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Centre of Mass Control is Reduced in Older People when Descending Stairs at an Increased Riser Height

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Abstract

Background: Maintaining body centre of mass (CoM) lowering velocity within manageable/safe limits during stair descent can be problematic for older individuals due to reduced ranges of motion at the involved joints (ankle and knee) and a reduced ability to generate adequate joint moments at the extremes in joint ranges of motion. These problems are likely to magnify in circumstances where the distance of lowering increases, or when misjudging the height of lowering.

Research Question: How does a 50% increase in standard stair riser-height affect control of CoM velocity and acceleration of older people during stair descent?

Methods: Fifteen older (75±3 years) and seventeen young (25±4 years) healthy adults descended a 4-step staircase, at two riser-heights: 170mm, 255mm. Changes in peak vertical CoM acceleration and velocity, and lower-limb joint kinetics (moments, work) during landing and lowering phases of stair descent were assessed using a mixed-design repeated measures analysis of variance.

Results: Peak CoM accelerations and velocities during landing and lowering were lower in older compared to young adults and increased in both groups at 255mm riser-height. Duration of lowering also increased, particularly for older adults. Peak ankle moments during landing and lowering, which were lower in older compared to young adults, increased when descending from 255mm riser-height, whilst the peak knee moment reduced. Both groups produced increased landing-limb negative (eccentric) ankle joint work when descending from 255mm, but increases were greater for older adults (87.8%) compared to young (76.1%).

Significance: Descending stairs became more challenging in both age groups as riser-height increased. Older adults adopted a strategy of reducing CoM velocity to lessen the eccentric landing demands. In both groups, but more so older adults, there was a greater reliance on using leading-limb eccentric plantarflexion at 255mm riser-height compared to 170mm, to arrest/control increased downward CoM velocity and acceleration during landing.

Key Words: Stair Descent; Aging; Joint Kinetics; Centre of Mass; Biomechanics

1. Introduction

Previous research highlighting age-related differences in lower-limb kinematics and kinetics for when descending and ascending stairs provide key insights into why older adults find stair negotiation a particularly challenging locomotor task [1-11]. Such findings also help explain why the incidence of falling in older adults is higher for stair descent compared to ascent [12]. We previously found that during stair descent (standard stair riser-height, with same-limb lead on each stair), older adults displayed an alternative strategy to young adults by limiting the downward velocity and acceleration of their CoM during the lowering phase of descent [1]. In contrast, young adults descended quickly to the stair below but arrested their downward velocity sooner, post foot contact, via sustained lead-limb plantarflexion (eccentric) activity. The older participants’ alternative strategy was achieved by stiffening (prolonged muscle co-activation at the knee and ankle) the supporting limb for a longer time period to reduce the rate at which it flexed when lowering the leading/contralateral limb and hence CoM to the next level. Maximal eccentric strength data, obtained by dynamometry, indicated that this stair descent strategy was a consequence of older participants having a diminished ability to generate sufficiently high ankle plantarflexor moments on the leading/landing limb during weight acceptance. Instances where older adults fail to adequately control the CoM downward velocity during lowering (by prolonged muscle co-activation at the knee and ankle of the supporting limb), and subsequently contact the stair below with a relatively high CoM downward velocity, may be a significant contributing factor to falls, as indicated from falls data on level ground [13-17]. Real-world scenarios when the velocity of lowering could increase include, when the height of lowering is greater than the recommended standard as in the case of non-standard private and public staircases [18], or when stepping off a bus or similarly high change in surface height. Previous research investigating stair negotiation (standard riser-heights) has shown that older individuals have a reduced ability to generate adequate moments at the extremes in joint ranges of motion [19,20,8,9]. Thus, lowering the CoM and the leading/contralateral limb from a greater than recommended standard height will position limbs even further towards their extremes of range of motion and be even more challenging for older adults.

To further advance the understanding of age differences in stair descent locomotion, the present study investigated how CoM control during step-over-step stair descent was affected by increasing standard stair riser-height by 50%. Previous research has reported peak absolute joint moments across the stance phase during step-over-step stair descent [8,21,5] but there are two distinct phases in CoM control during stair descent: a landing phase and a lowering phase [1]. The landing phase involves rapid loading of the leading-limb to bear weight. Once the leading-limb has accepted bodyweight, lowering occurs in order to lower the contralateral limb and CoM to the subsequent (lower) stair. The aim of this study was to determine if increasing riser-height had a differential effect on older compared to younger adults in terms of the CoM vertical velocity and acceleration profiles and the associated joint moments and joint work produced at the lower-limb joints during both the landing and lowering phases of stair descent. It was hypothesised (1) that peak CoM vertical velocities and accelerations, and peak hip, knee and ankle joint moment and work during both the landing and lowering phases, would all increase in both age groups when stair riser-height was increased but (2) that such increases would not be as marked for older compared to young adults due to their limited maximal muscular capacities.

2. Methods

Data presented in this study was collected as part of a large cross-sectional study that investigated the differences between young and older adults during stair ascent and descent. Previous reports based on aspects of this data are currently available in the literature [1,22,2,8,9]. This is the first study on the differences in CoM control and contribution of specific lower limb joints between young and older adults when descending stairs with increased versus standard stair riser-heights, using a step-over-step strategy, and focusing on two distinct phases of stance (landing and lowering).

2.1 Participants

Seventeen young adults (7 females; mean ± 1SD age: 25 ± 4 years, height: 1.76 ± 0.09 m, mass: 72.9 ± 11.7 kg) and fifteen older adults (10 females; mean ± 1SD age: 75 ± 3 years, height: 1.62 ± 0.07 m, mass: 69.3 ± 11.1 kg) participated, each providing written informed consent. Exclusion criteria included neuromuscular disorders, musculoskeletal injury/condition (e.g. osteoarthritis) that could affect movement, centrally acting medication that may affect balance, and uncorrected visual problems (none of the participants wore bifocals). We asked participants if they had previously experienced pain in general during stair negotiation, or on the day of testing, and all participants stated that they had not. Only individuals whose medical practitioner approved their participation took part. The study received institutional ethical approval and complied with the tenets of the Declaration of Helsinki.

2.2 Stair descent protocol

Participants completed two separate testing sessions ~1-2 weeks apart. Each consisted of completing up to 5 stair descent trials of a 4-step staircase set at one of two stair riser-height conditions (a standard stair riser-height; 170 mm, and a 50% increase in stair riser-height; 255 mm), with condition order counterbalanced across participants. The standard stair riser-height was typical of those encountered in domestic/public environments [23]. The riser-height of 255mm was selected to increase substantially the task demands. Although the 255mm value exceeds the maximum value of 220mm permitted in national building regulations [18], riser-heights can be much higher in real world settings, e.g. private and public stairs and steps not conforming to regulatory guidelines, or when stepping off from public transport [24], thus generating increased musculoskeletal demands. We believed the increased height would be a height that older adults would be able to cope with yet be large enough to confer a realistic/real-world challenge that might occasionally be encountered in their daily lives. Tread depth (280 mm) and width (900 mm) were constant for all stair riser-heights. Trials were completed at customary self-selected speeds using ‘step-over-step’ gait. Participants led with the right limb over the first stair edge for every trial, and the left limb was first over the second stair edge, and so on. The stairs were descended without use of the handrails and a trial finished after participants landed on the ground, taking one step forward before then coming to a stationary standing position with feet side-by-side.

Force platforms (270 x 500 mm; type Z17068, Kistler instruments, Winterthur, Switzerland), embedded in each stair and the floor at the base of the staircase (400 x 600 mm; Kistler type 9253A, Kistler instruments, Winterthur, Switzerland;), captured kinetic data at 1080 Hz. Whole-body kinematic data were captured at 120 Hz using a 10-camera motion capture system (Vicon system, Oxford Metrics, UK). Reflective markers were positioned according to Vicon’s ‘plug-in-gait’ full-body marker set (Oxford Metrics Ltd) [25]. Using plug-in-gait software data were filtered using the Woltering spline smoothing routine with ‘MSE’ set to 25, and the resulting C3D files uploaded (at 120Hz) to Visual 3D (C-Motion, Germantown, MD, USA) for further analysis. In Visual3D a whole-body CoM was calculated as the weighted average positions of the head, thorax, pelvis, thighs, shanks and feet [26].

2.3 Data analysis

Analysis determined, for the second and third stairs, whole-body kinematics (CoM velocity and acceleration profiles) and ankle, knee and hip joint kinetics (sagittal plane joint moments and rotational power) for the landing and then lowering phase on each stair. Joint kinetics determined any age and riser-height differences in motor control strategies. Joint moments were determined using standard inverse dynamics and joint powers were calculated as the product of the joint moment and joint velocity. The joint moment and joint power profiles for the ankle, knee and hip were summed to yield the ‘support moment’ (positive for extension, negative for flexion) and ‘combined joints power’ (positive for power generation, negative for power absorption), respectively [5,27]. Moment and power data were normalized to participant’s body weight and to 100% of stance phase. The second and third stairs were chosen for analysis as it represented ‘steady-state’ stair descent [3,4]. Descent was divided into the following phases:

> *Landing phase*: from the instant the foot contacted the stair below [touch-down; vertical ground reaction force ascended above a 20 N threshold], up to the instant when CoM downwards velocity reduced to zero following touch-down (the instant when the CoM ceased accelerating upwards) [1]. The landing phase therefore encapsulates weight acceptance and forward continuance as described by McFadyen and Winter [3].
>
> *Lowering phase*: From the end of the landing phase to contralateral-limb touch-down.

The following dependent variables were determined for each limb in turn for the second (left limb) and third (right limb) stairs respectively:

Duration of the landing and lowering phases. Peak sagittal joint moment at the hip, knee and ankle during landing and lowering. Joint work done at the hip, knee and ankle during landing and lowering: determined as the landing and lowering phase integrals of joint power at each joint respectively. Peak upwards CoM acceleration during landing (*peakAcc-Land*) (i.e. peak positive acceleration of the CoM in the downward direction) [1]. Peak downwards CoM velocity (*peakVel*) and acceleration (*peakAcc*) during lowering (i.e. peak negative velocity and acceleration of the CoM in the downward direction, respectively) [1]. Peak downwards (negative) velocity of the foot during lowering (*peakFootVel*) [1].

2.4 Statistical analysis

Mixed-design repeated measures analysis of variance (ANOVA, Statsoft; Statistica, Tulsa, USA) with age (young, old) as a between factor, and stair riser-height (170 mm, 255 mm) and limb (making contact with stair two, making contact with stair three) as repeated factors were used to determine main and interaction effects for each of the parameters. Post-hoc analyses were performed using Tukey’s HSD, and level of significance was set at $p=0.05$.

3. Results

Group ensemble mean hip, knee and ankle joint moment profiles and joint power profiles are shown in Figures 1 and 2 respectively, and group ensemble average CoM downwards acceleration profiles are presented in Figure 3. In both age groups, ankle and knee moment magnitudes were comparable for lowering and landing phases at the standard riser-height, but with an increase in riser-height ankle moment magnitudes increased whereas knee moment magnitudes decreased (Figure 1). Across both riser-heights and groups, ankle joint negative power was predominant during the landing phase, and knee joint negative power was predominant during the lowering phase; with the magnitude of negative ankle joint power increasing as riser-height increased (Figure 2). The greatest amount of negative joint work done in both groups was at the ankle during landing for the increased height condition (Table 1 and Table 2). For both age groups, hip moment and power contribution was minimal across each phase irrespective of riser-height. This finding was expected based on previous similar findings [3,5,7,10], and thus we make no further reference to the insignificant contribution of hip joint kinetics.

FIGURES ONE

FIGURE TWO

At the increased stair riser-height, both groups exhibited a significant increase in peak moment and work done at the ankle joint and an accompanying significant reduction in peak moment and work done at the knee joint; indicating much greater reliance on the ankle joint. When subtracting the ensemble knee moment profile from the ensemble ankle moment profile, the resulting moment difference profile (Figure 4) was predominantly positive, which indicates that the magnitude of the ankle moment was greater than the knee moment and particularly so during the lowering phase. Greater peak CoM downward accelerations and velocities (Figure 3), and greater peak foot velocity (Table 1 and Table 2) were also evident as riser-height increased. Older adults produced lower peak CoM downward accelerations and velocities and a reduction in peak moment at the ankle, coupled with a reduction in peak work done at the ankle and an increase in phase duration during the lowering phase, at both riser-heights.

3.1 Relationship between joint moment and CoM vertical acceleration:

Plotting the support moment and CoM downward acceleration profiles against each other (Figure 3) shows that a temporal relationship exists between the fluctuations in the two profiles for both age groups. The relationship highlights that when the support moment reduces in magnitude the COM accelerates downwards and when the moment increases in magnitude the COM downwards acceleration is slowed and/or begins to accelerate upwards. Figure 3 also illustrates that differences in movement control strategy exist between the young and older adults during the landing and lowering phases of descent. Young adults produced a greater support moment than older adults at both stair riser-heights following periods where there was an increase in CoM accelerations.

FIGURES THREE

FIGURE FOUR

3.2 Group differences and riser-height general effects:

Tables 1 and 2 present group mean kinematic and kinetic parameters for the landing and lowering phase. These tables highlight the differences in these parameters between age groups and changes because of increasing riser-height. As we were mainly interested in the effects of riser-height across the two age groups, the results described here do not refer to significant limb differences between stair two and stair three, or significant interactions between limb and age or riser-height. Limb effects are reported in Tables 1 and 2 for information purposes only.

3.2.1 Landing Phase:

Landing duration and Peak CoM upwards acceleration during landing (peakAcc-Land) were significantly affected by riser-height ($P < 0.001$), but unaffected by age ($p = 0.186$ and $p = 0.108$, respectively) and there was no interaction between terms. In both groups landing phase was longer at the standard compared to increased riser-height, and peak upwards acceleration was greater at the increased compared to standard riser-height.

Peak moment and negative (eccentric) work done by the ankle during landing were significantly affected by age ($p < 0.001$ and $p = 0.045$, respectively) and riser-height ($p < 0.001$), but there was no interaction between terms. At both riser-heights peak ankle moment and ankle negative work were greater in young compared to older adults. In both groups, peak ankle moment and ankle negative work were increased at the increased compared to standard riser-height, but the increases were slightly greater for the older adults (68.4% and 87.8%, respectively; increased versus standard riser-height) compared to young adults (64.5% and 76.1%, respectively; increased versus standard riser-height). Peak knee moment and negative work done by the knee during landing were significantly affected by riser-height ($p = 0.001$ and $p = 0.033$, respectively), but unaffected by age ($p \geq 0.128$), and there was no interaction between terms. In both groups, peak knee moment and negative knee work were reduced at the increased compared to the standard riser-height.

3.2.2 Lowering Phase

Duration of lowering, peak CoM downwards velocity (peakVel), acceleration (peakAcc), and lead-foot peak downwards velocity (peakFootVel) were significantly affected by age ($p \leq 0.010$) and riser-height ($p < 0.001$). There was a significant age by riser-height interaction for duration of lowering ($p = 0.009$); older adults took longer to lower themselves at both riser-heights, but the increase in duration was significantly greater at the increased riser-height. Young adults produced greater peak downward velocities, accelerations and lead-foot peak downwards velocities compared to older adults. Both groups exhibited greater peak downward velocities, accelerations and lead-foot peak downwards velocities at the increased compared to standard riser-height.

Peak ankle moment was significantly affected by age ($p = 0.016$) and riser-height ($p < 0.001$), but there was no interaction between terms. Peak ankle moment was greater in young compared to older adults, and in both groups was greater at the increased compared to the standard riser-height. Peak knee moment ($p < 0.001$), negative work done by the ankle ($p = 0.031$) and positive work done by the ankle ($p = 0.027$) were significantly affected by riser-height, but unaffected by age group ($p \geq 0.154$), and there was no interaction between terms. In both age groups, peak knee moment was reduced at the increased compared to the standard stair riser-height. Ankle negative and positive work done was greater at the increased compared to standard riser-height. The negative work done by the knee was unaffected by age ($p = 0.879$) and riser-height ($p = 0.235$).

TABLE ONE

TABLE TWO

4.0 Discussion

The aim of this study was to determine whether increasing riser-height had a differential effect on older compared to younger adults, in terms of the CoM vertical velocity and acceleration profiles and the associated moments and work produced at the lower-limb joints during both the landing and lowering phases of stair descent. The hypothesis (1) that peak CoM vertical velocities and accelerations, and peak hip, knee and ankle joint moment and work during both the landing and lowering phases, would all be greater in both age groups when stair riser-height increased, was only partially accepted due to minimal change at the hip and a decrease in knee joint moment and work. The hypothesis (2) that such increases would not be as marked for older compared to young adults, was also only partially accepted due to minimal differences between groups at the knee and hip joints. Our findings demonstrate that the velocity of lowering increases in both age groups when the height of lowering is greater than the recommended standard, as evidenced by increases in CoM accelerations and velocities, and increased ankle moments, during landing and lowering when descending from 255mm riser-height. This indicates that stair descent became more challenging when riser height was increased.

4.1 Landing Phase

At the increased riser-height during landing, both groups demonstrated an increased magnitude of ankle plantarflexion moment, a parameter known to play an important role in arresting downward momentum via controlling eccentric plantarflexion [1]. Young adults produced greater ankle plantarflexion moments than older adults. This may explain why there was a trend towards young adults exhibiting greater peak CoM upwards acceleration (i.e. positive acceleration of the CoM in the downward direction) during landing at both riser-heights; whereby the higher leading-limb plantarflexion ankle moment would create greater eccentric ankle resistance during the initial landing period (when the leading limb is in a plantarflexed position [7,8]) which would arrest downward momentum more abruptly (hence the greater upward acceleration). Along with an increase in plantarflexion moment at the increased riser-height there was also an increase in negative work done at the ankle in both groups. The negative ankle work highlights eccentric action at the ankle during initial landing. Older adults produced significantly less negative work at the ankle joint than young adults at both riser-heights. This reflects the lower eccentric maximum strength capabilities previously reported [1] and is likely linked to a more cautious lowering phase; that is, they deliberately reduced lowering speed to avoid the landing limb having to generate the increased plantarflexion moment (and negative work).

Landing-limb peak knee extensor moments were reduced during landing at the increased riser-height in comparison to the standard riser-height, and were of similar magnitude across groups. As a consequence, only a small amount of negative work done (power absorption) was evident at the knee. In contrast, landing-limb peak ankle moment generation at the increased riser-height was approximately twice that generated at the knee joint (Figure 4). This highlights a greater reliance on the leading-limb ankle plantarflexors (eccentric action) rather than the knee extensors, during the initial period of weight acceptance when transferring body weight from the supporting to the landing-limb. Prior to landing at the increased riser-height both the lead-limb ankle and knee will likely have been near-maximally extended to increase the overall leg length and ensure landing happened as soon as possible. Given the minimum work subsequently done at the knee during landing, this suggests the knee had minimal eccentrically controlled flexion. In contrast, the higher negative work done at the ankle indicates there was greater reliance on the ankle at the increased riser-height to control landing. By landing on the toes, eccentric dorsiflexion could then occur to lower the foot and hence CoM to the lower level and thus arrest downwards velocity. This underlines the key role of the ankle joint when coping with increased task demands, as reported previously [8].

4.2 Lowering Phase

Older adults took significantly longer, at both riser-heights compared to young adults, to lower themselves to the stair tread below and the increase in duration was greater for the increased compared to standard riser-height. This finding, coupled with significantly reduced CoM downwards velocities/accelerations, suggests older adults were more hesitant/cautious than young participants. Previous research reported that older adults adopted an alternative strategy during stair descent by stiffening the supporting limb (co-activation of the key musculature at the ankle and knee) for longer than young adults, thus slowing the rate of CoM lowering as weight was transferred from the supporting limb to the landing limb [28]. In the present study, peak ankle moments during lowering were increased for both groups at the higher riser-height whilst peak knee moments were reduced, indicating a much greater reliance on the ankle joint (Figure 4). This finding is supported by a previous report that highlighted the ankle as an important joint in controlling stair descent, with both young and older adults producing ankle joint moments at a level close to the limits of their joint capacity (75%), and much less involvement at the knee joint [8]. In the present study, the greater reliance on the ankle indicates that the older adults, like the young, were capable of modulating the joint moments required at the ankle and knee to cope with the increased demands of the task. However, older adults chose to be more cautious than younger adults in their lowering approach at the increased riser-height, producing lower peak CoM downward accelerations and velocities and a reduction in the ankle joint contribution. Here we further underline the importance of the ankle joint muscle groups in both age groups when adapting to the increased demands of a higher riser-height. This further confirms why current practice, regarding falls interventions in older adults focused on reducing falls risk, should include resistance training programmes focused on the ankle joint and particularly the ankle plantarflexor muscles. Recent findings also advocate the use of a side-step strategy to avoid increased loading of the ankle plantarflexors during stair descent [2].

It is not possible to say, based on the current data, whether a fall is more likely to occur in the landing or lowering phase during periods of excessive eccentric demand on the ankle joint. This is because the data from the current study show the contribution of the ankle joint during both phases of stair descent is important for maintaining the CoM within manageable limits. The supporting limb experiences high ankle joint moments over a large range of dorsiflexion and is responsible for lowering the body mass to the stair below. The landing limb requires high ankle joint moments with the ankle in a plantarflexed positon and is responsible for attenuating the impact of landing. Therefore, both phases are important and intimately linked to one another during step-over-step stair descent.

Many of the variables analysed were affected by limb-by-height interactions (Table 1), which indicates that participants, irrespective of age, exhibited different stepping behaviours on each stair. This is possibly because participants could have been affected by the biomechanical demands of transitioning at the top of the staircase (level-to-descent) during landing and lowering on/over stair two. Equally, when landing and lowering on/over stair three participants may have started to prepare for the transition at the bottom of the staircase (descent-to-level). For this reason, our analysis cannot be considered ‘steady-state stair descent’, and thus this is a limitation when interpreting the results. Ideally, a staircase with a larger number of stairs (e.g. 7-step staircase) would allow for participants to achieve continuous descent gait cycles to separate the transitions at the top and bottom of the stairs more clearly [29].

5.0 Conclusion

Descending stairs became more challenging in both age groups as riser-height increased as evidenced by the increase in CoM accelerations and velocities, and increased ankle moments, during landing and lowering when descending from 255mm riser-height. Older adults adopted a stair descent strategy, particularly so at the higher stair riser-height, whereby they ensured downward CoM velocity was maintained within manageable/safe limits as evidenced by their lower CoM velocity, longer duration of lowering and percentage increase in negative ankle work, compared to young adults. The reduced moment and power peaks in older adults during both the lowering and landing phases, particular at the ankle, suggests older participants were not capable of developing similarly high moments to the young. This reduced capacity likely explains why the older participants also limited their CoM lowering velocity. The results presented here support the approach of training interventions focussing on the ankle plantarflexors for older adults to cope with the physical demands of stair negotiation, particularly for when negotiating higher riser-heights.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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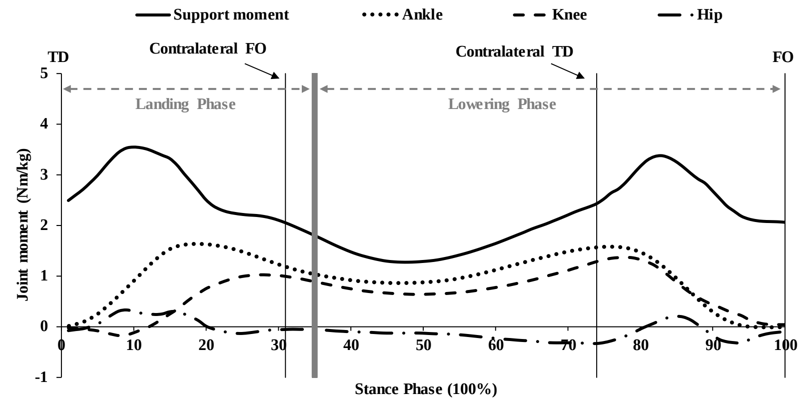
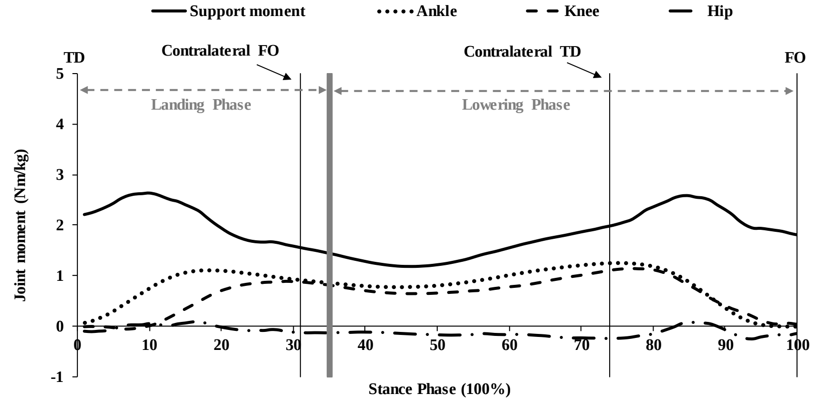
Figures



a)



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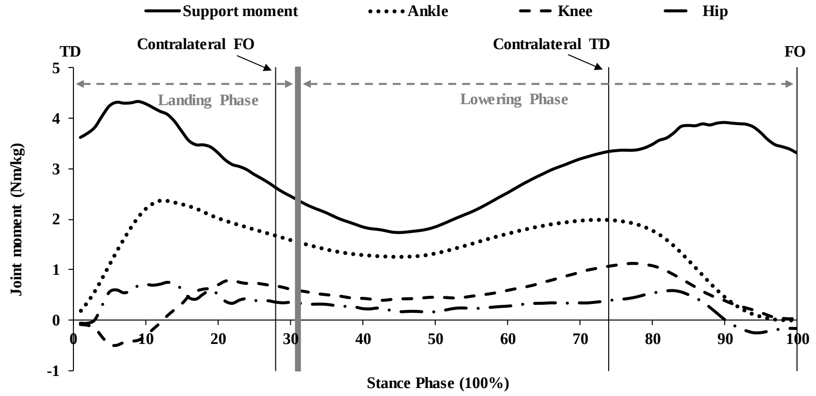

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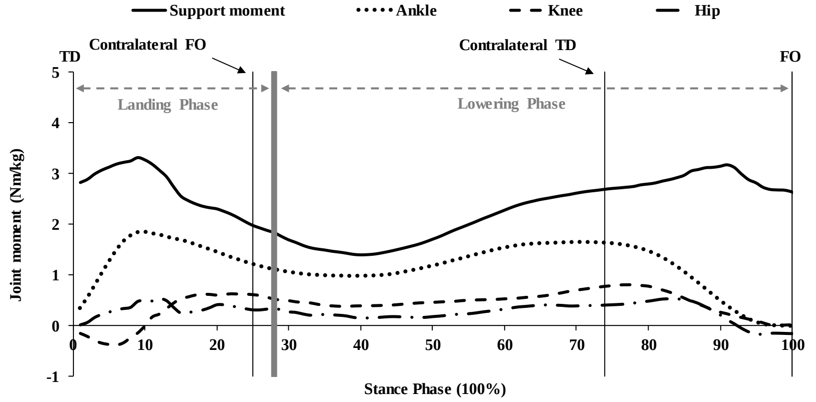

d)

Figure 1. Group ensemble average joint moments (normalised to body mass) for the ankle, knee, hip and the support moment (hip-knee-ankle) during the landing and lowering phases for young and older adults at the standard height (a and b, respectively) and increased height (c and d, respectively). NB; Positive values correspond to internal plantarflexor, knee extensor and hip extensor moments. Thin vertical black lines represent touch-down (TD) and foot-off (FO). Thick grey lines represent the end of the landing phase and start of the lowering phase. Horizontal grey dashed arrows represent landing and lowering phase durations.

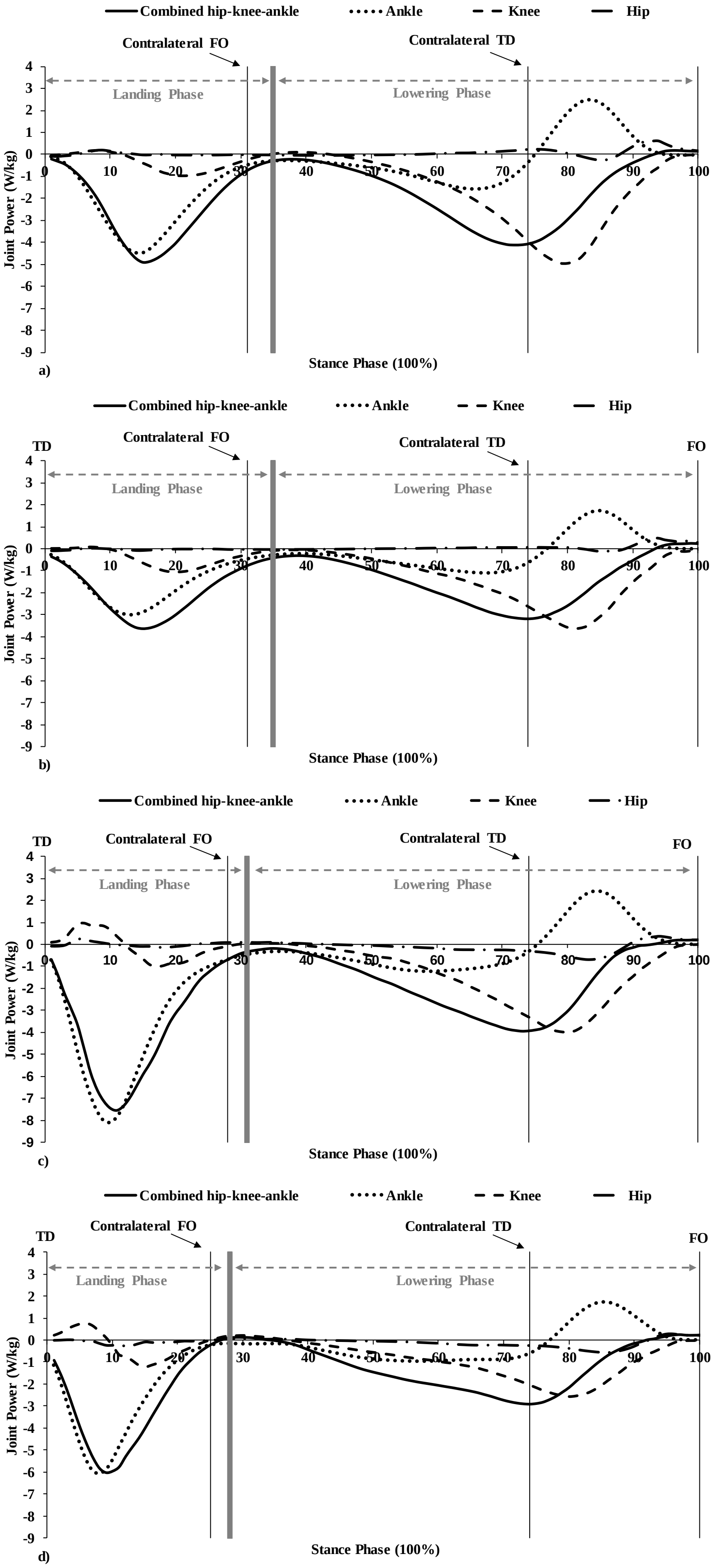
Combined hip-knee-ankle
Ankle
Knee
Hip
Contralateral FO
Contralateral TD
Landing Phase
Lowering Phase
Joint Power (W/kg)
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
60
70
80
90
100
Stance Phase (100%)
a)
Combined hip-knee-ankle
Ankle
Knee
Hip
TD
Contralateral FO
Contralateral TD
FO
Landing Phase
Lowering Phase
Joint Power (W/kg)
Stance Phase (100%)
b)
Combined hip-knee-ankle
Ankle
Knee
Hip
TD
Contralateral FO
Contralateral TD
FO
Landing Phase
Lowering Phase
Joint Power (W/kg)
Stance Phase (100%)
c)
Combined hip-knee-ankle
Ankle
Knee
Hip
TD
Contralateral FO
Contralateral TD
FO
Landing Phase
Lowering Phase
Joint Power (W/kg)
Stance Phase (100%)
d)

Figure 2. Group ensemble average joint powers (normalised to body mass) for the hip, knee, and ankle and for entire limb (hip-knee-ankle) during the landing and lowering phases for young and older adults at the standard height (a and b, respectively) and increased height (c and d, respectively). NB; the areas under the positive and negative portions of the curves represent the positive and negative work done at each joint. Thin vertical black lines represent touch-down (TD) and foot-off (FO). Thick grey lines represent the end of the landing phase and start of the lowering phase. Horizontal grey dashed arrows represent landing and lowering phase durations.

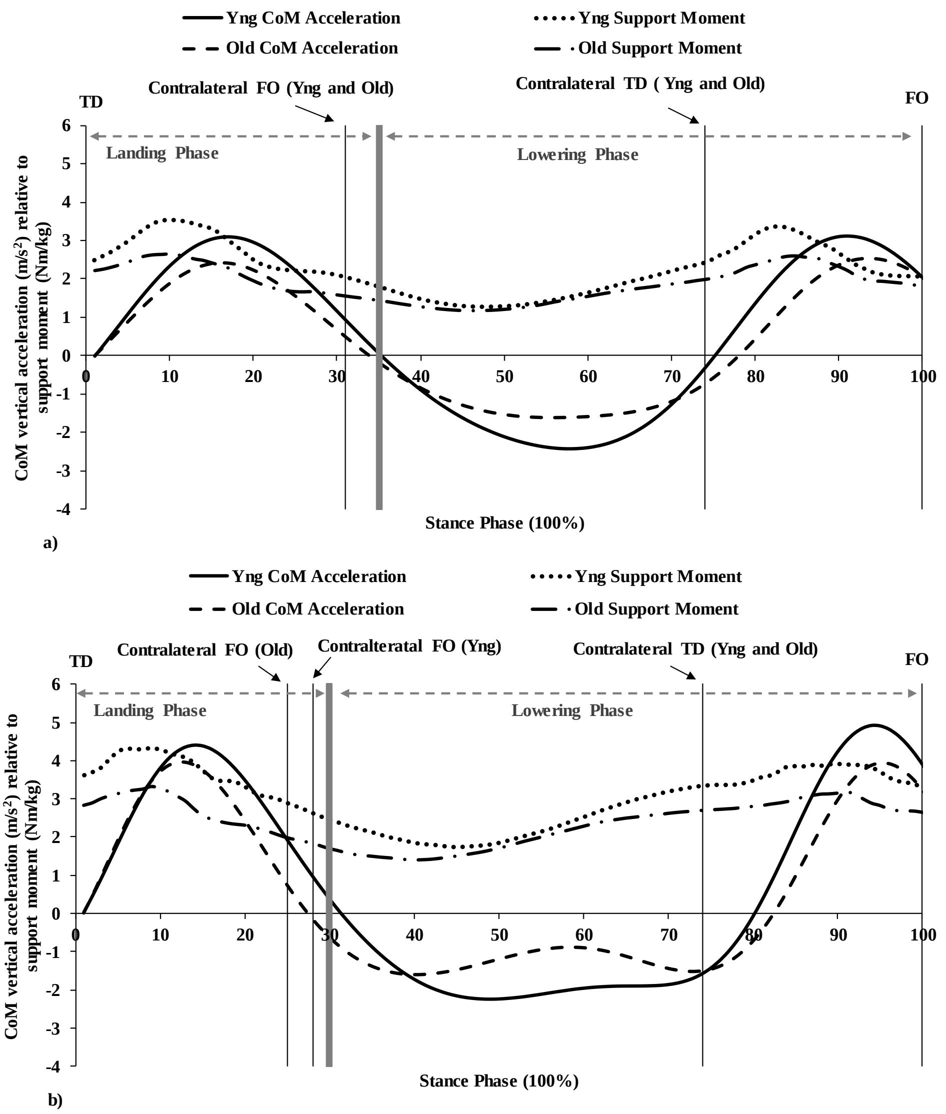

Figure 3. Group ensemble average centre of mass downwards acceleration and support moment profile during the landing and lowering phases for young and older adults at the standard (a) and increased stair riser-height (b). NB; Thin vertical black lines represent touch-down (TD) and foot-off (FO). Thick grey lines represent the end of the landing phase and start of the lowering phase. Horizontal grey dashed arrows represent landing and lowering phase durations.

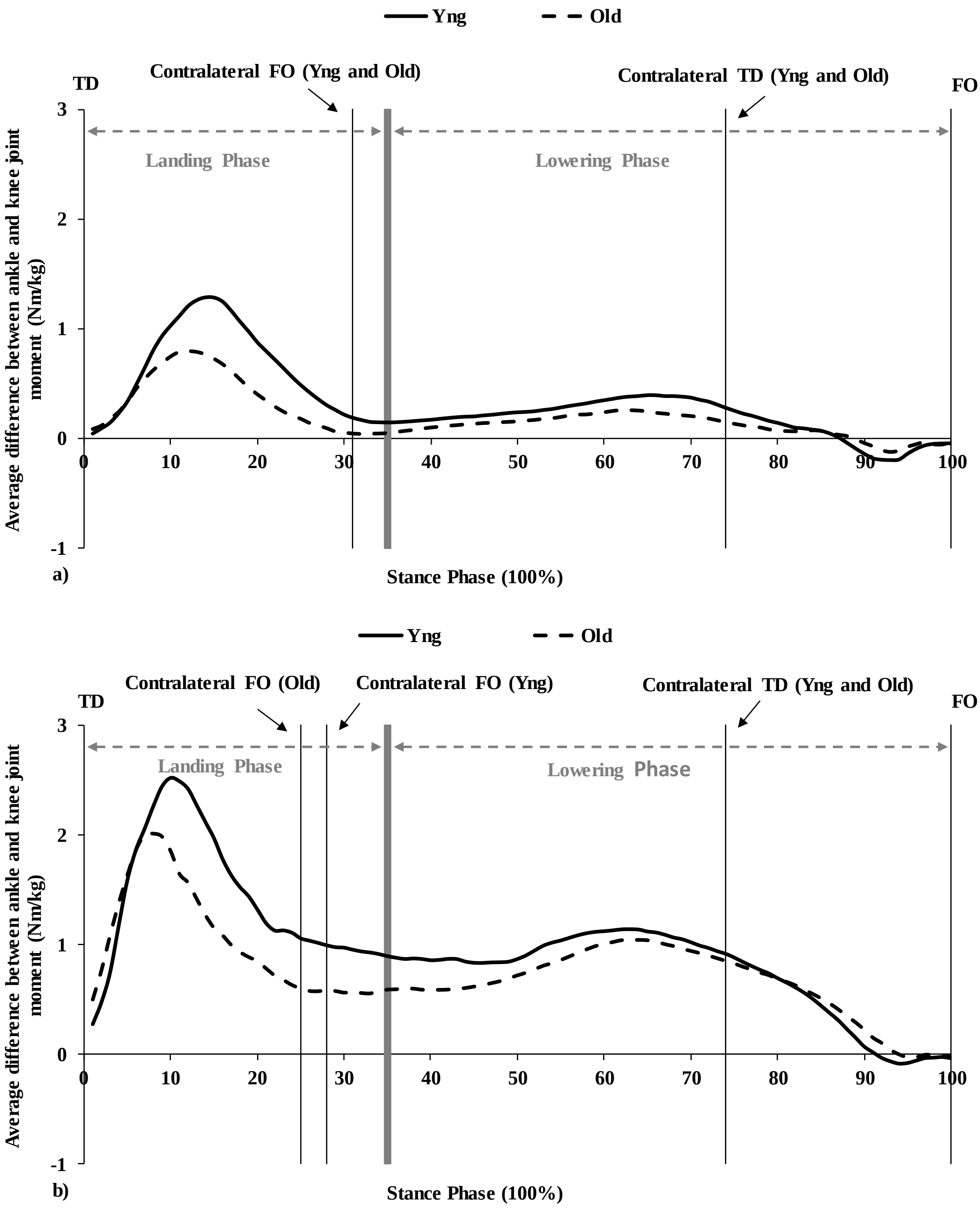

Figure 4. Group ensemble average difference between the ankle and knee joint moment contribution for young and older adults at the standard (a) and increased (b) stair riser-height during the landing and lowering phases. NB; A positive value indicates that the magnitude of the ankle moment was greater than the knee moment produced. Thin vertical black lines represent touch-down (TD) and foot-off (FO). Thick grey lines represent the end of the landing

phase and start of the lowering phase. Horizontal grey dashed arrows represent landing and lowering phase durations.

Table 1. Landing phase group mean (± SD) differences for young (Yng) and older (Old) adults when descending stairs two and three of a four step-staircase at riser-heights of 170 mm and 255 mm.

Landing	Age group	Height 170 mm		Height 255 mm		ANOVA (p value)
		Stair 2	Stair 3	Stair 2	Stair 3	
Phase duration (s)	Yng	0.28 ± 0.03	0.27 ± 0.02	0.25 ± 0.03	0.25 ± 0.04	Age (= 0.186) **Height (< 0.001)** Limb (= 0.087)
	Old	0.30 ± 0.04	0.28 ± 0.05	0.27 ± 0.03	0.26 ± 0.03	
CoM peakAcc-land (m/s^2)	Yng	2.99 ± 1.07	3.09 ± 1.02	4.62 ± 1.68	5.18 ± 1.71	Age (= 0.108) **Height (= 0.000)** **Limb (= 0.003)**
	Old	2.42 ± 1.05	2.83 ± 0.93	3.85 ± 1.25	4.31 ± 0.96	
Ankle Moment (Nm/kg)	Yng	1.75 ± 0.50	1.81 ± 0.37	2.75 ± 0.66	3.11 ± 0.76	**Age (= 0.001)** **Height (= 0.000)** **Limb (= 0.001)** **Height* Limb (= 0.003)**
	Old	1.26 ± 0.41	1.33 ± 0.59	2.00 ± 0.56	2.36 ± 0.49	
Knee moment (Nm/kg)	Yng	1.07 ± 0.38	0.98 ± 0.39	0.93 ± 0.34	0.68 ± 0.32	Age (= 0.886) **Height (= 0.001)** Limb (= 0.153) **Height* Limb (= 0.041)**
	Old	1.00 ± 0.36	1.05 ± 0.54	0.87 ± 0.49	0.81 ± 0.51	
Ankle neg work done (J/kg)	Yng	-0.53 ± 0.16	-0.68 ± 0.17	-0.85 ± 0.37	-1.28 ± 0.44	**Age (= 0.045)** **Height (= 0.000)** **Limb (= 0.000)** **Height*Limb (< 0.001)**
	Old	-0.42 ± 0.16	-0.52 ± 0.25	-0.68 ± 0.17	-1.09 ± 0.29	
Knee neg work done (J/kg)	Yng	-0.10 ± 0.06	-0.10 ± 0.07	-0.10 ± 0.06	-0.07 ± 0.08	Age (= 0.128) **Height (= 0.033)** Limb (= 0.338)
	Old	-0.14 ± 0.08	-0.15 ± 0.11	-0.12 ± 0.10	-0.11 ± 0.09	

Note. Boldface type indicates a statistically significant effect.

Table 2. Lowering phase group mean (± SD) differences for young (Yng) and older (Old) adults when descending stair two and three of a four step-staircase at riser-heights of 170 mm and 255 mm.

Lowering	Age group	Height 170 mm		Height 255 mm		ANOVA
		Stair 2	Stair 3	Stair 2	Stair 3	
Phase duration (s)	Yng	0.43 ± 0.04	0.43 ± 0.04	0.57 ± 0.08	0.52 ± 0.07	**Age (= 0.000)** **Height (= 0.000)** **Limb (= 0.024)** **Age*Height (= 0.009)**
	Old	0.53 ± 0.10	0.50 ± 0.05	0.72 ± 0.12	0.68 ± 0.10	
CoM peakVel (m/s)	Yng	-0.55 ± 0.09	-0.56 ± 0.08	-0.71 ± 0.13	-0.76 ± 0.13	**Age (= 0.008)** **Height (< 0.001)** **Limb (< 0.001)** **Height*Limb (= 0.002)**
	Old	-0.46 ± 0.09	-0.50 ± 0.08	-0.59 ± 0.10	-0.67 ± 0.09	
CoM peakAcc (m/s^2)	Yng	-2.38 ± 0.68	-2.46 ± 0.78	-2.80 ± 0.77	-3.01 ± 0.79	**Age (= 0.005)** **Height (< 0.001)** **Limb (= 0.011)** **Height*Limb (0.033)**
	Old	-1.80 ± 0.74	-1.80 ± 0.81	-2.08 ± 0.57	-2.41 ± 0.53	
peakFootVel (m/s)	Yng	-1.35 ± 0.14	-1.31 ± 0.18	-1.57 ± 0.20	-1.63 ± 0.19	**Age (= 0.010)** **Height (< 0.001)** Limb (= 0.167) **Age*Height*Limb (= 0.024)**
	Old	-1.17 ± 0.20	-1.24 ± 0.14	-1.42 ± 0.24	-1.45 ± 0.15	
Ankle Moment (Nm/kg)	Yng	1.60 ± 0.34	1.61 ± 0.35	2.15 ± 0.56	2.15 ± 0.50	**Age (= 0.016)** **Height (< 0.001)** Limb (= 0.203)
	Old	1.29 ± 0.25	1.44 ± 0.29	1.73 ± 0.40	1.74 ± 0.38	
Knee moment (Nm/kg)	Yng	1.37 ±0.44	1.27 ±0.25	1.15 ±0.33	1.07 ±0.34	Age (= 0.154) **Height (< 0.001)** Limb (= 0.734)
	Old	1.21 ±0.23	1.21 ±0.34	0.92 ±0.30	1.02 ±0.32	
Ankle Neg work done (J/kg)	Yng	-0.26 ± 0.11	-0.31 ± 0.16	-0.32 ± 0.22	-0.35 ± 0.20	Age (= 0.788) **Height (= 0.031)** Limb (= 0.076)
	Old	-0.25 ± 0.10	-0.30 ± 0.11	-0.31 ± 0.16	-0.33 ± 0.14	

Ankle Pos work done (J/kg)	Yng	0.22 ± 0.05	0.23 ± 0.03	0.24 ± 0.09	0.33 ± 0.11	Age (= 0.351) **Height (= 0.027)** **Limb (< 0.001)** **Age*Limb (< 0.001)** **Age*Height*Limb (= 0.043)**
	Old	0.17 ± 0.05	0.36 ± 0.20	0.22 ± 0.09	0.35 ± 0.10	
Knee Neg work done (J/kg)	Yng	-0.84 ± 0.25	-0.74 ± 0.14	-0.78 ± 0.30	-0.74 ± 0.21	Age (= 0.879) Height (= 0.235) Limb (= 0.634)
	Old	-0.79 ± 0.15	-0.80 ± 0.23	-0.70 ± 0.28	-0.77 ± 0.24	

Note. Boldface type indicates a statistically significant effect.