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Article

Negotiating stairs with an inconsistent riser: Implications for stepping safety

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Abstract:

Stairs are associated with falls, especially when step dimensions are inconsistent. However, the mechanisms by which inconsistencies cause this higher risk are mostly theoretical. In this experimental study we quantified the effect of inconsistent rise heights on biomechanical measurements of stepping safety from younger (n=26) and older adults (n=33). In ascent, both groups decreased foot clearance (~9 mm) over the inconsistently

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higher step (F(1,56)=48.4, p<0.001). In descent, they reduced foot contact length on the higher step by 3% (F(1,56)=9.1, p<0.01). Reduced clearance may result in a toe-catch potentially leading to a trip, while reduced foot contact lengths increase the risk of overstepping which may also lead to a fall. These effects occurred because participants did not alter their foot trajectories, indicating they either did not detect or were not able to adjust to the inconsistent rise, increasing the likelihood of a fall. Consistent stair construction is vital, and existing inconsistencies should be identified and safety interventions developed.

Key Words: Variable dimensions, Step geometry, Fall risk

Author Contributions

All listed authors meet the authorship criteria and have read the manuscript and agreed to it being submitted for publication. In brief, NCF, TOB, CM, MH, MR contributed to the conceptualisation and design of the study; NCF, TA, DH, to data acquisition; NCF, TA, DH, SE to data analysis; NCF, TA, DH, SE, CM, MH, KK, MR, TOB to the interpretation of results; NCF drafted the manuscript; NCF, TA, DH, SE, CM, MH, KK, MR, TOB contributed to the editing and revisions of the manuscript. There is nobody else who qualifies for authorship who has been excluded from the author list.

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1.1 Introduction

Stairs are one of the leading hazards within our environment, they are regularly associated with falls leading to serious injuries, concussions and even death (Startzell et al., 2000). In the UK approximately 10 fatalities per week are linked with stair falls (Roys, 2013). Although older adults are at the highest risk of serious injury from a stair fall (70% of fatal stair falls) (BSI, 2010), younger persons are also reported to have a high injury rate (Blazewick et al., 2018). The mechanisms behind stair falls are multifactorial and still to be properly understood. However, it is clear that the built environment, including stairway design and stairway maintenance, interacts with human behaviour, which can increase the risk of experiencing a fall (Jacobs, 2016; Nemire et al., 2016; Roys, 2001; Templer, 1992).

Building regulations govern the design of new stairs (HM Government, 2013; NFPA 101, 2000). In addition to defining the acceptable rise and going dimensions of each step, steps should be uniform. British Standards permit a variability of not more than 1% in step dimensions (BSI, 2010), while regulations in the USA state that a variation of 4.8 mm or greater between adjacent steps is not acceptable, and that the difference between the smallest and the largest step should not exceed 9.5 mm (NFPA 101, 2000). However, regulations only govern newly built stairs, and inconsistencies greater than those now permitted exist on older stairs (Cohen et al., 2009; Wright and Roys, 2008). These inconsistencies in step dimensions have been linked to an increased fall risk (BSI, 2010; Johnson and Pauls, 2010; Roys and Wright, 2005; Roys, 2001).

In fact, an investigation of 80 stair falls found that 60% of the stairs involved had an inconsistency in the rise, which was larger than the permitted limit of 9.5 mm (Cohen et al., 2009). In ascent, an inconsistently greater rise has been observed to increase the occurrence of toe-catches and trips (Johnson and Pauls, 2010; Templer, 1992). However, mechanisms of falls due to an inconsistent rise in descent have not been studied, although they are hypothesised to reduce foot contact length, increasing the risk of a slip (Roys and Wright, 2005). Given that more severe injuries occur during descent than ascent (Cohen et al., 2009; Templer, 1992) this gap in our knowledge prevents adequate intervention design or policy-making to reduce rates of the most important falls.

It is proposed that visual information is used to help create a cognitive plan of the stairs, which prepares the motor response and stair biomechanics (Hale and Glendon, 1987 as cited by Templer, 1992). With the inclusion of proprioceptive feedback from first few steps, a user is thought to have established their stepping pattern for the stairs after only three steps (Roys and Wright, 2005). It is hypothesised that step inconsistencies become dangerous when they are not detected or not interpreted as a danger, and there becomes a discrepancy between perception and the real stairs, consequently increasing the risk of a miss-step (Roys and Wright, 2005; Roys, 2001; Templer, 1992).

Older adults are generally at a greater risk of stair falls than younger adults (Blazewick et al., 2018; BSI, 2010), but it is not known whether they respond to stair inconsistencies in a different way. The ageing-associated deteriorations in vision, as well as musculoskeletal function and motor control (Startzell et al., 2000), may make older adults less able to detect inconsistencies and modify their behaviour to the environment appropriately, and be less able to respond to a loss of balance putting them at a greater risk of a fall.

Therefore, the aim of this study was to identify the mechanisms by which steps with inconsistent rise heights increase the risk of a toe- or heel-catch (trip) or overstep (possible slip), and to determine whether these risks for a fall are different between younger and older adults.

1.2 Hypothesis1

In stair ascent, for both younger and older adults, an inconsistent higher rise will cause a decreased foot clearance from the inconsistent step-edge (higher rise) and will reduce the amount of foot contact length on the inconsistent step.

1.3 Hypothesis2

In stair descent, for both younger and older adults, an inconsistent higher rise step will cause a reduced foot contact length on the inconsistent step (with a smaller rise) and will negatively affect subsequent foot clearances.

2.1 Materials and Methods

2.2 Participants

Twenty-six younger adults (24 ± 3 y, 1.74 ± 0.09 m, 71.41 ± 11.04 kg) and thirty-three older adults (70 ± 4 y, 1.68 ± 0.08 m, 67.90 ± 14.10 kg,) were recruited from the local area. Participants negotiated stairs regularly within their home or local environment and had been free from lower-limb injury for six months prior to testing. The study was approved by the NHS research ethics committee (IRAS ID: 216671) and local university ethics and was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent.

2.3 Protocol

Participants attended the laboratory, were familiarised with the seven-step stairs with consistent dimensions and were then asked to navigate the stairs with an inconsistent higher rise. Participants were not aware of the specific changes made to the stairs until after completion of the experiment.

During measurements, participants wore tight fitting clothes and their own comfortable shoes with a closed toe and no raised heel. Participants were fitted into a 5-point safety harness and were connected to an over-head safety rail via rope, which was controlled by a trained member of the team who was also secured via rope to the floor. Participants first ascended and descended the stairs with consistent dimensions representing those typically found within the home (200 mm riser, 250 mm going, pitch 38.7°, *see* Figure 1. a). Five ascent and descent trials were completed. All participants started from a self-selected distance away from the stairs, permitting one level ground step to be taken on the walkway before commencing stair ascent. Participants were always standing in double support prior to the start of the trial. On the researcher's signal, participants always stepped with their left foot on the walkway. Their right foot was always the first foot to step onto the stairs, participants continued in a step-over-step manner without use of the handrails towards the landing or walkway, and they took two level ground steps before stopping. Participants were offered the opportunity to rest for as long as they wanted between trials.

Participants then left the room while step dimensions were made inconsistent. Most stair inconsistencies occur when the edge of one step is out of place on the staircase of an otherwise consistent pitch. To represent this effect, we moved the stepping surface of Step3 upwards by 10 mm. This had the effect of increasing the rise between Step2 and Step3 surfaces and decreasing the rise between Step3 and Step4 surfaces (see Figure 1a and 1b), overall pitch was maintained to 38.7°. This magnitude of dimension inconsistency is not permitted in the UK or USA building regulations however inconsistencies of this magnitude and greater have been observed within home stairs (Nemire et al., 2016; Roys, 2013) and in the environment (Cohen et al., 2009; Nemire et al., 2016). The researchers wanted to use a realistic inconsistency that exceeds the permitted regulations.

Participants were not made aware of the specific changes made to the stairs and were told that the stairs may or may not change while they were out of the room. This time was also used as rest to avoid fatigue. Despite the information given to the participants the dimensions were always changed before the participants returned. When invited back in, participants were reconnected to the safety system and ascended and descended the inconsistent stairs. To minimize any learning effects for this study, only the first ascent and descent trial were analysed, however participants always ascended before they descended the stairs.

2.4 Instrumentation

For the measurement of foot clearance and percentage foot contact length, 3D motion of the foot was captured using 24 infra-red Vicon cameras covering the whole stairs, landing, and walkway (120 Hz, Vicon, Oxford Metrics, UK). Kinetic data were synchronously recorded from four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps of the stairs (Step1-4, *see* Figure 1). Foot markers were placed on the lateral and medial malleolus (ankle), first and fifth meta-phalange joints (base of big and little toe) and on the posterior calcaneus (heel). Additional markers were placed on the lateral and medial calcaneus and a rigid cluster of three markers were placed over the toes.

A rigid 2D surface model of the shoe sole outline was created by tracing the outline of the shoes onto paper. The outline was digitised, and the position of each digitised point was referenced to the centre of the lateral calcaneus (origin), first and fifth meta-phalange markers. These markers were tracked throughout the movement trials. For foot clearance, the boundary of the digitised shoe sole was used to determine the linear distance to the step-edge (during swing). For percentage foot contact length, the linear distance between the furthest forward (ascent) or backward (descent) point of the outline to the step-edge was calculated and converted to a percentage of the total length.

To calculate foot clearance and percentage foot contact length variables, kinematic and kinetic data were imported into Matlab (R2017b, The Mathworks, Natick, USA) along with step-edge locations (defined by custom-made clusters of known dimensions), the participant static calibration, and the digitized shoe sole outlines (ImageJ: National Institutes of Health, Bethesda, USA).

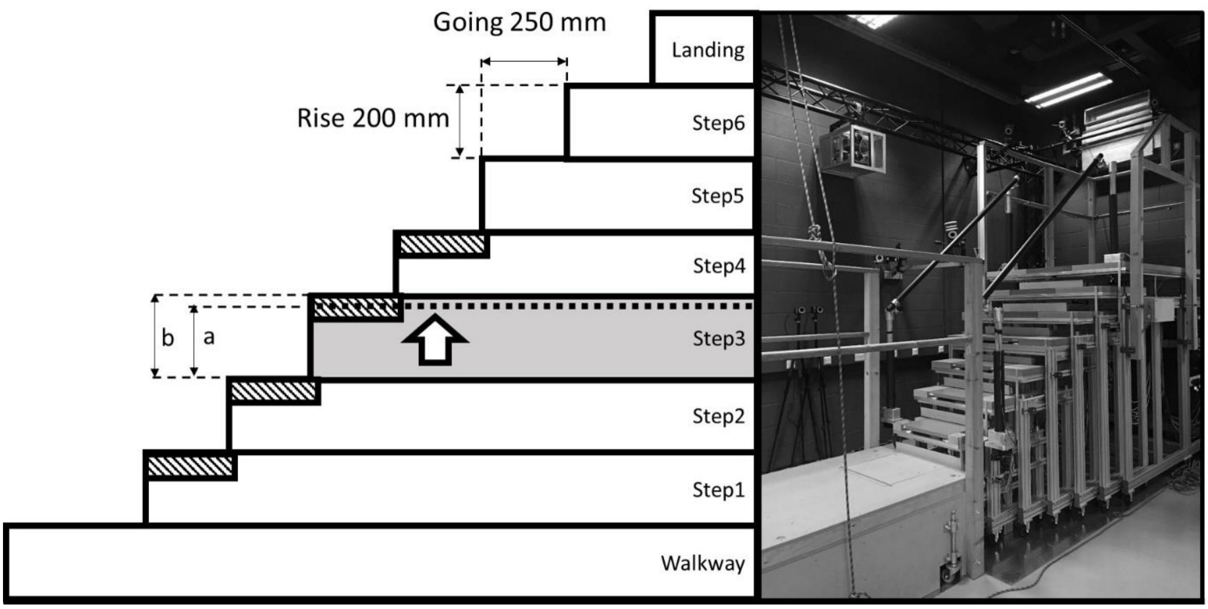

Figure 1. Seven-step stairs, with four force plates located in Step1-4. For the consistent condition a) all steps had a rise height of 200 mm, a going of 250 mm. For the inconsistent rise condition b) only Step3 was moved 10 mm upwards, increasing rise to Step3 to 210 mm thus reducing rise to Step4 to 190 mm, all other steps and pitch remained unaltered.

2.5 Data Analysis

Data from at least three trials were averaged (five where possible, average number of trials = 4.7 ± 0.6) for the consistent dimension condition and the first trial was used for the inconsistent higher rise condition, trials with incomplete force data or long periods of occluded markers were not included in the analysis. Kinetic and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6 Hz in Visual 3D (version 6.01.043 Visual3D, C-Motion, Germantown, USA). Foot centre of mass (CoM) was calculated according to Dempster's regression equations (Dempster, 1955) and were individualised to a participants height and mass as described by Hanavan (Hanavan, 1964).

Foot clearance was chosen as the outcome measure to quantify the risk of toe or heel catch. Foot contact length was chosen as the outcome measure to quantify the risk of over or under stepping.

2.5.1 Foot Clearance (mm) in ascent (*see,* Figure 2. A) was defined as the vertical distance from the step-edge to the most anterior point of the shoe sole outline (including toe-spring correction). Foot clearance was calculated at the instant the shoe outline passed the horizontal position of the step-edge. Toe-spring is the vertical gap that is created under the toes of most modern shoes and the floor, this was not reflected in the 2D surface model of the shoe and instead was applied post data collection. For this study, the toe-spring gap was estimated from a separate pilot study and was measured from the floor to the sole under the highest and most anterior point of the shoes, this value was considered relative to the height of the top of the shoes. It was possible to obtain the height of the top of the shoes for the participants post data collection, as a rigid cluster of known dimensions with three reflective markers was positioned consistently over the top of the shoe for all participants and was available in the motion capture videos. The mean toe-spring height for a range of shoes tested was 0.53 * height of top of the shoe from the floor. Each participant's toe-spring correction value was only applied to the most forward point of the shoe sole across both conditions.

2.5.2 Foot Clearance in descent (Figure 2. B) was measured as the horizontal distance between the step-edge and the posterior point of the digitised shoe sole at the instant the heel passed the vertical height of the step-edge. Toe spring did not need to be corrected in the descent trials.

2.5.3 Percentage Foot Contact Length (w) defined by the equation: $\mathrm{w} = \frac{\mathrm{x}}{\mathrm{x+y}} \cdot 100\ \%$, represents the proportion of the projected shoe sole, over the step at initial contact (force threshold of 50N). So in ascent (*see*, Figure 2. C), the ratio of the anterior portion of the projected shoe sole (x) to the sum of the anterior portion (x) plus the posterior portion of the projected shoe sole (y). In descent (Figure 2. D), the ratio of the posterior portion of the shoe over the step was of interest so the figure is reversed (note that at initial contact, the length of x represents the horizontal distance between the end of the shoe and the step-edge, as the foot would often be in plantar flexion at this time point).

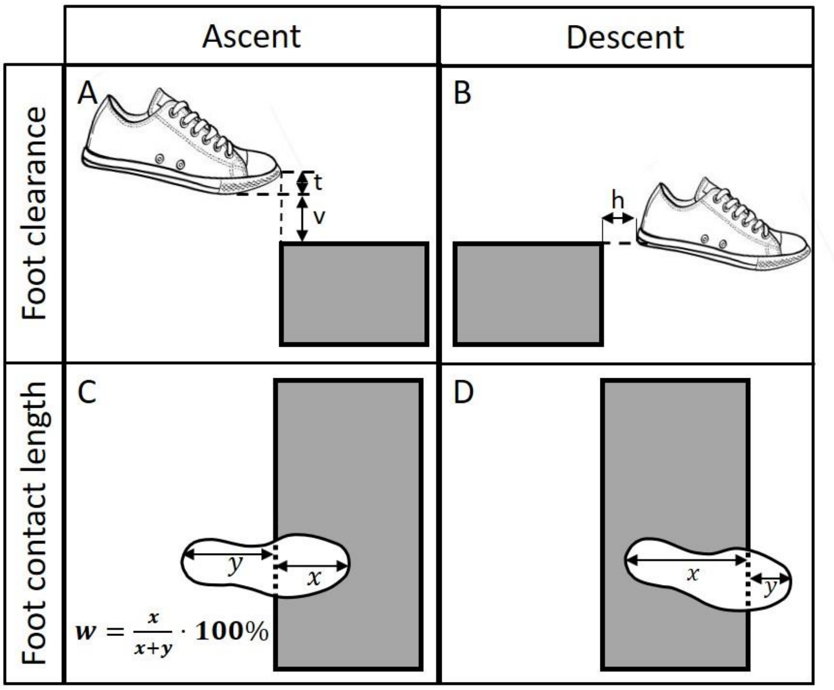

Figure 2. A) vertical (v) foot clearance in ascent, with toe-spring correction (t) added B) horizontal (h) foot clearance in descent, C) foot contact length percentage (w) in ascent and D) descent; length of foot over the step (x) length of foot not over the step (y).

2.6 Statistical Analysis

Primary analyses of the two outcome measures were performed using a 2-way mixed method design, Repeated Measures Analysis of Variance (ANOVA) for ascent and also descent. Foot clearance (Step1-Landing) and percentage foot contact lengths (Step1-Step4, where force plates were available for required event timings) were included in the same multivariate analysis. Comparisons were determined, within each condition (consistent versus inconsistent rise stairs) and between the two age groups (younger versus older adults) with an alpha level set at 0.05 at the univariate level, meaning that each step was treated independently of the other (some clearances/ contacts decreased while others increased).

When significant differences indicative of increased falls risk were found between conditions, further analyses were performed to understand the mechanisms behind the observed changes. Firstly, the open source one-dimensional Statistical Parametric Mapping package (SPM, www.spm1d.org) (Pataky, 2012) was used to compare the 3D kinematic trajectories of the foot Centre of Mass (CoM) on the approach to the inconsistent step. The foot CoM was used for these trajectory analyses, as opposed to a single marker, as it better reflects the position and orientation of the whole foot movement. Foot CoM trajectories were obtained during swing between toe off and one frame before contact on the next step; for the consistent condition trajectories were collected until 10 mm vertically higher than 1 frame before contact, thus ensuring that both conditions finished at a similar vertical point in space. For ascent, the vertical position data was plotted against 100% of horizontal progression. Due to the shape of the descent curve, it was not possible to normalise the horizontal progression in descent therefore vertical and horizontal position data was normalised to time. A SPM two by one-way ANOVA requires a balanced design between groups and conditions, a random number generation algorithm was used to exclude the appropriate number of older adults for each analysis. To ensure the random selection produced similar results, this process was repeated at least 5 times. Each repeat analysis produced similar results, consequently we report results from the first analysis.

Additional 2-way Repeated Measures ANOVAs were used on foot CoM position data to determine change in absolute lab coordinate positions during stance irrespective of the stair configuration. This enabled the researchers to disregard the altered position of the step-edge in the two conditions.

3.1 Results

On completion of the study, participants were not able to correctly identify the changes or the specific steps that had inconsistencies. They often stated that something felt different towards the bottom of the stairs.

3.2 Stair Ascent

In the ascending trial of the inconsistent higher rise condition, one older adult tripped on the inconsistent higher edge of Step3; this person's ascent data were excluded from the analysis. It is important to note that this person made contact with the riser of Step3, as the vertical foot clearance was not adequate to safely clear the inconsistently higher step-edge.

On the consistent stairs, on average older adults' foot clearances did not significantly differ over the middle steps (Steps2-6) (39.1 ± 14.8 mm) compared to the younger adults (37.4 ± 9.3 mm, $p = 0.624$). Also, the clearances over the transition step edges of Step1 and the Landing step edge were not significantly different between groups ($p = .231$ and $p = .602$, respectively). Older adults did have a significantly greater percentage foot contact length (76.7 ± 10.8 %) compared to the younger adults (Steps1-4) (67.4 ± 9.5 %, $p = 0.001$, *see* Supplementary Table S1. Section A for all individual step means and standard deviations during ascent).

In ascent, foot clearances of both groups were significantly reduced over the inconsistently higher Step3 (on average ~9 mm reduction) compared to the consistent condition ($p<0.001$). Foot clearance was also significantly reduced on the first step of the stairs for mostly older adults (on average ~7 mm reduction) compared to younger adults (~2 mm reduction, $p=0.019$). However, there was no interaction between condition and age group. After the inconsistent higher step, foot clearances increased over Step4 ($p < 0.001$) and Step5 ($p = 0.040$) in both groups. The only significant age*condition interaction for foot clearance was over Step4 ($p = 0.045$), where older adults had a larger increase (~17 mm) in clearance in the inconsistent rise condition compared to younger adults (~10 mm, *see,* Figure 3. A*)*.

Both groups significantly increased the percentage foot contact length on the inconsistent stairs on Step4 ($p < 0.001$). All other foot contact lengths were not significantly different between the two conditions. There were no interactions between stair condition and age group for contact length (*see*, Figure 3. B)*.*

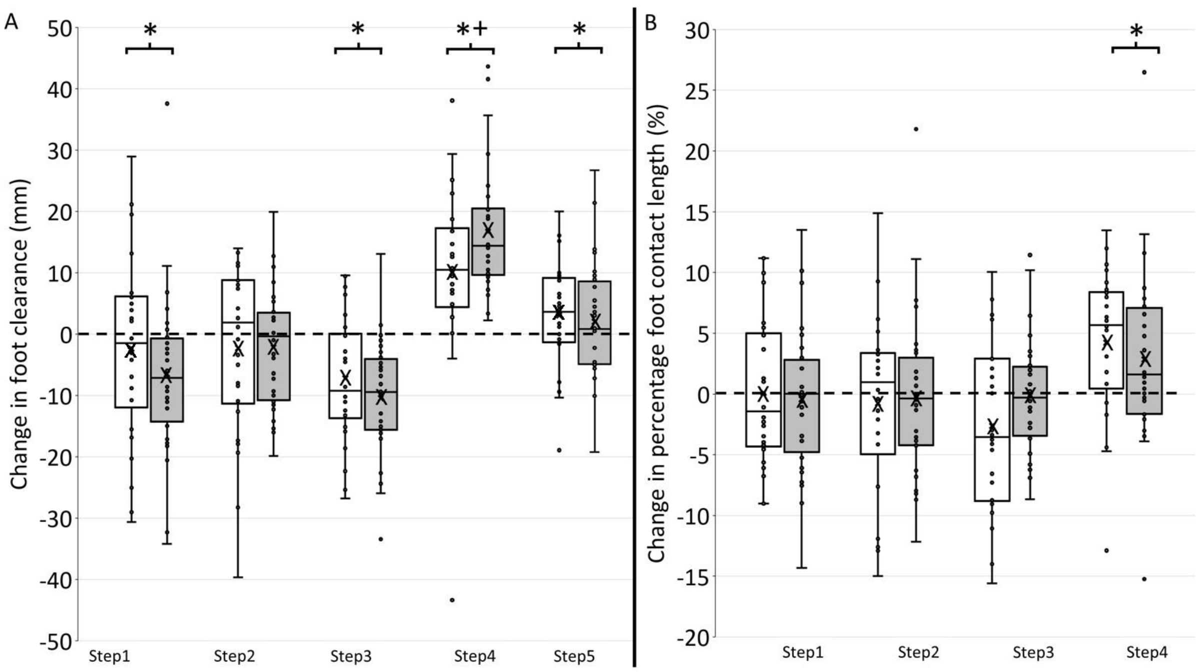

Figure 3. Stair ascent A), change in vertical foot clearance from the step-edge and B), change in percentage foot contact length on each step, from consistent to inconsistent rise condition (Step3 10 mm higher), a negative value represents a reduction and thus increased level of risk during the inconsistent rise condition compared to the consistent condition. ▬ ▬ = No/zero change, X represents group mean, ☐ = younger adults, ☐ = older adults. A two by two-repeated mixed methods ANOVA was run on values recorded for foot clearance and foot contact, during the consistent and inconsistent rise conditions for younger and older adults. * = stair condition effect where differences between consistent and inconsistent rise condition exist, + = interaction effects between stair condition and age group; $p < 0.05$, all significance levels reported at the significance level $p \leq 0.05$.

3.3 Ascent Secondary Analysis

To understand how foot clearances over Step3 became smaller on the inconsistent higher rise, SPM was used to compare the trajectory of the foot CoM on the approach to Step3. On average for both groups (N=13), foot CoM trajectories were not significantly different between conditions up to the point that the foot passes the step-edge of Step3 (~75% of swing, see Figure 4.). Significant differences between conditions emerged only on the approach to contact (p = 0.019), after 88% of swing.

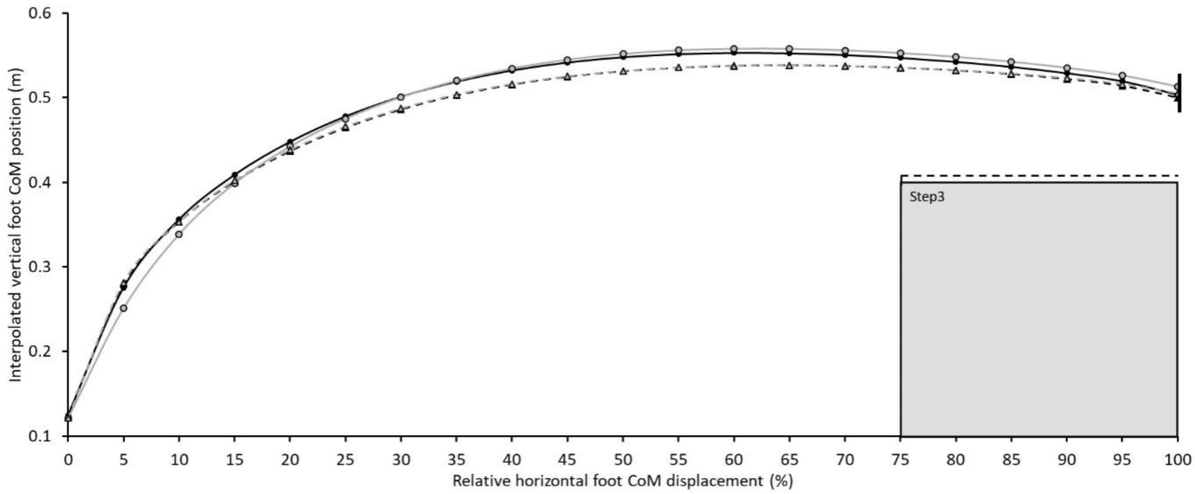

Figure 4. Stair ascent, vertical trajectory of the CoM of the foot relative to the total horizontal displacement travelled during swing from toe off Step1 until before touch down on Step3 (same relative vertical position irrespective of stair dimensions). Trajectories are shown at 5% intervals. —●— = younger adults (YA) consistent condition, —O— = younger adults inconsistent rise, -▲- = older adults (OA) consistent condition, -Δ- = older adults inconsistent rise, ▬ = end of SPM analysis (similar vertical point in space). Foot position was only significantly different between condition after 85% of displacement, p = 0.019 (N = 14 per group). Step3 edge vertical position in consistent condition = 0.401 m and inconsistent condition = 0.412 m.

3.4 Stair Descent

For the first inconsistent descending trial, the data of one younger adult were excluded from the analysis due to missing force data. There were no known occurrences of slips or trips during descent. There were the occasional heel marker catches on the underneath of the steps during terminal stance (pre-swing), the marker would then snap off its attachment to the shoe. Because movement continued, it was not thought to disrupt the natural foot trajectory so remained included in the analysis. The posterior calcaneus marker was not used in the processing of foot clearances but was included in the foot CoM calculations. The marker protruded 14 mm backward from the participant's shoe and may have caused increases in clearances for some participants as this was the same for both conditions, we do not believe it had a large impact on results.

During descent on the consistent stairs, on average older adults had greater foot clearance and larger variability over the steps (Land-Step2) (26.0 ± 11.1 mm) than the younger adults (20.3 ± 7.9 mm, $p = 0.035$) and also had a greater percentage foot contact length (Step4-Step1) (85.7 ± 7.4 %) compared to the younger adults (81.0 ± 6.4, $p = 0.015$, *see* supplementary Table S1. B).

Percentage foot contact length of both groups decreased on the inconsistent higher Step3 (smaller rise, $p = 0.004$) and then increased on Step2 (higher rise, $p<0.001$) compared to the consistent condition. There was an interaction between stair condition and age group on Step4 ($p = 0.016$), whereby foot contact length on Step4 prior to experiencing the inconsistency, in the inconsistent rise condition increased for younger adults but not for the older adults (*see* Figure 5B). There were no significant changes in foot clearances for either group during descent of the inconsistent stairs compared to the consistent condition (*see,* Figure 5A).

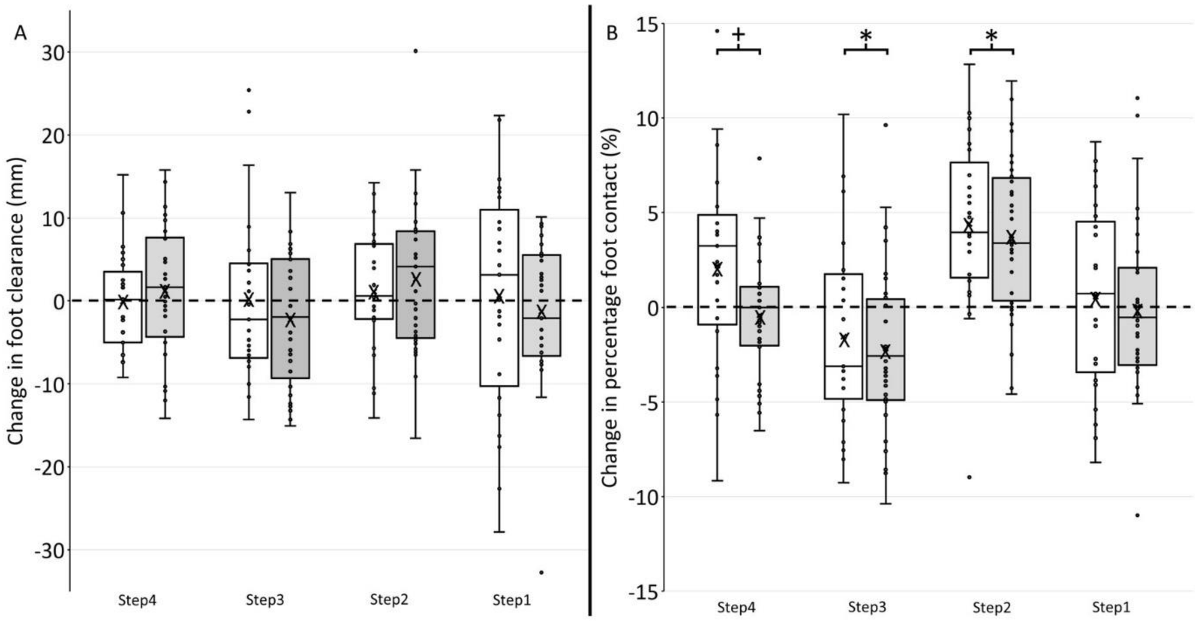

Figure 5. Stair descent A), change in horizontal foot clearance from the step-edge and B), change in percentage foot contact on each step, from consistent to inconsistent rise condition (Step3, 10 mm higher), a negative value represents a reduction and thus increased level of risk during the inconsistent rise condition compared to the consistent condition. – – = No/zero change, X represents group mean, □ = younger adults, □ = older adults. A two by two repeated mixed methods ANOVA was run on actual values recorded for foot clearance and foot contact, during the consistent and inconsistent rise conditions for younger and older adults. * = stair condition effect where differences between consistent and inconsistent rise condition exist, + = interaction effects between stair condition and age group; $p < 0.05$, all significance levels reported at the significance level $p \leq 0.05$.

3.5 Descent Secondary Analysis

To help understand how and why percentage foot contact length decreased on the inconsistent Step3 (smaller rise) during descent, additional analyses were performed to test whether foot trajectories were different between conditions. To achieve similar time and space normalisation for both conditions, the consistent condition foot CoM trajectory from Step5 to Step3 was trimmed 1 cm vertically higher than its position the instant before contact on Step3. This end point represents the same vertical position in space as the inconsistent rise trajectory curve.

We first determined if the horizontal foot CoM position the instant before contact on Step3 was different between the consistent condition 1 cm vertically higher and the inconsistently higher rise step. A two-way repeated measures ANOVA did not find differences between the horizontal CoM positions at this crucial time point for the younger adults (consistent: 46.3 ±13.5 mm *vs* Inconsistent: 47.0 ±17.8 mm) or the older adults (consistent: 65.1 ±17.2 mm *vs* inconsistent: 65.4 ± 18.8 mm).

An SPM analysis (n = 25 for each group) of the horizontal foot CoM trajectories to the same vertical position end point, revealed that despite differences between stair conditions early to mid-swing (9-48%, p = 0.006), after mid-swing foot trajectories were not significantly different between conditions and were not different when passing the step-edge of Step4 (between 75-80% of swing, explaining similar clearances at this point) or until the end of the analysis (*see,* Figure 6.).

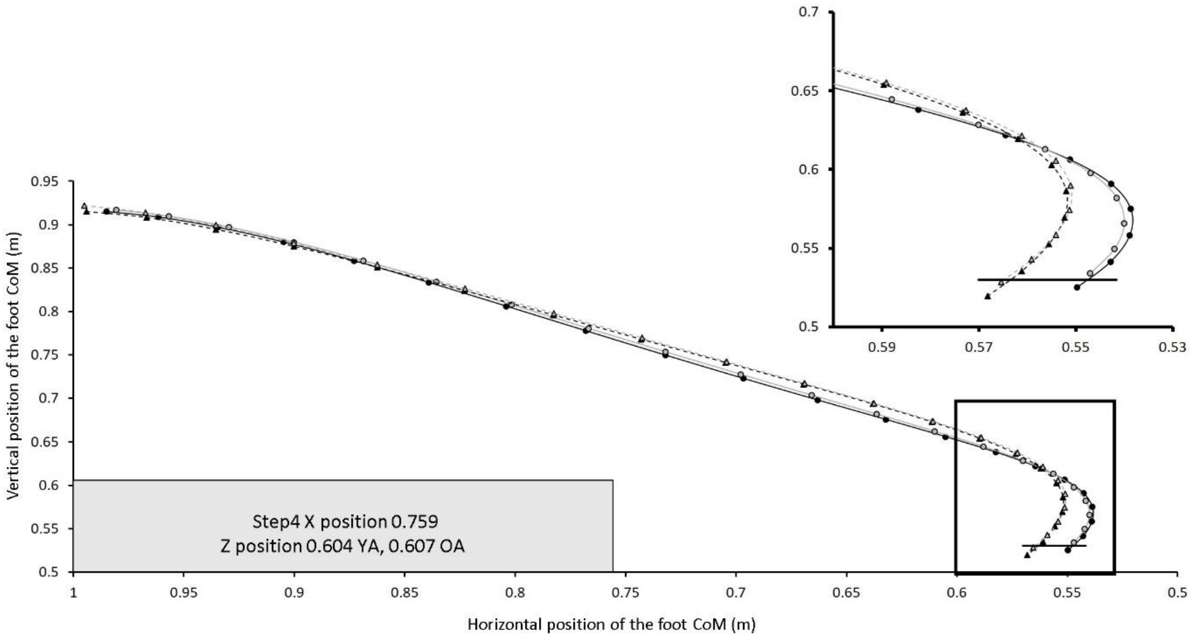

Figure 6. Stair descent horizontal and vertical trajectory of the foot CoM. Data are time normalised from toe off Step5 until one frame before contact on Step3, data points are sampled at every 5% of swing. = younger adults (YA) consistent condition, = younger adults inconsistent rise, = older adults (OA) consistent condition, = older adults inconsistent rise, = end of SPM analysis (similar vertical point in space). Horizontal position was significantly different between conditions at 9-48% (p = 0.006) of trajectory included in SPM. Vertical position was not significantly different.

4.1 Discussion

This study was the first to experimentally document the interactions between stairs with inconsistent rise heights and human stepping behaviour. As hypothesised, and consistent with previous theoretical literature (Nemire et al., 2016; Roys, 2013; Templer, 1992), neither younger nor older adults altered their stepping behaviour when exposed to an inconsistent step rise. Consequently, they were at an increased risk of tripping on the step with an increased rise in ascent, and overstepping on the step following a reduced rise in descent.

Results from the consistent stairs (see Supplemental Table S1) confirmed existing knowledge that older adults typically appeared to use more cautious stepping strategies, with greater foot contact lengths compared to the younger adults. Despite differences in behaviour between the two age groups, the effect of the inconsistent rise was similar for the older and younger adults (no age x condition interactions were detected). Therefore, it is expected that both groups would be at an increased fall risk, and by the same mechanisms, on stairs with inconsistent rise heights. However, it is likely that the consequences will be more severe for the older adults who may not be able to control their CoM as well as younger adults (Foster et al., 2019) as they do not have adequate strength reserves to recover should they lose balance (Pijnappels et al., 2008; Reeves et al., 2008). It previously been reported that poor lighting conditions (Kim, 2009; Thomas et al., 2020) and dual-tasking such as talking on the phone (Di Giulio et al., 2020) can further compromise stepping mechanics, these factors could be detrimental to safety and may inhibit good balance control when navigating stairs with inconsistent dimensions.

During ascent, vertical foot clearances over the inconsistent higher Step3 were reduced, increasing the risk of a toe-catch, whereas foot contact lengths were not significantly different. Therefore, only the first part of Hypothesis1 was accepted. The reduced clearance occurred because the foot followed the same stepping trajectory through space even though the edge of Step3 was higher (Figure 4). This would increase the risk of a toe-catch and fall due to tripping, which was evidenced during our experiments with three toe-catch events occurring during ascent. All three participants were able to regain their balance without assistance from the handrails or support from the safety system and continued to ascend the stairs. Weaker or distracted individuals in non-laboratory situations may not be able to recover their balance and may experience a serious fall.

During stair descent, foot contact lengths on the step following the inconsistent smaller rise (on Step3 which had been moved up) were reduced. However, foot clearances did not significantly differ. Therefore, only the first part of hypothesis2 was accepted.

The reason for this reduced contact length can, like in ascent, be attributed to the lack of change in the foot's trajectory despite the surface of Step 3 being higher. However, the mechanism is more complex than in ascent. The terminology of stair descent often describes movement as forwards and downwards during swing (Templer, 1992). Although the foot does follow this path for a large portion of swing, our descent trajectories (*see* Figure 6) and the work of Pauls (Pauls, 2013) visualise that the foot actually moves backwards during late swing. As a result, when the foot travels on the same trajectory but hits the higher inconsistent step sooner and out of place, there was less time and space for the foot to travel backwards along the expected path compared to the consistent condition, resulting in a reduced foot contact length.

This reduced foot contact length increases the chances of over-stepping and increases the potential for the foot to slip forwards over the edge (Templer, 1992) causing a backward loss of balance (Nicol et al., 2011; Roys, 2013, 2001; Templer, 1992). A recent paper has documented the types of fall recovery used by young adults when a backward loss of balance is induced (Gosine et al., 2019), not all individuals were able to achieve a successful handrail grab, but did use at least one additional step to regain control of balance, this could increase the demand on lower-limb muscles to arrest the fall (Gosine et al., 2019). A loss of balance at this point is likely to cause a backward fall, concussion, and serious fractures (Jacobs, 2016; Templer, 1992).

A 10 mm smaller rise in descent (stepping down to Step3) led to an average 5 mm reduction in contact length. This presents the same risk and hypothesised fall mechanism as a similar magnitude reduction in step going length, which has previously been considered to be most risky during descent (Roys, 2013, 2001). According to the literature on reducing going length, this 5 mm reduction in contact length is predicted to increase the likelihood of a large over-step by as much as 4.5 fold (Roys, 2013). More empirical research is required to determine the true level of risk on stairs with inconsistencies, but this finding demonstrates that inconsistencies in step rise should be treated as seriously as inconsistencies in going.

The analyses in this paper present comparisons between negotiation of consistent stairs and the first trial on the inconsistent stairs. This approach was chosen to avoid a potential learning effect confounding our comparisons. However, in many situations, such as at home, individuals will use the same stairs multiple times and a learning effect may be possible to mitigate the risky inconsistent step. To test this, we conducted a further exploratory analysis of stepping behaviours of 24 of the younger adults and 20 of the older adults when ascending and when descending the inconsistent stairs a total of five times. Specifically, foot contact lengths on Step3 in descent and clearance of Step3 in ascent were quantified as these were the parameters that increased the risk of a fall. We found no changes in either parameter across repeated trials on the inconsistent stairs (Figure 7). These additional analyses support the primary findings of the study and indicate that neither older nor younger adults adapt their stepping behaviours to improve safety even after multiple exposures to inconsistent rise heights. This goes even further than previous work which hypothesised that inconsistencies would remain undetected until they were contacted (Roys, 2013, 2001; Roys and Wright, 2005; Templer, 1992). It is not yet known if longer-term exposures would lead to adaptations.

In addition to the inconsistencies that increased fall risk, which have been discussed thus far, in ascent a smaller rise led to an increased foot clearance (over Step4) and in descent a larger rise increased foot contact length on the following step (Step2). Both of these effects would decrease the risk of a fall on those steps. According to the additional analyses (described in preceding paragraph), these effects persisted across multiple trials. However, we do not know whether they might cause a negative effect on subsequent steps, and this should be studied in future work to fully understand the risks associated with stair inconsistencies.

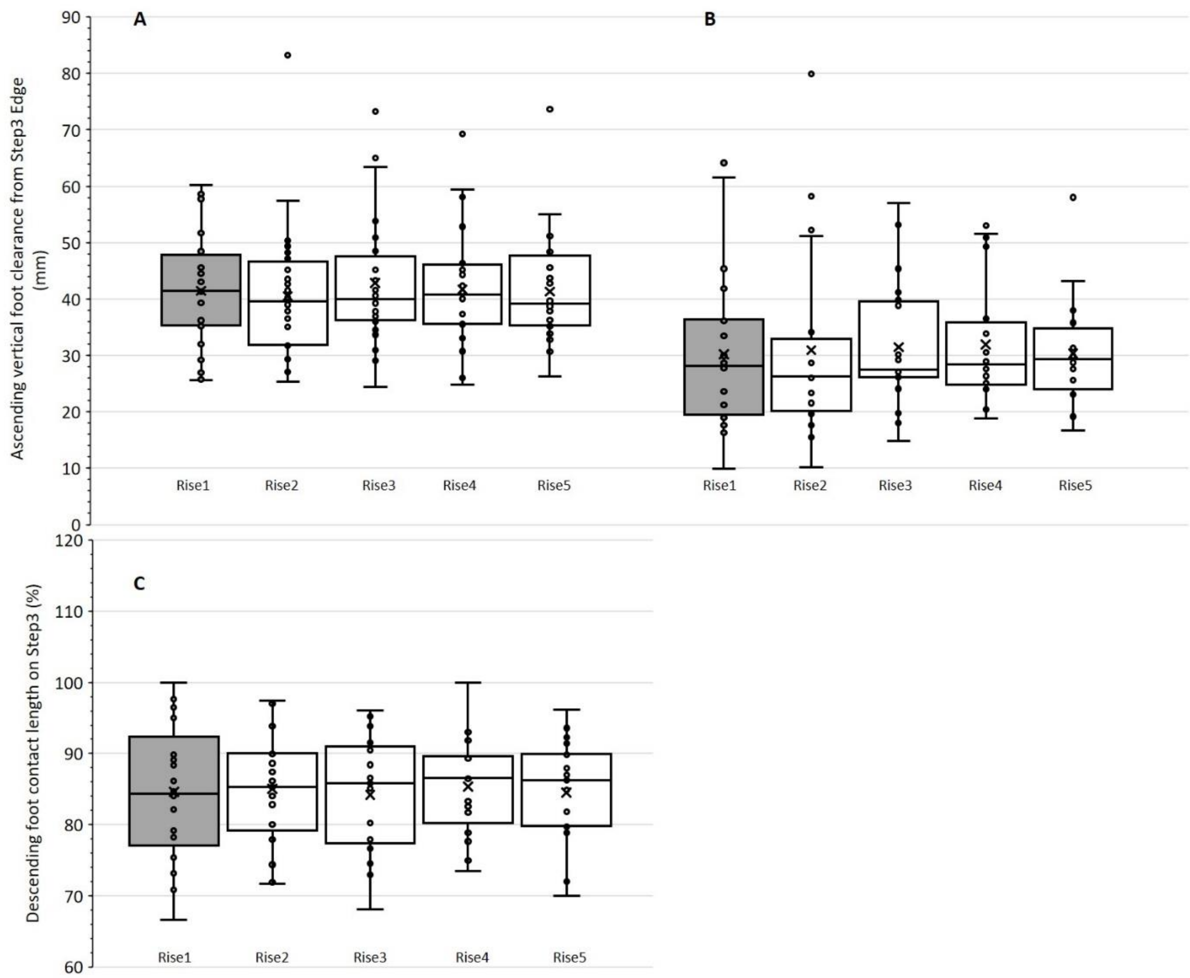

Figure 7. The effect of repeated trials negotiating stairs with inconsistent rise heights (Step3) on A) young adults' foot clearance in ascent, N= 24; B) older adults' foot clearance in ascent, N= 20 and C) older adults' percentage foot contact during descent, N = 20. Repeated measures ANOVAs detected no significant differences between repeated rise trials (p>0.05 for all).

4.2 Implications and Limitations

We have evidenced that inconsistencies in rise height, greater than those permitted within the regulations but in line with those observed on real stairs (Cohen et al., 2009), seem to go undetected putting the users at an increased risk because foot trajectories are not adapted accordingly. In order to reduce the risk of falls it may be necessary to: control compliance to legislation including remodelling of stairs with large inconsistencies (Nicol et al., 2011), manipulate the visual environment to alert users to the inconsistency, such as strategically placed highlights or visual illusions which may encourage changes to the stepping behaviour (Foster et al., 2015), or promote long-term safer stepping strategies. All of these options would require experimental research to establish potential benefits.

This paper has investigated the stepping-mechanisms that can lead to a fall on stairs with inconsistent rise heights. Future research should also consider the whole-body response and dynamic control of the centre of mass after contact with the inconsistent rise steps, and the effects of inconsistent going dimensions on young and older adult stability, as stairs with consistent but challenging dimensions are already difficult to navigate (Novak et al., 2016). It is also important to establish whether, inconsistencies within the permitted dimensions are safe enough or whether regulations need revising further.

In interpreting the present results, it is important to consider methodological limitations and their potential impact. One limitation is that it was conducted in a lab environment with use of a safety harness, which may have influenced the stepping behaviour in non-laboratory settings. Participants had, however, been familiarised to the lab environment and stairs with less demanding but consistent dimensions on a previous occasion. Another limitation is that participants knew that something was going to happen or could be different and this may have influenced how they responded, but as we have already stated participants were not able to verbalise the correct changes to the stairs, so we do not believe this has confounded the results. Additionally, we configured the inconsistency so that in ascent participants experienced a higher rise followed by a smaller rise, and vice versa in descent. This proved optimal for exposing participants to the "riskiest" step first in both directions. However, we cannot assume findings would be identical had we reversed this order, and future work should establish the stepping biomechanics when the riskiest step is experienced second.

4.3 Conclusion

When approaching a step with an inconsistent rise than the rest of the stairs, the foot trajectories did not differ from the consistent condition for older or younger adults. This suggests that the inconsistency was undetected, which increased the risk of a toe-catch on the step with a higher rise in ascent, and a risk of over-stepping on the step after the smaller rise during descent, both increasing the likelihood of a fall. These mechanisms underpin the interactions between the stairs and human behaviour. The findings indicate the importance of designing, constructing, and installing stairs with consistent risers. Given inconsistencies already exist in many environments, it is necessary to identify occurrences and the magnitude of those inconsistencies, as well as establish safety promoting interventions.

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Table S1. Mean and standard deviations (SD) of foot clearance and percentage foot contact length on consistent dimension stairs and an inconsistent stairs (one higher rise, Step3) for younger and older adults.

Variables	Younger adults				Older adults				Condition effect		Age effect		Interaction effect	
	Consistent stairs		Inconsistent stairs		Consistent stairs		Inconsistent stairs							
	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	F value	Sig.	F value	Sig.	F value	Sig.
A *Ascent vertical foot clearance (mm)*														
Step1	54.6	16.9	52.2	15.0	60.0	19.4	53.5	20.3	5.9	**.019**				
Step2	38.5	11.8	36.2	13.1	39.8	14.0	37.6	15.4	2.2	.148				
Step3	41.6	10.6	34.4	12.4	42.0	18.0	31.5	19.8	48.4	**.001**				
Step4	37.3	11.1	47.3	15.1	38.3	14.6	55.0	18.0	68.5	**.001**			4.2	**.045**
Step5	35.2	10.2	38.2	12.4	37.6	18.4	39.6	19.4	4.4	**.040**				
Step6	34.6	9.6	30.7	10.0	37.7	13.3	38.4	14.3	1.4	.247				
Landing	47.5	18.8	49.9	18.1	50.1	19.0	52.6	19.5	2.2	.145				
Ascent percentage foot contact (%)														
Step1	70.9	9.0	71.0	9.6	78.2	9.7	77.7	10.3	0.0	.832	8.3	**.006**		
Step2	67.6	10.2	66.8	12.0	77.5	11.1	77.3	11.2	0.3	.603	13.3	**.001**		
Step3	66.9	10.4	64.3	11.9	76.3	10.7	76.2	9.7	3.2	.081	15.6	**.001**		
Step4	64.5	10.3	68.7	9.9	74.9	11.6	77.7	12.1	16.4	**.001**	12.1	**.001**		
B *Descent horizontal foot clearance (mm)*														
Landing	18.7	11.2	17.6	11.7	23.2	12.3	20.7	12.0	3.3	.074				
Step6	22.8	9.7	26.1	12.9	29.5	14.7	28.9	15.3	1.3	.259				
Step5	22.2	11.3	22.2	12.0	28.3	13.5	32.2	15.7	3.6	.064	5.6	**.022**		
Step4	20.1	6.9	20.0	8.7	25.8	13.7	27.0	16.8	0.4	.534	3.9	.054		
Step3	17.4	10.3	17.6	14.7	25.7	13.6	23.4	13.2	0.8	.378	4.0	**.050**		
Step2	20.9	8.7	22.0	11.0	23.3	11.8	25.9	14.6	2.9	.093				
Step1	40.5	19.0	41.1	18.6	39.2	28.5	38.0	29.1	0.0	.837				
Descent percentage foot contact (%)														
Step4	79.3	7.0	81.5	9.0	84.5	9.1	84.0	10.2	2.2	.144			6.2	**.016**
Step3	81.3	6.4	79.8	8.4	85.5	7.7	83.4	9.1	9.1	**.004**				
Step2	81.1	7.2	85.5	7.3	85.3	8.4	89.1	9.3	52.5	**.001**				
Step1	82.5	6.3	83.1	7.8	87.2	6.9	87.2	8.8	0.2	.692	5.3	**.025**		

Note: Two separate repeated measures analysis of variance (ANOVA) were used to compare differences between conditions (consistent versus inconsistent), between groups (younger versus older) and the Interactions between condition and groups for ascent (**A**) and descent (**B**). Alpha level was set $p < .05$; degrees of freedom 1:56, significant results are highlighted in **bold** font.