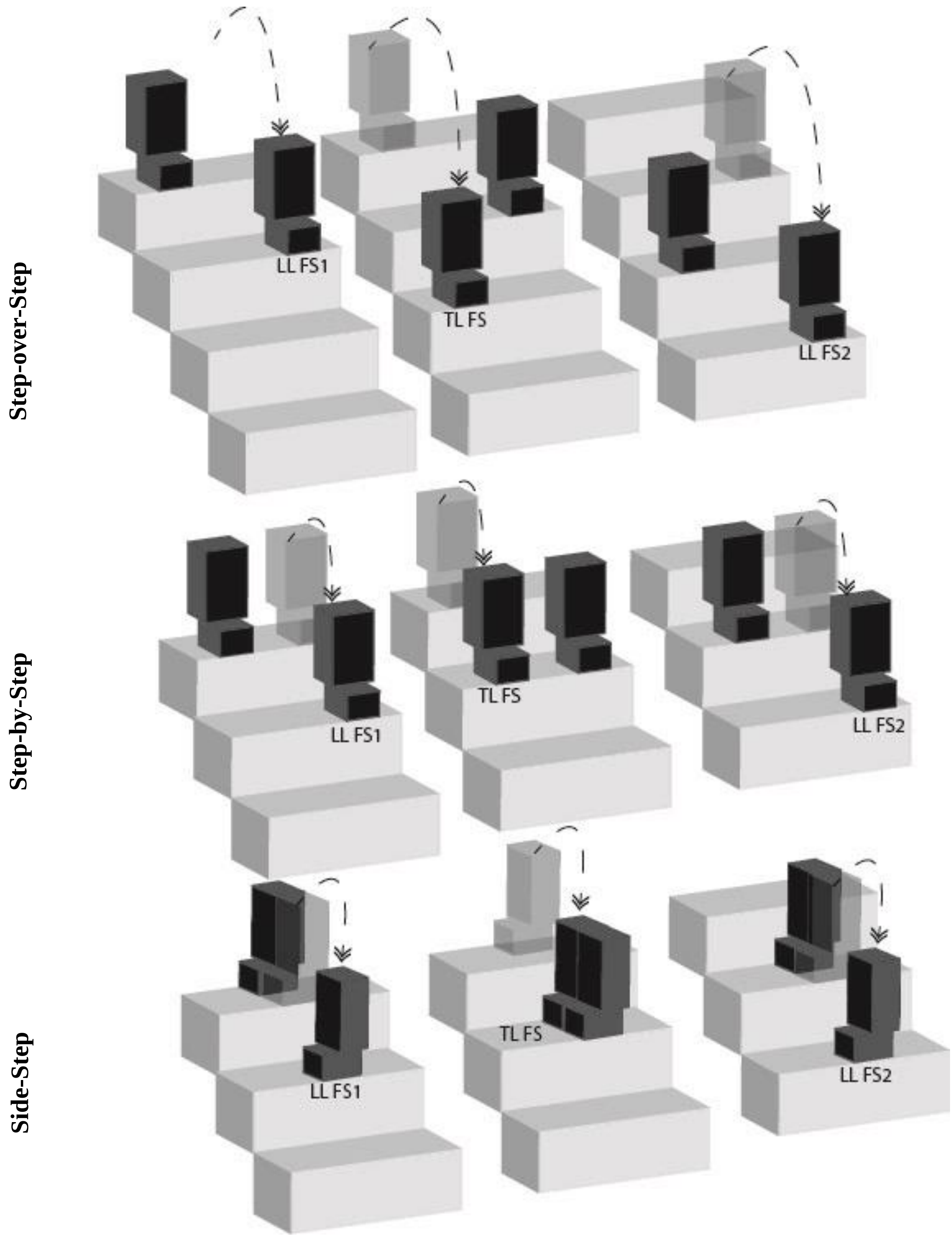

Figure 1. Stair negotiation strategies for Step-over-Step, Step-by-Step and Side-Step. One gait cycle was defined from LL FS1 to LL FS2 for all strategies. LL = Lead Limb, TL = Trail Limb, FS = Foot strike

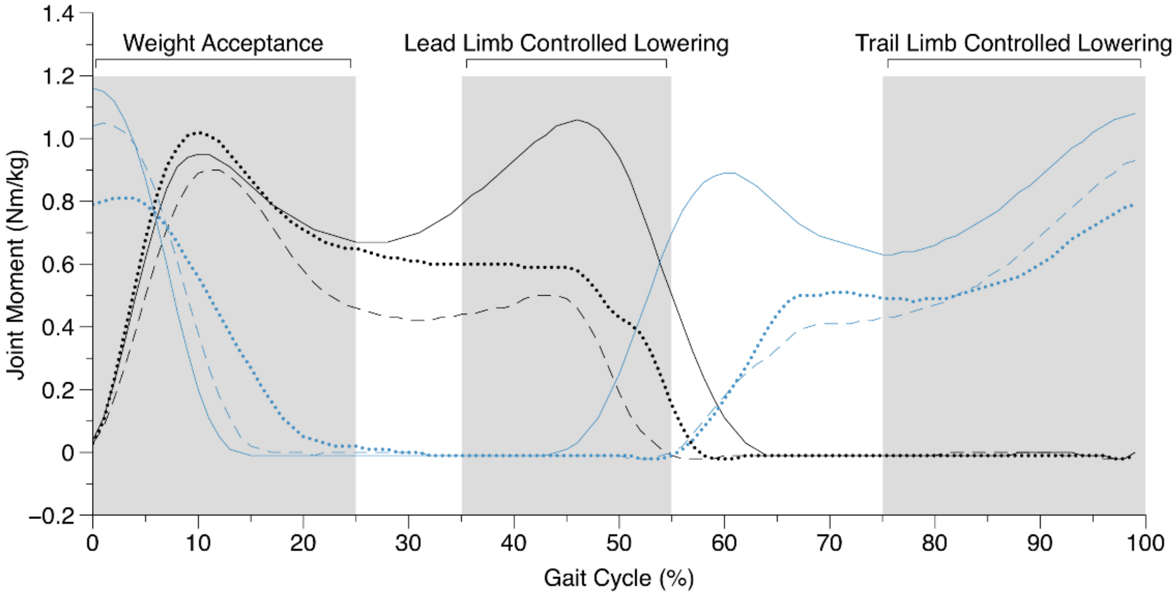

Figure 2. Example joint moment profile for the lead limb (black) and trail limb (blue) plotted on one graph across a full gait cycle of the leading. Shaded areas represent the phases used for data extraction and further analysis for all three negotiation strategies. Solid line represents SoS strategy,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

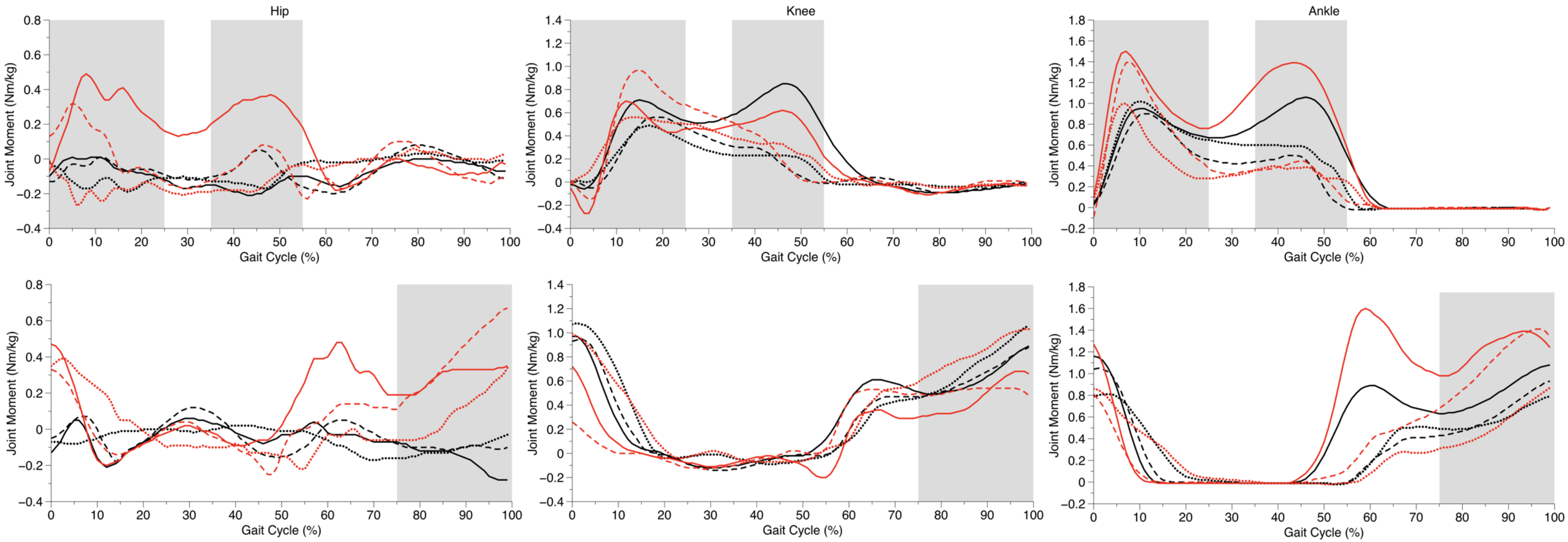

Figure 3. Group mean joint moments for the leading limb (top row) and trailing limb (bottom row) across a full lead limb gait cycle from foot contact to subsequent ipsilateral foot contact for the hip, knee and ankle. Positive values indicate hip and knee extensor moment and plantarflexor moment. STD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