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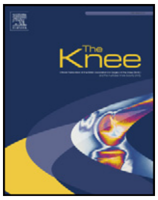

Effects of increased step width on frontal plane knee biomechanics in healthy older adults during stair descent

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ABSTRACT

Background: Peak internal knee abduction moment is a common surrogate variable associated with medial compartment knee loading. Stair descent has been shown to yield a greater peak knee abduction moment compared to level-walking. Changes in step width (SW) may lead to changes in frontal plane lower extremity limb alignment in the frontal plane and alter peak knee abduction moment. The purpose of this study was to investigate the effects of increased SW on frontal plane knee biomechanics during stair descent in healthy older adults.
Methods: Twenty healthy adults were recruited for the study. A motion analysis system was used to obtain three-dimensional lower limb kinematics during testing. An instrumented 3-step staircase with two additional customized wooden steps was used to collect ground reaction forces (GRF) data during stair descent trials. Participants performed five stair descent trials at their self-selected speed using preferred, wide (26% leg length), and wider (39% leg length) SW.
Results: The preferred normalized SW in older adults during stair descent was 20% of leg length. Wide and wider SW during stair descent reduced both first and second peak knee adduction angles and abduction moments compared to preferred SW in healthy adults.
Conclusions: Increased SW reduced peak knee adduction angles and abduction moments. The reductions in knee abduction moments may have implications in reducing medial compartment knee loads during stair descent.

1. Introduction

Older adults deem stair negotiation one of the most challenging locomotor tasks of daily living [1]. In healthy adults, stair descent has been shown to yield greater impact ground reaction force (GRF), greater loading rate of impact GRF and greater peak internal knee abduction moment compared to stair ascent and level-walking during loading response of stance [2–8]. In addition, aging is associated with the development of knee osteoarthritis (OA), with over 40% of adults over the age of 65 exhibiting symptoms [9]. The peak knee internal abduction moment during walking is one of the most common surrogate variables for medial compartment knee loading in knee OA patients during gait [10–14]. In addition, studies have shown that peak knee adduction angles are good predictors of peak knee abduction moment during gait [15,16].

In considering non-surgical strategies to reduce such loading, it is potentially important to recognize that step width (SW) alterations may lead to changes in lower extremity limb alignment in the frontal plane and alter the peak knee abduction moment. An increase in SW could place the knee in a more adducted position which could decrease the GRF vector moment arm to the knee joint center and thus, reduce peak knee abduction moments during gait tasks. Zhao et al. [17] reported a slight reduction in peak knee abduction moment during walking with increased SW at normal speed compared to preferred SW at normal, fast, and slow walking in a case-study of an 80 year old man eight months post-surgery. Additionally, a musculoskeletal simulation model in a case study predicted reductions in peak stance phase knee abduction moments when SW was increased compared to normal walking in a male knee OA patient [18]. A reduction in peak knee abduction moments could have implications in reducing medial compartment knee loads during a high impact gait task such as stair descent [7,8]. Currently, no cross-sectional studies in the literature have examined the effects of altered SW on peak knee abduction moment during stair descent. The external knee *add*uction moment (often reported as an

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internal *abd*uction moment) is calculated as the product of the frontal plane GRF vector and the perpendicular distance from the vector to the knee joint center (i.e., moment arm). Therefore, GRF variables and knee angular position can provide important information regarding potential changes in knee abduction moments.

The primary purpose of the study was, therefore, to investigate the effects of increased SW on frontal plane knee biomechanics during stair descent in healthy older adults. We hypothesized that an increased SW would reduce the first and second peak knee adduction angles and abduction moments during stair descent. In addition, based on the importance of GRF variables for calculating knee abduction moments, we also analyzed GRF variables in order to identify potential mechanisms related to changes in abduction moments.

2. Methods

2.1. Participants

Twenty (10 women and 10 men) healthy adults (age: 54.8 ± 8.9 years, mass: 71.0 ± 9.5 kg, height: 1.7 ± 0.1 m, BMI: 24.7 ± 2.6 kg/m^2) were recruited through flyers and online forums to participate in the study. An *a priori* power analysis (Sample Power 3.0, IBM SPSS, Chicago, IL) showed that a minimum of 15 participants were needed to obtain an alpha level of 0.05 and a beta of 0.80 based on previously reported GRF loading rate values of healthy adults during level-walking at three different speeds [19]. Potential participants were excluded if they had knee pain during previous six months during daily activities, any type of lower extremity joint osteoarthritis, any lower extremity joint replacement, lower extremity joint arthroscopic surgery, intra-articular injection within past three months, BMI greater than 35, and inability to ascend or descend stairs without use of handrails. Prior to participating in data collection, all participants signed an informed consent document approved by the Institutional Review Board.

2.2. Instrumentation

A nine-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain three-dimensional (3D) kinematics during testing. Participants wore a standardized laboratory running shoe (Noveto, Adidas, USA) during the experiment. Reflective anatomical markers were placed on the second toe, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, and iliac crests. Clusters of four reflective markers on semi-rigid thermoplastic shells secured on neoprene velcro wraps were used as tracking markers and placed on posterior-inferior trunk, lateral thigh, and lateral shank. Two thermoplastic clusters of two markers were placed bilaterally on the posterior lateral aspect of the pelvis, velcroed onto a neoprene strap around the pelvic area. This strap was situated between the greater trochanters and the iliac crests [20]. Four individual tracking markers were placed on medial, posterior, lateral and dorsal-lateral aspects of the shoe. Stair descent conditions were collected in the same testing session, and markers were in place for all conditions in order to remove potential errors due to marker replacement between conditions. An instrumented 3-step staircase (Force Plate-Stairs, American Mechanical Technology Inc., Watertown, MA, USA; first, second and third steps) with two additional customized wooden steps (fourth and fifth steps) was used in the study (Fig. 1a). The FP-Stairs bolted independently to two force platforms (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the GRF and the moments of forces.

2.3. Testing protocol

All participants performed three stair descent practice trials before the experimental trials using the wider SW in order to establish each participant's mean preferred descent speed. A speed range (mean ± 5%) was then used to control each participant's stair descent speed during the experimental trials. Two pairs of photo cells (63501 IR, Lafayette Instrument Inc., IN, USA) in line with the first and fourth steps and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA) were used to monitor walking speed. Participants were asked to perform five trials of stair descent with a step-over-step pattern (i.e., alternating foot on each step) for each of the following conditions at their established self-selected speed at: preferred SW, wide SW, and wider SW. A previous study reported a preferred SW of 13% of leg length during level-walking [21]. Thus, the wide and wider SW conditions were set at 26 (twice the self-selected SW in level-walking) and 39% (three times the self-selected SW in level-walking) respectively to ensure distinct SW increases from preferred SW. Leg length was defined as the vertical distance between the anterior superior iliac spine and the medial malleolus of the tested limb measured during a standing position. The three SW conditions were presented in a randomized order to reduce any testing condition order effect. SW was measured as the mediolateral distance between the center of masses (COM) of the testing foot at contact and the contralateral foot. At the start of each descent trial, participants stood on the top platform and took one step on the platform before initiating stair descent and continued to walk for at least two steps once they stepped on the laboratory floor. Before each new condition, participants were given two or three practice trials to become familiar with the new SW condition. Black ink marks on a strip of masking tape were placed on each step to control SW during the trials (Fig. 1b). For the wide and wider SW conditions, participants were instructed to cover the ink mark with their foot but no other instructions were given. Participants were also instructed to not use the handrail unless needed. If participants used the handrail, a new trial was collected. Each participant was instructed to descend the stairs one foot at a time. Following each test condition, all participants were given a rest period of at least two minutes, or more if requested, to avoid fatigue.

2.4. Data Analysis

Visual3D biomechanical analysis software suite (C-Motion, Inc., Germantown, MD, USA) was used to compute the three dimensional (3D) kinematic and kinetic variables. A right-hand rule with a Cardan rotational sequence (x-y-z) was used for the 3D angular computations. Joint moments were expressed as internal moment. Kinematic and GRF data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 8 Hz [7,22]. The primary dependent variables were absolute and leg length normalized SW at foot contact on step of interest, first peak knee adduction angle and abduction moment during loading response of stance, and second peak knee adduction angle and abduction moment during push-off phase of stance. In addition, we also examined peak medial GRF, stance time, peak vertical impact GRF, and timing of knee adduction angle and abduction moment peaks. The GRF data were normalized to body weight (BW) and joint moments to body mass (N·m/kg). GRF and joint variables were analyzed from self-reported dominant limb. These variables were analyzed during stance phase on the second step off the ground (Fig. 1a) to capture the middle portion of the stair descent task to ensure that participants were descending at a constant speed.

2.5. Statistical analyses

A one-way repeated measures analysis of variance (ANOVA) was performed on selected variables to detect any differences between SW conditions (19.0, IBM SPSS, Chicago, IL). Mauchly's Test of Sphericity was used in order to test the assumption of sphericity. When the assumption of sphericity was not met (i.e., $p < 0.05$), the Greenhouse–Geisser adjustment was used to assess within subject differences.

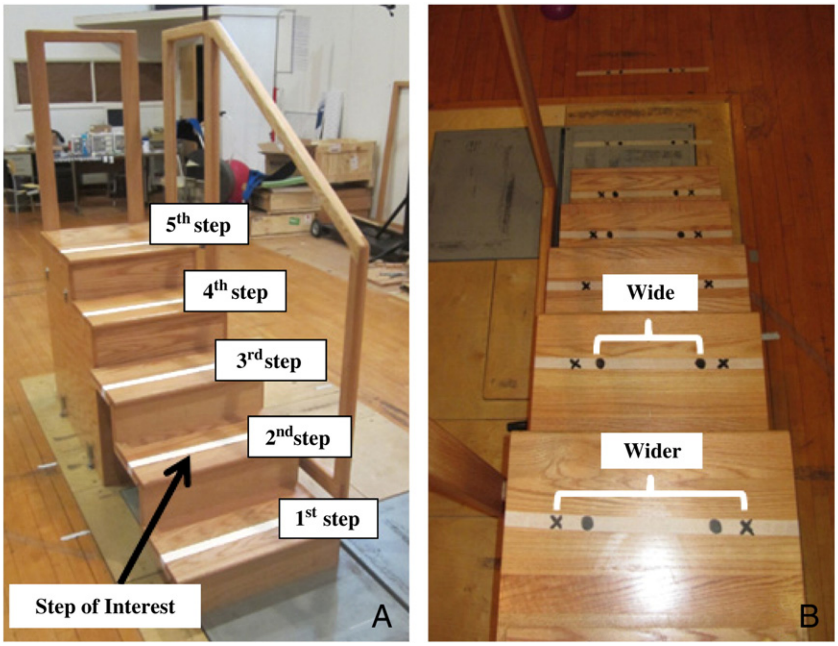

Fig. 1. Illustration of staircase (A) and step wide tape with black ink marks to control step width during the wide and wider step width conditions (B).

When the ANOVA revealed a main SW effect, post-hoc comparisons using a least significant difference (LSD) method was used to detect mean differences between SW conditions. The alpha level was set at 0.05.

3. Results

3.1. Walking speed and step width

The mean self-selected stair descent speed for all participants was 0.57 ± 0.06 m/s. The post-hoc test confirmed that absolute SW was smaller in preferred (0.17 ± 0.04 m) compared to wide (0.22 ± 0.03 m, $p < 0.001$) and wider SW (0.32 ± 0.04 m, $p < 0.001$) and smaller in wide compared to wider SW ($p < 0.001$, Fig. 2). Normalized SW was also significantly smaller in preferred (19.8 ± 4.2%) compared to wide (25.3 ± 1.8%, $p < 0.001$) and wider SW (37.0 ± 2.9%, $p < 0.001$) and smaller in wide compared to wider SW ($p < 0.001$).

3.2. Ground reaction forces

The impact GRF was smaller in wide compared to preferred ($p = 0.013$) and wider SW ($p = 0.05$, Table 1). The peak medial GRF was smaller in preferred compared to wide ($p < 0.001$) and wider SW ($p < 0.001$) and smaller in wide compared to wider SW ($p < 0.001$).

3.3. Knee joint angles

One participant demonstrated knee abduction motion as opposed to adduction for all SW conditions. Therefore, both peak knee adduction angles and peak knee abduction moments of this participant were not included in the statistical analyses ($N = 19$). First peak knee adduction angle was greater in preferred compared to wide ($p = 0.006$) and wider SW ($p = 0.007$). Time to first peak adduction angle was earlier in wide ($p = 0.003$) and wider SW ($p = 0.014$) compared to preferred SW. Second peak knee adduction angle was greater in preferred compared to wide ($p = 0.015$) and wider SW ($p = 0.003$) and greater in wide compared to wider SW ($p = 0.001$). Time to second peak adduction angle was earlier in wide ($p = 0.006$) and wider SW ($p = 0.002$) compared to preferred SW and earlier in wide compared to wider SW ($p = 0.038$; Fig. 3).

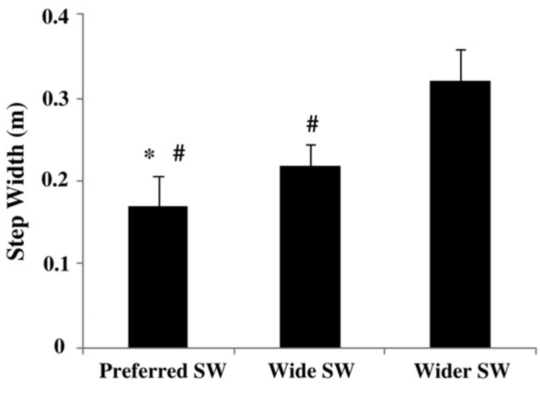

Fig. 2. Absolute step width for each condition (mean ± SD). *Significantly different than wide SW; #Significantly different than wider SW.

3.4. Knee joint moments

First peak knee abduction moment was greater in preferred compared to wide SW ($p = 0.006$; Table 2). Time to first peak abduction moment was earlier in wide ($p = 0.030$) and wider SW ($p = 0.001$) compared to preferred SW and delayed in wide compared to wider SW ($p = 0.035$). Second peak knee abduction moment was greater in preferred compared to wide ($p = 0.012$) and wider SW ($p < 0.001$) and greater in wide compared to wider SW ($p < 0.001$). Time to second peak abduction moment was earlier in wider ($p = 0.023$) compared to preferred SW.

4. Discussion

The primary purpose of the current study was to investigate the effects of increased SW on knee adduction angles and abduction moment during stair descent in healthy older adults. We hypothesized that increased SW would reduce peak knee adduction angles and abduction moments during stair descent. The primary hypothesis was supported as first peak knee abduction moment was reduced in wide compared to preferred SW. Although smaller, first peak abduction moment was not significantly different in wider SW compared to preferred SW. Previous case-studies have also observed slight reductions in peak knee abduction moments with increased SW compared to normal walking [17,18] but this is the first cross-sectional study to report such findings. One explanation for a reduction in peak abduction moment with increasing SW is a smaller frontal plane moment arm to the knee joint center. Previous research suggest that reductions in knee abduction moment are caused by a shift of the GRF vector closer to the knee joint due to a lateral shift of COP in knee OA patients and as a result, a reduction in the frontal plane moment arm [23]. The increase in initial peak medial GRF with the unchanged peak vertical GRF would shift the resultant frontal plane GRF medially to increase the GRF moment arm and as a result, increase the internal knee abduction moment. Thus, the smaller first peak knee abduction moment does not appear to be caused by a

Table 1
GRF variables for all three step width conditions (mean ± SD) with test of within-subjects effect p-value.

Variables	Preferred SW	Wide SW	Wider SW	*p*
Contact time (s)	0.67 ± 0.07	0.67 ± 0.06	0.66 ± 0.07	0.496
Impact peak GRF (BW)	1.50 ± 0.20 *	1.45 ± 0.17 #	1.48 ± 0.19	**0.018**
Peak medial GRF (BW)	−0.12 ± 0.03 * #	−0.15 ± 0.02 #	−0.22 ± 0.03	**0.001**

*Significantly different from wide SW; #Significantly different from wider SW, [a]in the foot coordinate system, [b]from foot contact to peak ML COP.

more vertical resultant frontal plane GRF vector (i.e., smaller frontal plane moment arm).

The smaller first peak knee adduction angle found in wide and wider SW may provide an explanation for the reduced first peak knee abduction moment in wide compared to preferred SW. Studies have shown that peak knee adduction angles are positively correlated with peak knee abduction moment during level-walking in healthy adults [15] and knee OA patients [16]. Fregly et al. [24] showed that a customized simulation model produced a "medial-thrust" gait pattern that predicted reductions in first and second peak knee abduction moment compared to a non-optimized gait pattern. A 9-month self-training program led to peak abduction moment reductions in one medial compartment knee OA patient compared to his normal gait pattern. The authors suggest that the "medial-thrust" gait pattern shifted the knee joint medially below the body COM (i.e., reducing the GRF moment arm to knee joint center). In the current study, the smaller knee adduction angle with increased SW could have caused a similar medial shift of the knee joint relative to the body COM to contribute to the reduction in peak knee abduction moment. Thus, the reduced first peak knee adduction angle found in the current study may be related to the reduced first peak knee abduction moment in wide SW.

Another explanation for the reduction in peak abduction moments may be related to changes in frontal plane trunk position during stair descent. Hunt et al. [25] reported a significant negative correlation between lateral trunk lean and peak knee abduction moments in medial compartment knee OA patients during level-walking. We did not measure trunk angles in the current study but it is possible that older healthy increased their lateral trunk angle (i.e., greater lean towards the stance limb) with increased SW to reduce the 1st peak knee abduction moment. It is unclear why first peak knee abduction moment was not reduced in wider SW compared to preferred SW. Slightly greater knee abduction moment variability in wider SW may explain the lack of a significant difference. It is possible that during the higher impact loading response phase, the wider SW condition resulted in more variable lower limb placement to successfully achieve the targeted SW. Although we did not study the effects of SW on knee biomechanics after an adaptation period, it is possible that the novel task of descending stairs with a wider SW is responsible for the high variability.

The increased SW reduced the second peak abduction moment in wide and wider SW compared to preferred SW and, in wider compared to wide SW. The second peak abduction moment has a smaller magnitude than the first peak abduction moment but still contributes to the total medial compartment knee loading during late stance. The reduction in both peak abduction moments with increased SW, especially with larger reductions of the second peak abduction moment, may indicate an overall reduction in medial compartment knee loading during stair descent in these increased SW conditions. Similar to the first peak abduction moment, reductions in second peak abduction may be related to the smaller second peak knee adduction angles in wide and wider SW compared to preferred and wider compared to wide SW. The timing of peak adduction angle and peak abduction moment may further explain the reduction in second peak abduction moment. At the time of first and second peak abduction moments, peak knee adduction angles for wide and wider SW have already occurred and the knee is abducting. The ensemble curves in Fig. 3 illustrate that second peak knee abduction moment is reduced in wide and wider SW as the knee moves toward an abducted position in late stance during stair descent. The timing of knee adduction and knee abduction moment appear to be important in explaining the relationship between these two variables and future studies should further investigate their timing when SW is altered.

Greater peak knee abduction moment has been associated with medial compartment knee OA in gait [13,26–28] and has been used as a surrogate of loading to the medial knee compartment. In addition, increased peak knee abduction moment has been linked to reductions in medial femoral cartilage thickness in osteoarthritic knees [14]. Thus,

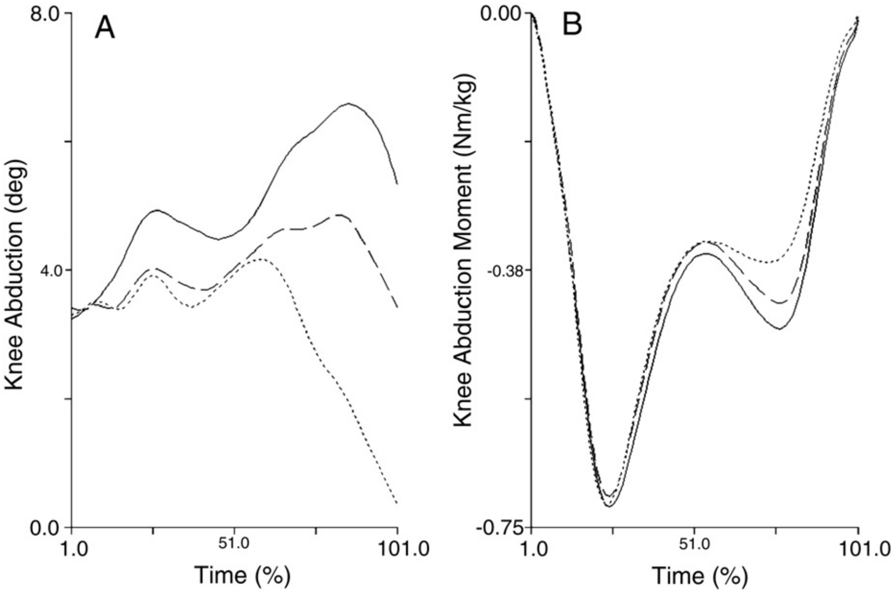

Fig. 3. Ensemble curves of knee adduction angle (A) and abduction moment (B).

Table 2
Knee kinematics and kinetics for all three step width conditions (mean ± SD) with test of within-subjects effect p-value.

Variables	Preferred SW	Wide SW	Wider SW	*p*
First peak adduction angle (°)	5.9 ± 2.6 $^{*\#}$	4.7 ± 2.9	4.6 ± 2.8	**0.004**
Time to first peak adduction angle (s)	0.17 ± 0.06 $^{*\#}$	0.14 ± 0.06	0.14 ± 0.06	**0.011**
Second peak adduction angle (°)	8.4 ± 4.5 $^{*\#}$	6.0 ± 2.6 $^{\#}$	4.9 ± 2.8	**0.004**
Time to second peak adduction angle (s)	0.50 ± 0.10 $^{*\#}$	0.45 ± 0.09 *	0.43 ± 0.11	**0.001**
First peak abduction moment (N·m/kg)	−0.77 ± 0.16 *	−0.73 ± 0.15	−0.73 ± 0.16	**0.026**
Time to first peak abduction moment (s)	0.17 ± 0.02 $^{*\#}$	0.16 ± 0.02 *	0.16 ± 0.02	**0.001**
Second peak abduction moment (N·m/kg)	−0.48 ± 0.14 $^{*\#}$	−0.44 ± 0.09 $^{\#}$	−0.38 ± 0.11	**0.001**
Time to second peak abduction moment (s)	0.50 ± 0.05 *	0.49 ± 0.04	0.47 ± 0.06	**0.040**

*Significantly different from wide SW; $^{\#}$Significantly different from wider SW.

our findings of reduced knee abduction moment in healthy aging adults with greater SW during stair descent may be of importance in helping to reduce medial compartment knee loads during a high impact gait task such as stair descent. We did not conduct a correlation analysis, but based on the variables analyzed in this study, reduced knee adduction angles appear to play a role in altering the peak knee abduction moments with increased SW. Future studies should focus on identifying predictors of knee abduction moments during stair walking.

The mean normalized wide and wider SWs were 25.3% and 37.0% of leg length, respectively. These findings indicate that our method of controlling SW to 26% and 39% using ink marks was successful. This is the first study to report a normalized preferred SW during stair descent and this value in healthy adults during stair descent is approximately 20%, which is greater than the reported preferred SW value of 13% reported in level-walking [21]. Previous studies have reported absolute SW values in healthy adults during stair descent of 0.20 m [29], 0.12 m [30], 0.18 m [31] and 0.14 m [32]. Our reported preferred absolute SW value of 0.17 m falls within the range of previously reported SWs in healthy adults during stair descent.

The current study only reports acute effects of increased SW on knee abduction moment and long term effects deserve further attention. The method of using tape marks to control SW was successful but it is unknown whether or not individuals could reproduce normalized SW values of 26% and 39% of leg length without the use of visual cues. The tape marks placed on the steps may have required participants to gaze down at the marks which may have increased trunk flexion angle. Participants were given practice trials to minimize the need to look down at the tape marks during the testing trials. One study showed that healthy older adults spent 91.3% of their stair descent time gazing down at the staircase [33]. Therefore, it is unlikely that our participants were required to change their usual trunk position to see the tape marks during stair descent. Finally, although increased SW significantly reduced peak knee abduction moments, these changes were small and may not have clinical significance. However, the percent differences between peak moment means were relatively large (i.e., 5 to 26%), which may suggest clinical significance. Additionally, any changes in peak knee abduction moment will contribute to the chronic, repetitive loading to the joint and thus, even small peak normalized mean changes can contribute greatly to chronic cumulative load.

5. Conclusion

In summary, the increased SW appears to be successful in reducing peak knee abduction moment, especially in late stance, and peak knee adduction angles and their timing appear to be related to this reduction. These findings may have implications in reducing medial compartment knee loads in a high impact stair descent in healthy adults and, potentially, in medial compartment knee OA patients. In aging healthy adults, reductions in medial compartment knee loads over time may help prevent or delay onset of medial compartment knee OA. This is the first study to report changes in knee joint kinematics and kinetic as a result of increased SW in stair descent. Finally, the effects of increased SW on knee joint variables should be investigated in individuals with medial compartment knee OA to confirm whether or not this gait strategy can also be useful in reducing loading to the medial knee compartment of patients with knee OA.

6. Conflict of interest statement

The authors have no conflicts of interest to declare.

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