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Effects of High Heel Wear and Increased Weight on the Knee during Walking

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Abstract

Knee osteoarthritis (OA), a leading cause of disability, is more prevalent in women than men. Wearing high heeled shoes has been implicated as a potential contributing factor for the higher lifetime risk of osteoarthritis in women. This study tests the hypotheses that changes to knee kinematics and kinetics observed during high heeled walking increase in magnitude with increasing heel height and are accentuated by a 20% increase in weight. Fourteen healthy females were tested using marker-based gait analysis in combinations of footwear (flat athletic shoe, 3.8 cm and 8.3 cm heeled shoes) and weight (with and without 20% bodyweight vest). At preferred walking speed, knee flexion angle at heel-strike and midstance increased with increasing heel height and weight. Maximum knee extension moment during loading response decreased with added weight; maximum knee extension moment during terminal stance decreased with heel height; maximum adduction moments increased with heel height. Many of the changes observed with increasing heel height and weight were similar to those seen with aging and OA progression. This suggests that high heel use, especially in combination with additional weight, may contribute to increased OA risk in women.

Keywords

osteoarthritis; high-heeled shoes; women's footwear; loaded gait; biomechanics

INTRODUCTION

Altered walking biomechanics have been suggested to play a role in knee osteoarthritis (OA) development and progression.[1,2] Knee OA is roughly two times more common in women compared to men, with incidence increasing substantially in females over age 50.[3] Because women and men were observed to have similar knee biomechanics during barefoot

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walking,[4] gender differences in footwear, specifically high heeled shoes, have been implicated as a possible factor for the higher incidence of OA in women.[5] According to a survey done by the American Podiatric Medical Association (APMA) in 2003, 72% of women wear high heeled shoes, with 39% of these women wearing them on a daily basis.[6] The high rate of high heel use in women presents a unique opportunity to study the effects of altered gait mechanics on OA risk in female cohorts that are representative of the general population. Defining populations at risk for developing OA or in pre-clinical OA disease states is critical to developing new treatment strategies to prevent or delay the onset of OA.[7]

Previous studies have shown that wearing high heeled shoes can significantly change walking kinematics and kinetics.[5,8–11] As heel height increases, changes in knee kinematics include increased flexion in early stance[11] while changes to kinetics include increased peak external flexion moment,[5,11] decreased second peak of external extension moment,[11] and increased peak external adduction moments.[10,11]

It is well known that increased bodyweight directly correlates with increased joint loads,[12] and obesity has been associated with cartilage thinning,[13] changes in walking mechanics,[14] and knee OA,[13] especially in women.[15] However, it is unknown whether gait alterations seen in high heeled walking are compounded by the addition of weight.

Specific measures of knee flexion-extension angle and moment have previously been associated with aging and OA progression.[16] Additionally, increased knee adduction moment has been associated with medial compartment OA severity.[1] Since this study considers high heels as a possible risk for knee OA, it is important that each of these measures be analyzed.

Thus, the purpose of this study was to examine whether high heeled walking, with and without additional weight, produces gait changes similar to those associated with increased risk of knee OA. The following hypotheses were tested: H1) There are significant changes to knee kinematics and kinetics during walking that increase in magnitude with increasing heel height; and H2) The changes to knee kinematics and kinetics during walking with high heels are significantly amplified by a 20% increase in weight.

MATERIALS AND METHODS

Participants

Fourteen healthy female volunteers of height 1.68±0.06 m, weight 57.4±4.6 kg (mean ±standard deviation), and ages 20 to 51 (min, max) participated in this study after providing Institutional Review Board approved informed consent. Inclusion criteria included age between 20 and 60 years, BMI below 30 kg/m^2, and no self-reported chronic pain or serious lower extremity or back injury or surgery.

Gait Analysis

Participants completed 10 m gait trials at their preferred walking speed, slower than preferred, and faster than preferred with three different types of footwear: a standard flat athletic shoe (New Balance, Boston, MA), and 3.8 and 8.3 cm heeled shoes (CAMiLEON, Bangkok, Thailand). The standard athletic shoe was included to allow comparison between heeled shoes and typical walking shoes. Furthermore, the unique design of the CAMiLEON heeled shoe, which converts from a low heel to a high heel without changing shoe structure, allowed for the examination of differences in walking mechanics based purely on heel height. In addition, trials were also recorded for each footwear type and walking speed while the subjects wore a weight vest (TKO Sports Group USA Limited, Houston, TX) of a mass equivalent to 20% of their bodyweight. The weight vest was adjustable to 1 lb increments, with these 1 lb weights symmetrically distributed in the anterior-posterior and medial-lateral directions. Subject experience and usage frequency wearing high heels were assessed using a questionnaire filled out prior to the gait analysis. Linear regressions were performed to test for correlation between experience level and usage frequency with gait variables wearing high heels (8.3 cm). A 10-camera optoelectronic system (Qualisys Medical, Gothenburg, SE) and a force plate (Bertec, Columbs, OH) embedded in the floor were used to measure subjects' motion at 120 Hz. For each shoe and walking speed, with and without the weight vest, subjects completed three 10 m gait trials for each condition where the foot of test leg entirely struck the force plate in the middle of the walkway. For safety reasons, weighted walking was only collected at preferred speed. Subjects were given at least one minute to acclimate to each heel height and loading condition prior to collection of gait data. Subjects verbally confirmed that they were comfortable and had sufficient time to acclimate before the gait study at each heel height began. The software application BioMove (Stanford University, CA) was used to calculate knee kinematics and kinetics using the previously validated point cluster technique.[17,18] The foot, shank, and thigh segments' anatomical frames were determined as previously described[16] using a standing reference pose collected before the walking trials. To examine the kinematics of the knee in the sagittal plane, the flexion-extension angle was analyzed using methods described previously.[16,19] The external joint moments were normalized to percent bodyweight and height (%BW*Ht). Weighted trials were normalized to percent bodyweight plus the weight of the vest and height (%(BW +vest)*Ht), to facilitate comparison between the unloaded and loaded trials.

Data Analysis

Average curves for each shoe and loading scenario were generated for the knee flexion-extension angle, knee flexion-extension moment, and knee abduction-adduction moment at each walking speed. This was accomplished by first generating the mean curves for each individual participant, and averaging the result to generate average curves for the whole group. Seven characteristic magnitudes from the curves generated for knee flexion-extension angle and moment, and knee abduction-adduction moment during the stance phase of gait were selected for comparison between the three shoes and two loading conditions at preferred walking speed. For completeness, two additional magnitudes were analyzed to characterize knee function. Gait speed was also considered, yielding a total of 10 variables for comparison (Table 1). As described previously,[16] the time points of loading response, midstance, and terminal stance (Table 1) correspond to the first, second, and third characteristic peaks in the joint moments when plotted against percent stance, respectively. Heel-strike (Table 1), the instant at which a subject's heel strikes the force plate, corresponds to 0% stance while 100% corresponds to the toe-off event during the gait cycle. Preferred speed was chosen for analysis in order to best represent normal everyday walking in low and high heels, as opposed to controlling gait speed which could lead to altered walking mechanics. One leg was randomly selected for each subject and data was averaged over the three trials, resulting in one value per variable for each subject and footwear/loading condition (Table 2). Matlab (Mathworks, Natick, MA), version R2010b, was used for all data processing.

The significance level for the statistical analysis was set at 5% and corrected for multiple comparisons using the Hochberg sequential procedure. A two-way repeated ANOVA was performed to determine which variables were affected by shoe type and which were affected by increased body mass or a combination of both. When necessary, post hoc pair-wise comparisons of shoe type were made using Bonferroni. IBM SPSS Statistics (IBM, Armonk, NY), version 20, was used for all statistical tests.

Because measures of gait kinematics and kinetics are dependent on walking speed, supplementary analysis was performed to evaluate the variables at a comparable speed. This allows for better comparison with previous studies examining high heeled walking at a fixed speed. Each subject's 9 walking trials in each shoe (3 trials for 3 different speeds) were used to form a linear regression between each gait variable and walking speed. Each subject's regression equation for each variable in each shoe was evaluated at the median speed of all the walking trials (1.277 m/s). This yielded speed-corrected values for each subject's variables in each shoe (Table 3). The significance level for the statistical analysis was set at 5% and corrected for multiple comparisons using the Hochberg sequential procedure. A one-way repeated ANOVA was performed to determine which variables were affected by shoe type. When necessary, post hoc pair-wise comparisons of shoe type were made using Bonferroni.

RESULTS

Subjects reported variable experience and usage frequency of wearing heels greater than 5 cm with mean of 10.41±6.44 years (range: [3.75,30.00]) of experience and a mean usage of 2.10±2.55 hours/week (range: [0.06,9.00]). No significant correlations were observed between usage frequency or experience level and any of the gait variables wearing high heels (8.3 cm).

There were significant gait changes associated with increasing heel height and increased weight (Tables 2–3 and Figures 1–3). Walking speed significantly declined with heel height, but was not affected by weight (Table 2). At the subject's preferred walking speed, knee flexion angle at both heel-strike and midstance increased with increasing heel height and weight (Figure 1, A&B). This difference was magnified when correcting for speed in the supplementary analysis (Figure 1, A&B).

Increasing heel height and weight also resulted in changes to knee kinetics. Maximum extension moment at loading response decreased with added load, but no trends were observed with heel height (Figure 2A). At preferred speed, maximum knee flexion moment was not significantly influenced by shoe type or weight. However, after correction for speed, there was a threshold effect with heel height with a significant increase in the 8.3 cm heel and no change with the 3.8 cm heel and control shoe (Figure 3). Increased loading also showed a trend ($p = 0.009$) towards a higher maximum flexion moment, especially in heels (Figure 3). Maximum extension moment during terminal stance was decreased in the 8.3 cm heels compared to the control shoe and the 3.8 cm heels, while loading had no effect (Figure 2B). Correction for speed did not change this result. All three characteristic magnitudes of the knee abduction-adduction moment curves were significantly affected by shoe type (Tables 2–3) but not increased weight. In general, higher heel height resulted in decreased maximum abduction moment around heel-strike and increased maximum adduction moments during midstance and terminal stance (Figure 2C, D, & E). Note these increases are presented in terms normalized moments and did not include the added weight since the normalized moments were used to test if mechanistic changes in walking influenced loading independently.

DISCUSSION

The results of this study provide new insight on specific features of high heeled gait, alone and in combination with increased weight, that potentially increase osteoarthritis risk in women. Specifically, the changes in knee mechanics of flexion-extension angle, flexion-extension moment, and knee abduction-adduction moment found in this study were similar to those seen in aging and the progression of OA.[1,16] These findings suggest that high heel wear, especially in combination with additional weight, induces significant changes in knee joint loading due to altered gait kinematics and kinetics. However, it remains unknown how these changes in loading, when coupled with repeated use of high heels, affect cartilage health. Further studies are needed to determine if these changes contribute to the development of knee OA.

An important finding in the current work was that the knee adduction moment increased with heel height, and that this occurred despite decreased walking speed. Because knee adduction moment is considered a surrogate measure of the *relative* medial-to-lateral distribution of force across the joint, the actual medial compartment force depends on a combination of both dynamic forces and forces generated by muscles and ligaments spanning the joint.[20] Additionally, peak knee adduction moment has been associated with medial compartment OA progression.[1,2]

While the results appear consistent with prior studies,[5,6,8–11] in terms of increases in early stance knee flexion angle and both peaks of external knee adduction moment as heel height increased, a closer look at the influence of walking speed provides new insight. For example, other studies reported a higher maximum knee flexion moment during midstance in high heels compared to low heels,[5,10,11] while this study indicated that the maximum knee flexion moment did not increase at preferred speed. However, correction for walking speed in the supplementary analysis resulted in increased maximum flexion moment in the 8.3 cm heel compared with the 3.8 cm heel and control shoe (Figure 3, Table 3). The observed variability at preferred speed suggests a variable adaption to the high heels where certain individuals compensate more than others for the decreased stability in the high heeled shoes, resulting in a higher flexion moment. This suggests that there may be movement patterns that can be adopted when wearing high heels to minimize increases in knee flexion moment. Because these changes in knee kinematics and kinetics increase patellofemoral joint stress and pain,[21] reducing these loads while wearing high heels could be beneficial to joint health and function. Further studies are necessary to investigate whether gait retraining can achieve this effect.

This study also shows that increased weight, alone and in combination with heels, alters knee gait kinematics and kinetics in the sagittal plane. While the use of a weighted vest may not perfectly simulate an increase in body mass, this method permitted within subject comparisons. Because the weighted vest shifts the center of gravity upward, this situation more closely simulates truncal obesity than an increase in body mass that is more uniform or predominantly below the waist. Additionally, it is unknown whether the changes in gait observed using a symmetrically distributed weighted vest were due purely to increased mass, an alteration in the center of mass, or a combination of these factors. Nevertheless, the use of the weighted vest resulted in increased knee flexion angle at heel-strike and throughout early stance and reduced maximum extension moment during loading response, both of which are similar to gait changes that have been associated with aging and OA progression in the sagittal plane.[16] These similarities to that of conditions carrying higher OA risk suggest that upper body weight gain or carrying loads while wearing high heeled shoes amplify loading patterns that may adversely affect knee joint health.

This study reports on data obtained using a unique shoe design where it was possible to employ paired analyses to evaluate moderate and large increases in heel height. While previous studies have separately examined moderate height[9] and high heeled shoes,[5,8] this work confirms a threshold effect previously suggested by Kerrigan[9] where maximum flexion moment and the first peak in adduction moment increased with a large increase in heel height but were not affected by a modest increase in heel height. This effect was also observed with maximum extension moment during terminal stance, which showed decreases only in the highest heel. These data support existence of a threshold heel height where aberrant loading patterns are amplified. Future studies looking at a higher resolution of heel heights with constant shoe structure are necessary to determine where this threshold is.

By showing similarities between high heeled gait and specific features of gait associated with OA development, this study suggests that high heel use, especially when combined with increased weight, may contribute to increased OA risk in women. The results of this study have isolated specific variables that can be used as a basis for larger longitudinal studies to further evaluate high heel induced gait changes as a risk factor for knee OA. It is also important to note that the gait measures identified in this study can be modified (e.g. shoe design or gait retraining) in a manner to mitigate the mechanical factors due to wearing high heels that may contribute to the higher incidence of OA in women compared to men.

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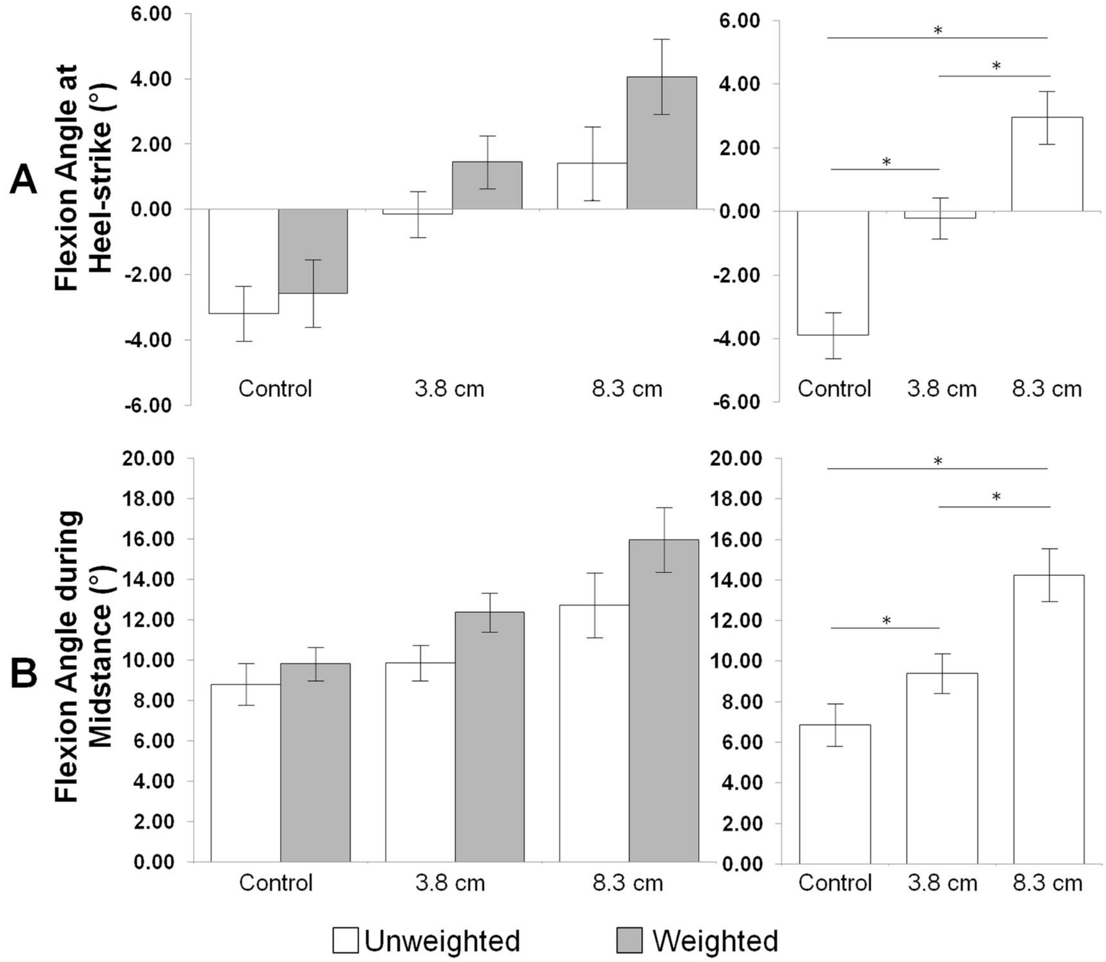

Figure 1. Sagittal plane knee kinematic variables of interest

Left column: Mean values ± SEM for both unweighted and weighted walking at preferred speed in each shoe type. Significant differences due to both shoe type and loading condition are outlined in Table 2. Right column: Mean values ± SEM for unweighted walking when compared at the median walking speed for all unweighted trials. * indicates significant difference between shoe types.

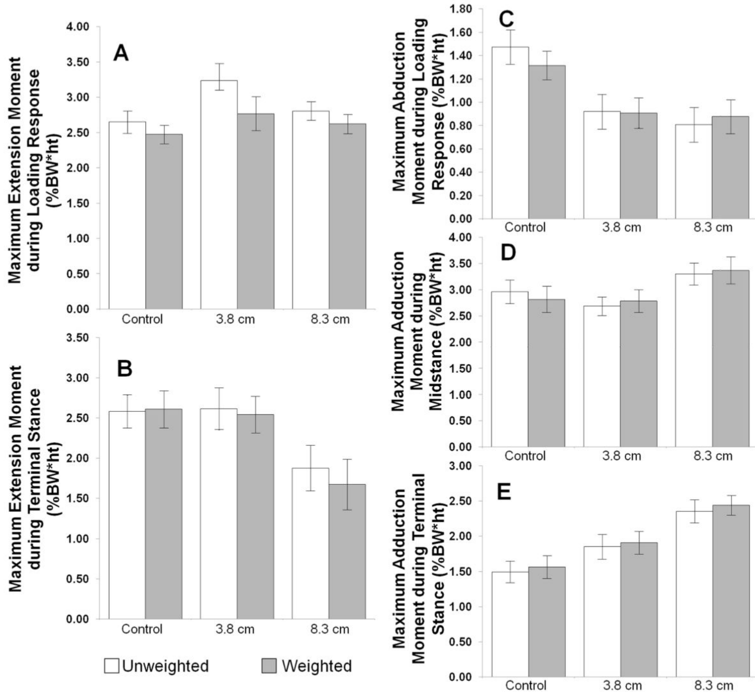

Figure 2. Kinetic variables of interest showing significant differences at preferred walking speed

Mean values ± SEM for both unweighted and weighted walking at preferred speed in each shoe type. Significant differences due to both shoe type and loading condition are outlined in Table 2. Left column: Sagittal plane knee moments. Right column: Coronal plane knee moments.

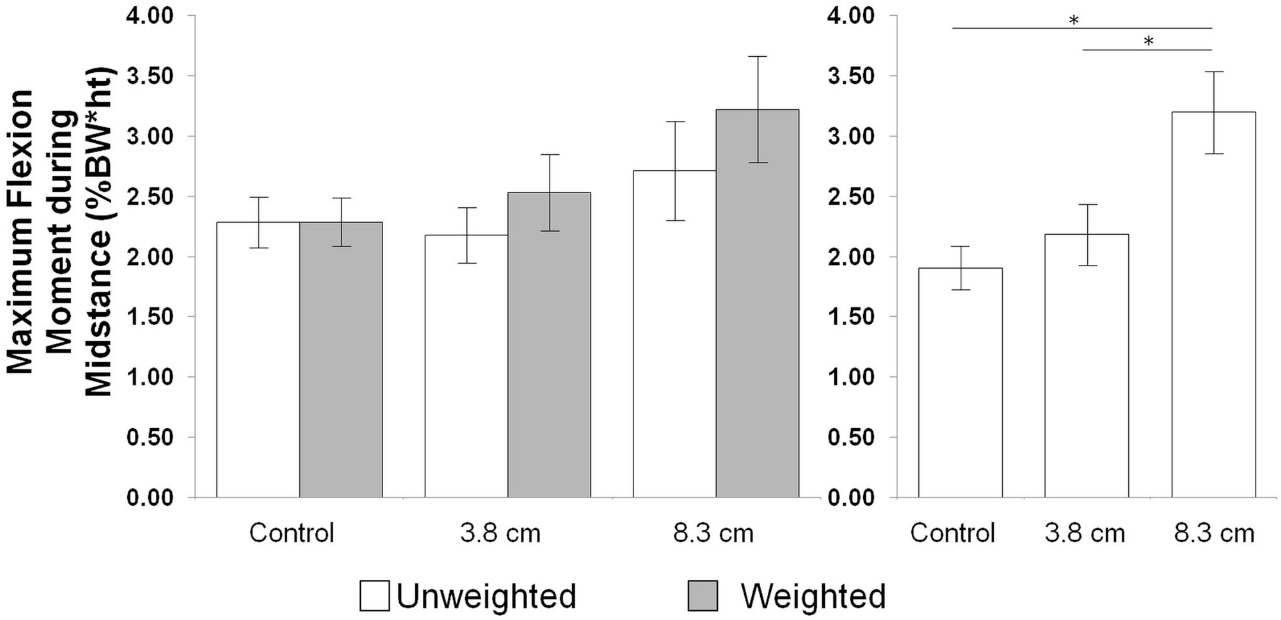

Figure 3. Maximum knee flexion moment during midstance

Left column: Mean values ± SEM for both unweighted and weighted walking at preferred speed in each shoe type. Significant differences due to both shoe type and loading condition are outlined in Table 2. Right column: Mean values ± SEM for unweighted walking when compared at the median walking speed for all unweighted trials. * indicates significant difference between shoe types.

Table 1

Definition of kinematic and kinetic variables.

Variable	Abbreviation	Definition
Knee flexion-extension angle, °	KFA_{hs}	Knee flexion-extension angle at heel-strike
	KFA_{ms}	Maximum knee flexion angle during midstance
	KFA_{ts}	Maximum extension angle during terminal stance
Knee flexion-extension moment, %BW*Ht	KFM_{lr}	Maximum extension moment during loading response
	KFM_{ms}	Maximum flexion moment during midstance
	KFM_{ts}	Maximum extension moment during terminal stance
Knee abduction-adduction moment, %BW*Ht	KAM_{lr}	Maximum abduction moment during loading response
	KAM_{ms}	Maximum adduction moment during midstance
	KAM_{ts}	Maximum adduction moment during terminal stance

Table 2

Kinematic and kinetic variables at preferred walking speed.

Variable	Control Athletic Shoe		3.8 cm Heels		8.3 cm Heels		2-Way ANOVA		
	Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded	Shoe Type	Loading Condition	Shoe* Loading
KFA_{hs}	−3.20 (3.15)	−2.56 (3.87)	−0.15(2.61)	1.45(3.03)	1.41(4.19)	4.06 (4.28)	**<0.0001**$^{\#,¶,§}$	**0.0002**	0.073
KFA_{ms}	8.80 (3.88)	9.81 (3.06)	9.86(3.32)	12.37(3.64)	12.72(6.05)	15.97 (6.06)	**0.0023**¶,§	**0.0006**	0.065
KFA_{ts}	−1.74 (3.92)	−2.28 (3.58)	−1.93(3.46)	−1.75(3.90)	−0.84(4.94)	−0.26 (6.24)	0.223	0.806	0.248
KFM_{lr}	2.65 (0.60)	2.47 (0.49)	3.24(0.92)	2.77(0.91)	2.81(0.50)	2.62 (0.51)	0.111	**0.0001**	0.079
KFM_{ms}	2.28 (0.80)	2.29 (0.75)	2.18(0.87)	2.53(1.18)	2.71(1.54)	3.22 (1.65)	0.014	0.009	0.138
KFM_{ts}	2.59 (0.77)	2.61 (0.86)	2.62(0.98)	2.55(0.85)	1.88(1.07)	1.67 (1.18)	**<0.0001**¶,§	0.194	0.344
KAM_{lr}	1.47 (0.55)	1.32 (0.46)	0.92(0.56)	0.91(0.48)	0.81(0.56)	0.88 (0.54)	**<0.0001**$^{\#,¶}$	0.451	0.165
KAM_{ms}	2.96 (0.83)	2.82 (0.93)	2.68(0.66)	2.78(0.80)	3.30(0.78)	3.37 (0.95)	**<0.0001**¶,§	0.904	0.017
KAM_{ts}	1.49 (0.57)	1.56 (0.61)	1.85(0.65)	1.91(0.61)	2.36(0.62)	2.44 (0.52)	**<0.0001**$^{\#,¶,§}$	0.102	0.933
Gait Speed	1.41 (0.14)	1.38 (0.13)	1.28(0.10)	1.29(0.12)	1.17(0.13)	1.18 (0.14)	**<0.0001**$^{\#,¶,§}$	0.800	0.337

Note: Data are presented as mean (standard deviation). The three columns on the right present the p-values of the two-way ANOVA testing for the effects of shoe type and loading condition. Significant effects are reported in bold type (Hochberg sequential procedure, $\alpha = 0.05$). Results of post hoc pair-wise comparisons (Bonferroni) are indicated with superscript symbols (#: control shoe different from 3.8 cm heeled shoe, ¶: control shoe different from 8.3 cm heeled shoe, §: 3.8 cm heeled shoe different from 8.3 cm heeled shoe).

Table 3

Speed-matched kinematic and kinetic variables at median speed.

Variable	Control Shoe	3.8 cm Heels	8.3 cm Heels	ANOVA
KFA_{hs}	−3.90(2.71)	−0.21(2.42)	2.95 (3.11)	**<0.0001**$^{\#,¶,§}$
KFA_{ms}	6.86(3.90)	9.39(3.66)	14.25 (4.90)	**<0.0001**$^{\#,¶,§}$
KFA_{ts}	6.86(3.90)	9.39(3.66)	14.25 (4.90)	0.082
KFM_{lr}	2.43(0.33)	3.24(0.46)	3.14 (0.79)	**0.0001**$^{\#,¶}$
KFM_{ms}	1.90(0.68)	2.18(0.95)	3.20 (1.28)	**<0.0001**¶,§
KFM_{ts}	2.59(0.58)	2.70(0.89)	1.87 (1.04)	**<0.0001**¶,§
KAM_{lr}	1.31(0.42)	0.89(0.47)	0.96 (0.59)	**0.007**$^{\#}$
KAM_{ms}	2.80(0.70)	2.75(0.66)	3.49 (0.78)	**<0.0001**¶,§
KAM_{ts}	1.44(0.56)	1.89(0.64)	2.36 (0.53)	**<0.0001**$^{\#,¶,§}$

Note: Data are presented as mean (standard deviation). The column on the right presents the p-values of the one-way ANOVAs testing for the effect of shoe type. Significant effects are reported in bold type (Hochberg sequential procedure, $\alpha = 0.05$). Results of post hoc pair-wise comparisons (Bonferroni) are indicated with superscript symbols (#: control shoe different from 3.8 cm heeled shoe, ¶: control shoe different from 8.3 cm heeled shoe, §: 3.8 cm heeled shoe different from 8.3 cm heeled shoe).