Kinetics of High-Heeled Gait

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A within-subject comparative study of walking while wearing low-heeled sports shoes *versus* high-heeled dress shoes was performed to identify and describe changes in lower-extremity joint kinetics associated with wearing high-heeled shoes during level overground walking. A volunteer sample of 15 unimpaired female subjects recruited from the local community underwent quantitative measurement of sagittal and frontal plane lower-extremity joint function, including angular motion, muscular moment, power, and work. When walking in high-heeled shoes, a significant reduction in ankle plantar flexor muscle moment, power, and work occurred during the stance phase, whereas increased work was performed by the hip flexor muscles during the transition from stance to swing. In the frontal plane, increased hip and knee varus moments were present. These differences demonstrate that walking in high-heeled shoes alters lower-extremity joint kinetic function. Reduced effectiveness of the ankle plantar flexors during late stance results in a compensatory enhanced hip flexor "pull-off" that assists in limb advancement during the stance-to-swing transition. Larger muscle moments and increased work occur at the hip and knee, which may predispose long-term wearers of high-heeled shoes to musculoskeletal pain. (J Am Podiatr Med Assoc 93(1): 27-32, 2003)

Surveys on shoe use have shown that 37% to 69% of women wear high-heeled shoes on a daily basis.[1, 2] Societal and fashion customs encourage the continued use of high-heeled shoes despite concerns regarding their detrimental effects on gait and lower-extremity function. Complaints of leg and back pain are common among wearers of high-heeled shoes, and the possible role of high-heeled shoes in the development of degenerative joint disease has been noted.[2-5] Given the large number of people who wear high-heeled shoes, understanding the gait biomechanics associated with their use may offer insights into clinically preventable musculoskeletal problems. This is especially important in today's environment of preventive medicine, medical cost reduction, and heightened health awareness.

Previous investigations[6-10] have shown that high-heeled shoes align the foot in plantarflexion; change the relative orientation of the skeletal structures of the ankle, midtarsal, and metatarsophalangeal joints; and alter the insertion angles of the foot and ankle muscles. The altered anatomical position of the foot results in functional changes that include a shift in ground reaction forces toward the medial forefoot, a reduction in foot pronation during midstance, and an increase in the vertical ground reaction force at heel strike.[5, 10] The abnormal forefoot loading documented by these studies underlies many of the painful forefoot disorders associated with the use of high-heeled shoes.

The effect of wearing high-heeled shoes on joint kinematic and kinetic changes proximal to the ankle has not been studied as extensively. Increased hip

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and knee flexion during stance occurs as a postural adaptation to the plantarflexed foot position and as a potential compensatory mechanism for absorbing impact loads.[3, 4, 11] Unfortunately, such mechanisms have also been implicated as a potential source of knee pain and degeneration.[3] Investigations[4, 5, 11-13] driven by concerns regarding the role of high-heeled shoes in the alteration of posture and the development of low-back pain have explored the effect of heel height on compensatory and adaptive changes in the lumbar spine. Contrary to the conventional clinical assumption of increased lumbar lordosis, most studies[4, 11, 12] have shown that experienced high-heeled shoe wearers show no change or a reduction in lumbar spine extension. Inexperienced users tend to increase trunk lordosis as well as pelvic and limb rotation while walking.[12]

The literature reveals scant evidence regarding proximal joint kinetic changes during high-heeled gait. The present study was undertaken to better describe the lower-extremity kinetic changes associated with high-heeled shoes in a healthy population. This information is needed to better identify abnormal loads and potentially adverse compensatory muscular demands placed on proximal musculoskeletal structures due to exaggerated heel height.

Materials and Methods

Institutional review board–approved consent was obtained from 15 women for study during level overground walking under two conditions: wearing low-heeled sports shoes and wearing high-heeled dress shoes. The women had no known neuromuscular or musculoskeletal disorders. The shoes were commercially available and were standardized for style, composition, and manufacturer. All shoes fit the subjects comfortably. The low-heeled sports shoe had a flexible composite sole with a 1-cm heel. The high-heeled dress shoe consisted of a man-made upper, a round toe box, and a hard composite heel measuring 5.5 cm wide and 6 cm high.

Combined lower-extremity kinematic data and ground reaction forces were collected using a VICON Motion Analysis System (Oxford Metrics Ltd, Oxford, England). Reflective markers identifying body segments were placed on the second metatarsophalangeal joint, heel, lateral malleolus, lateral aspect of the shank midway between the knee and ankle joints, lateral femoral epicondyle, lateral aspect of the thigh midway between the hip and knee joints, anterior superior iliac spine, sacrum, and C7 spinous process. Three-dimensional marker locations were sampled at 60 Hz, along with simultaneous ground reaction forces, as subjects walked across a force plate (AMTI Technologies Inc, Oxford, England) embedded in the floor of the walkway. Marker data were filtered at 6 Hz. Gait events (heel strike and toe-off) were identified using visual observation of the motion and the synchronized ground reaction force data.

A seven-segment linked-segment model consisting of the right/left foot, right/left shank, right/left thigh, and trunk was used to define body segments and joint angles. Inverse dynamic modeling was used to determine joint moments and power outputs for each walking trial. Data were normalized and interpolated to 2% intervals of the gait cycle.

The order of the two footwear conditions was randomized for each subject. Self-selected walking speed was used to best mimic actual shoe use, although this may increase the variability in speed-dependent kinematic and kinetic measures. As described by Kadaba et al,[14] a statistical assessment of the between-trial repeatability was performed by using the coefficient of multiple correlation for each motion pattern per subject for each shoe condition. Repeatability was high between trials for each subject; the three trials that showed the highest repeatability were chosen for averaging. All subsequent analyses were derived from these averaged data sets.

Muscle work performed at each of the lower-extremity joints was calculated using custom software. Positive muscle work indicates work generation through concentric contraction, and negative work represents power absorbed by eccentric muscle contraction. Nomenclature for describing work phases is adapted from Winter.[15] Matched paired-sample *t*-tests ("dependent *t*") were performed for each moment and work variable using SPSS for Windows (SPSS Science, Chicago, Illinois). To minimize the likelihood of type I errors from the multiple comparisons performed, a Bonferroni correction using the Holm modification was used to adjust *P* value significance.

Results

Subjects ranged in age from 23 to 42 years and had a mean ± SD weight of 66 ± 13 kg and a mean ± SD height of 172 ± 6.8 cm. The mean ± SD coefficients of multiple correlation representing between-trial repeatability for all of the subjects for each shoe condition are given in Tables 1 through 4. The use of high-heeled shoes reduced the self-selected walking speed by 6%, from 1.3 to 1.2 m/sec, owing to a reduction in stride length from 137 to 131 cm. Despite the slower walking speed, the peak vertical ground reaction force during limb loading was 5% greater with high-heeled shoes, although this did not achieve statistical

Table 1. Temporal and Spatial Characteristics of High-Heeled and Low-Heeled Shoe Gait

	Low-Heeled Shoe		High-Heeled Shoe		
Variable	Mean ± SD	Between-Trial CMC	Mean ± SD	Between-Trial CMC	*P* Value
Temporal/spatial					
Stride length (cm)	136.6 ± 8.96	1.7 ± 0.5	130.8 ±7.93	1.6 ± 0.6	<.001[a]
Cadence (steps/min)	113.4 ± 10.6	1.8 ± 0.7	112.0 ± 10.2	1.9 ± 0.8	.063
Walking speed (cm/sec)	129.4 ± 15.4	3.1 ± 1.6	122.2 ± 12.1	2.9 ± 1.8	<.001[a]
Ground reaction force (GRF)					
GRF_z peak	1.06 ± 0.08	0.98 ± 0.002	1.11 ± 0.07	0.99 ± 0.001	.03
GRF_z second peak	1.11 ± 0.06	0.97 ± 0.001	1.12 ± 0.05	0.98 ± 0.003	.27
GRF_x fore	0.25 ± 0.25	0.98 ± 0.003	0.24 ± 0.21	0.99 ± 0.002	.10
GRF_x aft	–0.15 ± 0.10	0.99 ± 0.001	–0.16 ± 0.08	0.98 ± 0.003	.16

Abbreviation: CMC, coefficient of multiple correlation.
[a] Statistically significant.

Table 2. Stance Phase Ankle Joint Kinetic Characteristics of High-Heeled and Low-Heeled Shoe Gait

	Low-Heeled Shoe		High-Heeled Shoe		
Variable	Mean ± SD	Between-Trial CMC	Mean ± SD	Between-Trial CMC	*P* Value
Maximum dorsiflexor moment	–0.11 ± 0.07	0.99 ± 0.005	–0.16 ± 0.10	0.98 ± 0.007	.07
Maximum plantar flexor moment	1.56 ± 0.13	0.99 ± 0.007	1.34 ± 0.20	0.97 ± 0.005	<.001[a]
A1: Eccentric plantar flexor work	–0.15 ± 0.05		–0.12 ± 0.06		.01
A2: Concentric plantar flexor work	0.35 ± 0.17		0.25 ± 0.08		<.001[a]

Abbreviation: CMC, coefficient of multiple correlation.
[a] Statistically significant.

Table 3. Stance Phase Knee Joint Kinetic Characteristics of High-Heeled and Low-Heeled Shoe Gait

	Low-Heeled Shoe		High-Heeled Shoe		
Variable	Mean ± SD	Between-Trial CMC	Mean ± SD	Between-Trial CMC	*P* Value
Maximum varus moment	0.51 ± 0.12	0.94 ± 0.046	0.64 ± 0.09	0.95 ± 0.057	.09
Maximum extensor moment, early stance	0.19 ± 0.21	0.97 ± 0.037	0.27 ± 0.23	0.94 ± 0.033	.003[a]
Maximum flexor moment	–0.39 ± 0.21	0.98 ± 0.027	–0.33 ± 0.20	0.97 ± 0.047	.27
Maximum extensor moment, late stance	0.18 ± 0.07	0.96 ± 0.017	0.21 ± 0.06	0.98 ± 0.095	.01
K1: Eccentric knee extensor work	–0.01 ± 0.01		–0.009 ± 0.009		.19
K2: Concentric knee extensor work	0.01 ± 0.01		0.03 ± 0.02		<.001[a]
K3: Eccentric knee extensor work	–0.11 ± 0.05		–0.12 ± 0.04		.18

Abbreviation: CMC, coefficient of multiple correlation.
[a] Statistically significant.

Table 4. Stance Phase Hip Joint Kinetic Characteristics of High-Heeled and Low-Heeled Shoe Gait

	Low-Heeled Shoe		High-Heeled Shoe		
Variable	Mean ± SD	Between-Trial CMC	Mean ± SD	Between-Trial CMC	*P* Value
Maximum abduction moment	0.91 ± 0.14	0.97 ± 0.017	1.02 ± 0.21	0.98 ± 0.021	.01
Maximum extensor moment	0.52 ± 0.14	0.98 ± 0.041	0.52 ± 0.14	0.97 ± 0.034	.77
Maximum flexor moment	–1.07 ± 0.26	0.97 ± 0.041	–1.11 ± 0.29	0.99 ± 0.071	.53
H1: Concentric hip extensor work	0.06 ± 0.03		0.07 ± 0.04		.17
H2: Eccentric hip flexor work	–0.21 ± 0.11		–0.23 ± 0.10		.23
H3: Concentric hip flexor work	0.13 ± 0.04		0.16 ± 0.05		.003[a]

Abbreviation: CMC, coefficient of multiple correlation.
[a] Statistically significant.

significance. The plantarflexed posture of the foot in high-heeled shoes was associated with a reduction in the peak plantar flexor moment in late stance (Fig. 1). Reflecting the reduced moment, plantar flexor muscle work with high-heeled shoes was reduced by 29% during late stance (A2 phase) (Table 2).

The knee muscular moments for high-heeled and low-heeled shoes were similar throughout the stance phase, except for a larger extensor moment for a longer duration during limb loading when wearing high-heeled shoes (Fig. 2). Although there was a 200% increase in concentric knee extensor work (K2), the absolute magnitude of the increased work was small. In the frontal plane, the peak knee varus moment during stance was increased by 25% when wearing high-heeled shoes (Fig. 3).

Similar patterns of hip moment and power were present for both shoe conditions (Fig. 4). Peak hip

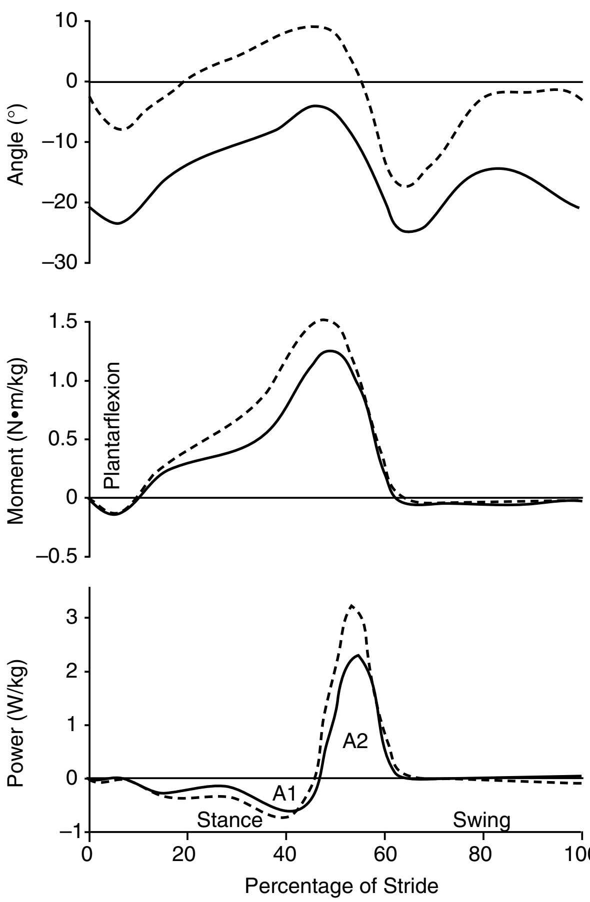

Figure 1. Comparison of ankle joint angle, moment, and power between low-heeled shoes (broken line) and high-heeled shoes (solid line). A1, Eccentric plantar flexor work; A2, concentric plantar flexor work.

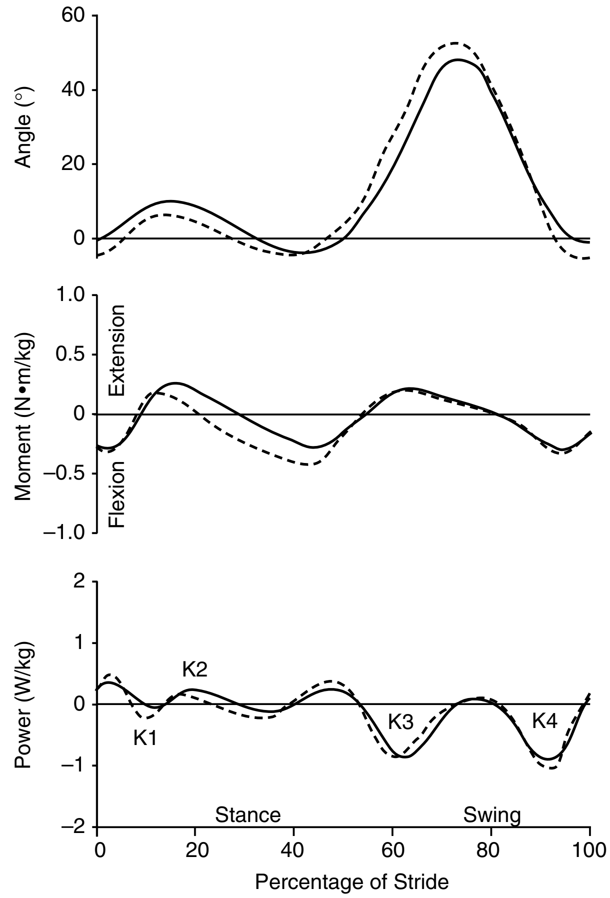

Figure 2. Comparison of knee joint angle, moment, and power between low-heeled shoes (broken line) and high-heeled shoes (solid line). K1, Eccentric knee extensor work; K2, concentric knee extensor work; K3, eccentric knee extensor work; K4, eccentric knee extensor work.

flexion moment was similar in magnitude but prolonged in duration when wearing high-heeled shoes, resulting in a 23% increase in concentric hip flexor muscle work (H3) (Table 4). In the frontal plane, peak hip abduction moment was increased by 11% when wearing high-heeled shoes, but this did not achieve statistical significance (Fig. 4).

Discussion

Walking in high-heeled shoes produces changes in lower-extremity joint kinetics that begin in the early stance phase. Echoing the results of previous studies,[6, 7] this study found that wearing high-heeled shoes biased the ankle joint into 14° of plantarflexion and created a compensatory increase in knee and hip flexion during the first half of stance. Associated

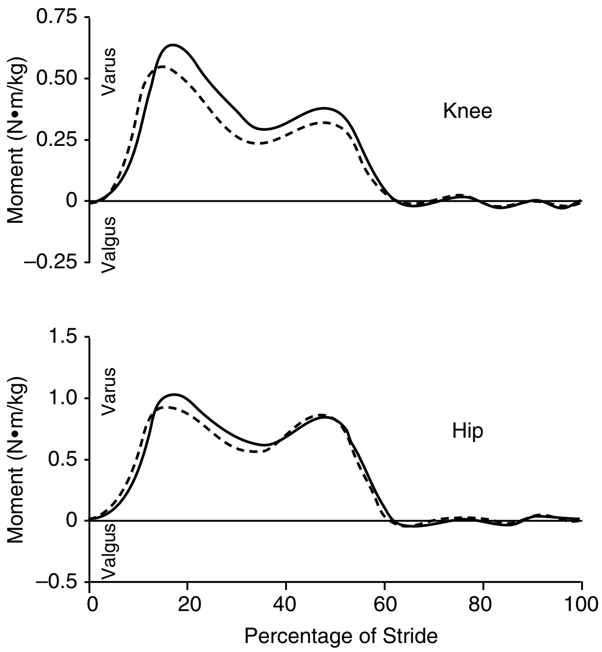

Figure 3. Comparison of hip and knee joint frontal plane moments between low-heeled shoes (broken line) and high-heeled shoes (solid line).

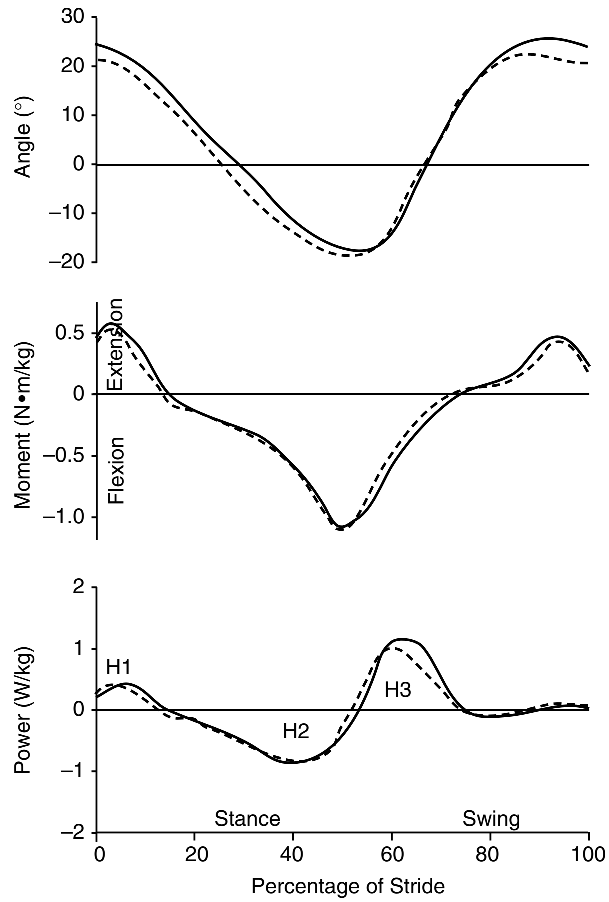

Figure 4. Comparison of hip joint angle, moment, and power between low-heeled shoes (broken line) and high-heeled shoes (solid line). H1, Concentric hip extensor work; H2, eccentric hip flexor work; H3, concentric hip flexor work.

with the altered limb position is an early stance muscular knee extensor moment of larger magnitude. The increase in the knee moment stabilizes the joint as the limb is loaded and the trunk decelerates. Underlying the need for the larger moment are several factors. First, the increased flexion moves the knee joint center relatively more anterior in early stance, increasing the knee bending or flexion torque from the vertical ground reaction force. Second, and probably more important, the use of a higher heel increases the floor-to-knee distance, thereby increasing the tibial lever arm through which the posteriorly directed ground reaction force flexes the knee. As a compensatory mechanism, a larger extensor muscle moment is needed to resist this reactive tendency to flex at the knee (Fig. 2). This finding is similar to that reported by Kerrigan et al.[3]

During the first half of stance, a trend toward reduction in the eccentric ankle plantar flexor control of forward tibial advancement is seen, as reflected by the smaller magnitude of ankle moment (Fig. 1). The reduced plantar flexor moment persists into terminal stance and limits the power output and concentric work of the gastrocnemius and soleus muscle group during limb acceleration (push-off). The 29% reduction in concentric push-off work represents a major loss of work needed for limb advancement. Several mechanisms probably lead to the reduced plantarflexion moment. The plantarflexed posture of the ankle effectively shortens the forefoot lever arm, moving the ground reaction force closer to the ankle and lessening the restraining plantar flexor moment demand.[16] In addition, the plantarflexed position of the ankle joint places the gastrocnemius and soleus muscles at a shortened and thus less favorable point on its muscle length-tension curve. Under such conditions, the plantar flexors are in a less favorable position for power and work generation and, consequently, for propulsive abilities.

To adapt to and compensate for the loss of distal limb acceleration, hip flexor torque generation is prolonged during the transition from stance to swing. This prolongation leads to an increase in the overall concentric work of the proximal hip flexor muscles (H3 phase), enhancing "pull-off" and acceleration of the limb into swing. This is the only significant increase in muscle work during stance in high-heeled shoe wearers. The increased use of the hip flexor muscles for limb acceleration and pull-off is similar to adaptations seen in the gait patterns of other populations with distal strength loss[17] and appears to be a common adaptive strategy.

Frontal plane gait alterations at the hip and knee were also present with high-heeled shoes. During stance, hip joint adduction is increased, moving the hip lateral relative to the foot and contributing to a medial shift in the location of the center of pressure.[10] The more medially placed ground reaction force creates a larger knee varus moment and hip adduction (varus) moment (Fig. 4). Correspondingly, the hip abduction muscular moment needed to ensure hip stability and limit pelvic drop was increased by 10%.

Several clinical consequences of the altered joint kinetics seen in this study can be inferred. At the hip, abductor muscle moment magnitude increased, although not significantly, and the duration of hip flexor muscle moment was prolonged, leading to an increase in overall muscle work. These changes, although modest, could lead to overuse syndromes and underlie the complaints of hip and back discomfort frequent in high-heeled shoe wearers. Of greater concern is the increase in knee loading that occurs through a combination of increased vertical ground reaction force and the increased magnitude of the early stance knee extensor and varus moments. The effect of this repetitive loading may increase the risk of degenerative joint disease or exacerbate existing knee weakness or pain. A similar pattern of increased knee moments has been reported by Kerrigan et al.[3]

Conclusion

The findings of this study indicate that the use of high-heeled shoes alters selected proximal lower-extremity joint kinetic function. These changes represent adaptive strategies that maintain limb stability as the ankle is forced into an exaggerated plantarflexed posture and substitute for reduced plantar flexor function in limb advancement through the increased use of hip flexor muscle activity. The changes are modest but could contribute to the creation of abnormal and potentially injurious forces that may underlie some of the proximal joint and spine pain complaints of habitual high-heeled shoe wearers. The potential role of foot posture in the development of musculoskeletal disorders needs to be considered when evaluating pain complaints or prescribing shoes, insoles, lifts, and surgical treatments.

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