

Long-term use of high-heeled shoes alters the neuromechanics of human walking

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Cronin NJ, Barrett RS, Carty CP. Long-term use of high-heeled shoes alters the neuromechanics of human walking. *J Appl Physiol* 112: 1054–1058, 2012. First published January 12, 2012; doi:10.1152/jappphysiol.01402.2011.—Human movement requires an ongoing, finely tuned interaction between muscular and tendinous tissues, so changes in the properties of either tissue could have important functional consequences. One condition that alters the functional demands placed on lower limb muscle-tendon units is the use of high-heeled shoes (HH), which force the foot into a plantar-flexed position. Long-term HH use has been found to shorten medial gastrocnemius muscle fascicles and increase Achilles tendon stiffness, but the consequences of these changes for locomotor muscle-tendon function are unknown. This study examined the effects of habitual HH use on the neuromechanical behavior of triceps surae muscles during walking. The study population consisted of 9 habitual high heel wearers who had worn shoes with a minimum heel height of 5 cm at least 40 h/wk for a minimum of 2 yr, and 10 control participants who habitually wore heels for less than 10 h/wk. Participants walked at a self-selected speed over level ground while ground reaction forces, ankle and knee joint kinematics, lower limb muscle activity, and gastrocnemius fascicle length data were acquired. In long-term HH wearers, walking in HH resulted in substantial increases in muscle fascicle strains and muscle activation during the stance phase compared with barefoot walking. The results suggest that long-term high heel use may compromise muscle efficiency in walking and are consistent with reports that HH wearers often experience discomfort and muscle fatigue. Long-term HH use may also increase the risk of strain injuries.

muscle fascicle; ultrasound; locomotion; tendon stiffness; gait

HUMAN MUSCLES AND TENDONS exhibit changes in both size and material properties in response to chronic changes in mechanical load or length (10, 21). For example, Achilles tendon stiffness decreases after prolonged disuse (25) and increases after resistance training (3). Human movement requires an ongoing, finely tuned interaction between muscular and tendinous tissues, so changes in the properties of either tissue could have important functional consequences.

During common movements such as walking, muscle-tendon units (MTUs) undergo cyclic length changes that are distributed between muscular and tendinous tissues in accordance with their relative compliance, whereby the tissue with the greater relative compliance absorbs a larger proportion of MTU stretch (24). In humans, one condition that alters the functional demands placed on lower limb MTUs is the use of high-heeled shoes (HH), which force the foot into a plantarflexed position. Csapo et al. (9) found that long-term HH use induced shortening of the medial gastrocnemius muscle fascicles and increased

Achilles tendon stiffness, which contributed to a reduction in the active range of motion of the ankle joint. During walking, these adaptations could cause a shift in MTU stretch distribution away from the tendinous tissues and toward the muscle fascicles, potentially altering neural activation patterns and decreasing MTU efficiency (8, 19).

To date, studies of the effects of wearing HH on walking have focused on kinematic, kinetic, and/or neural parameters (13, 27, 28), but the neuromechanics of this task have not been explored. Furthermore, relatively few studies of high-heeled gait have examined individuals who are habituated to wearing HH (9, 23). Therefore, the aim of this study was to examine the effects of habitual HH use on the neural and mechanical behavior of triceps surae muscles during walking. Two hypotheses were tested: 1) within the HH group, walking in HH would lead to larger fascicle strains and greater muscle activation during the stance phase because of the functional demands imposed on the MTU by high-heeled shoes; 2) during barefoot walking, long-term HH wearers would exhibit larger fascicle strains and greater muscle activation than controls because of the greater tendon stiffness of long-term HH wearers.

METHODS

Participants

The study population consisted of two groups. In the habitual HH group 9 women (age 25 ± 7 yr; height 168 ± 7 cm; mass 65 ± 17 kg) were recruited. Participants in this group had to have worn shoes with a minimum heel height of 5 cm for at least 40 h/wk and for a minimum of 2 yr. The control group consisted of 10 women (age 25 ± 4 yr; height 166 ± 5 cm; mass 60 ± 7 kg) who habitually wore heels for less than 10 h/wk. Differences in age, height, and mass between groups were nonsignificant (independent *t*-tests; $P = 0.359$ – 0.989). Prior to testing, participants were fully informed of the experimental procedures and provided written consent. The study was approved by the Institutional Human Research Ethics Committee and was performed in accordance with the Declaration of Helsinki.

Protocol

Participants walked at a self-selected speed over a level walkway ~ 8 m in length, with a force platform embedded in the laboratory floor in the center of the walkway. Control participants performed the task 10 times walking barefoot, and HH participants performed 10 barefoot trials and 10 wearing the HH to which they were most accustomed (heel area: 1 cm^2 ; heel height: 11 ± 2 cm or $6 \pm 1\%$ of stature). The barefoot and HH trials were separated by a rest period of 4–5 min. Prior to data collection, participants performed several practice trials to determine the optimal start point to prevent targeting of the force platform and were instructed to look forward at all times. After the walking trials, two dorsi- and two plantarflexion maximal voluntary contractions (MVCs) were performed at an ankle angle of

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90° on a dynamometer (Biodex, Shirley, NY) with 2-min rest periods between contractions. For the HH group, this was also repeated at 20° of plantar flexion to replicate the average ankle angle when wearing high heels (15) and thus, presumably, the resting length of the triceps surae MTU in long-term HH wearers (9).

Data Collection and Analysis

Gait characteristics. Trajectories of 51 reflective markers attached to the head, trunk, pelvis, and upper and lower limbs were recorded at 100 Hz using a 10-camera, three-dimensional motion capture system (Vicon Motion Systems, Oxford, UK). Three-dimensional gait kinematics were computed using the method described by Barrett et al. (4). Ground reaction force (GRF) data were acquired at 1 kHz using a single 900 × 600 mm piezoelectric force platform (Kistler, Amherst, NY). Kinematic and GRF data were low-pass filtered at 6 Hz. The vertical GRF was used to determine the step and stride times as well as the peak GRF for each step, and all GRF values were normalized to body mass. Sagittal knee and ankle joint moments were subsequently obtained using the inverse dynamics tool in OpenSim (12) based on body segment parameter estimates from de Leva (11).

Surface electromyography. Surface electromyography (EMG) activity was recorded using bipolar surface electrodes (Duo-trode, Myotronics) with an interelectrode distance of 2 cm. Data were collected telemetrically (Aurion ZeroWire, Milan, Italy) from the soleus, medial gastrocnemius, and tibialis anterior muscles of the right leg at 1 kHz. EMG signals were band-pass filtered (10–500 Hz), rectified, low-pass filtered (40 Hz), and ensemble averaged to produce EMG profiles. Mean background EMG was quantified as the mean EMG throughout the stance phase. For both groups, EMG data acquired during walking were normalized to the average EMG over the 1-s period corresponding to maximal torque during the respective MVC. For the HH group, all EMG data in the RESULTS are shown normalized to the MVC recorded at 20° of plantar flexion as the normalization method did not affect the between- or within-group differences.

Ultrasound. A personal computer-based ultrasound system (Echo-blaster 128; Telemed, Vilnius, Lithuania) and a 96-element linear probe (B-mode; 7 MHz; 60 mm field of view) were used to image the medial gastrocnemius muscle fascicles at a sampling frequency of 80 Hz. The probe was aligned with the fascicle plane (6) to minimize errors attributable to probe orientation (18) and secured over the skin surface with a compressive bandage to minimize probe movement relative to the skin. Rotation of the probe was also minimized due to its flat shape, which leads to very little inertia around the sagittal plane axis [$\sim 0.8^\circ$ rotation in the mediolateral direction (20)]. A digital output signal from the ultrasound system was used to synchronize data collection. Medial gastrocnemius muscle fascicle lengths were determined throughout the stance phase using an automated fascicle tracking algorithm validated previously (7, 14). To determine fascicle strain, fascicle length values from each condition were normalized to the length obtained during quiet standing for that condition. Medial gastrocnemius muscle thickness was determined as the distance be-

tween the superficial and deep aponeuroses from the center of the image recorded during barefoot standing.

Statistical analysis. As the Levene's test for equality of variances always produced nonsignificant results, comparisons of all variables between groups were performed using independent *t*-tests. Comparisons within the HH group between walking in heels and barefoot were performed using paired samples *t*-tests. Significance was accepted for $P < 0.05$.

RESULTS

Spatio-Temporal Parameters

Within the HH group, step length was significantly shorter in heels compared with barefoot walking. No other differences in spatio-temporal measures were detected for any group comparisons (Table 1).

Comparisons between Control and HH Participants

During walking, average EMG activity was similar for soleus and TA ($t = -1.707$ to -1.756 , $P = 0.097$ – 0.106) but larger in MG in the HH group ($t = -4.691$, $P < 0.001$). Peak GRF during the stance phase did not differ between groups for the first or second force peaks ($t = 0.149$ – 0.476 , $P = 0.640$ – 0.726). Fascicle length during standing and at the instant of ground contact were both statistically shorter in the HH group ($t = 2.798$ – 2.918 , $P = 0.033$). Although absolute fascicle lengthening during stance was larger in controls ($t = 2.436$, $P = 0.044$), peak fascicle strains did not differ between groups ($3.6 \pm 1.5\%$ for controls, $3.8 \pm 1.4\%$ for HH; $t = 0.198$, $P = 0.846$) because of the shorter resting fascicle length in HH. No statistical between-group differences were observed in ankle or knee range of motion (ROM) during stance ($t = 0.253$ – 0.466 , $P = 0.648$ – 0.804) or ankle or knee angle at ground contact ($t = -0.183$ – 0.710 , $P = 0.733$ – 0.862). Similarly, no differences were observed in peak flexor or extensor moments at the ankle or knee ($t = -1.076$ – 0.375 , $P = 0.299$ – 0.713 ; Fig. 1). During barefoot standing, there was no statistical difference in MG muscle thickness between groups ($t = -0.088$, $P = 0.931$).

Comparison of HH Participants Barefoot and in Heels

Average EMG was similar for MG ($t = 4.899$, $P = 0.058$) but higher in soleus and TA when walking with high heels ($t = 13.360$ – 121.566 , $P < 0.01$). Peak GRF also increased with heels for both force peaks ($t = 7.245$ – 35.350 , $P < 0.001$). Fascicle length was shorter in heels during standing and at the point of ground contact ($t = 55.436$ – 63.519 , $P < 0.001$).

Table 1. Mean spatio-temporal gait parameters

	Group			Between		Within	
	Controls	HH Flat	HH Heels	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>
Walking speed, m/s	1.19 ± 0.05	1.22 ± 0.04	1.20 ± 0.03	−0.645	0.529	0.766	0.488
Step length, m	0.62 ± 0.01	0.63 ± 0.02	0.61 ± 0.02	−0.607	0.553	4.101	0.003*
Step time, s	0.53 ± 0.01	0.53 ± 0.01	0.53 ± 0.01	−0.257	0.800	0.202	0.845
Stride length, m	1.28 ± 0.02	1.32 ± 0.03	1.30 ± 0.03	−0.779	0.448	1.172	0.275
Stride time, s	1.09 ± 0.03	1.08 ± 0.02	1.08 ± 0.02	0.037	0.971	0.320	0.757
Support time, s	0.66 ± 0.01	0.65 ± 0.02	0.67 ± 0.01	0.106	0.917	2.051	0.074

Data are means ± SD; $n = 9$ for high heel wearers (HH) and 10 for controls. Between, control vs. HH barefoot comparisons; Within, HH barefoot vs. HH in heels comparisons. *Significant difference at the $P < 0.05$ level.

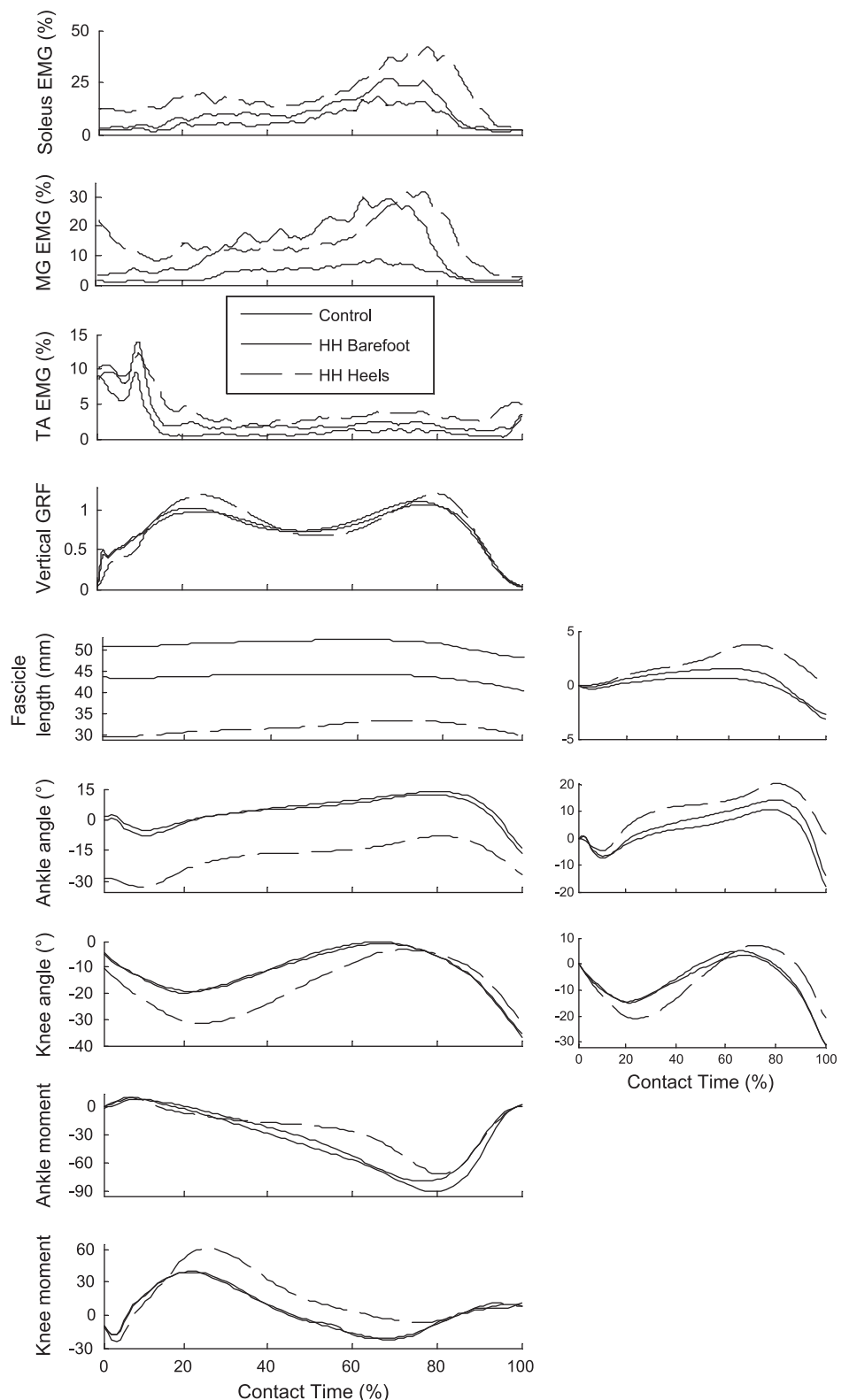


Fig. 1. Group data [$n = 9$ for high heel shoe wearers (HH); $n = 10$ for controls] averaged over 10–15 trials per condition within participants and then averaged by group. EMG data are normalized to maximal voluntary contraction (MVC). Sagittal joint moments are normalized to body mass. Contact time is expressed as a percentage of stance phase duration. *Insets:* fascicle length and joint kinematics corrected for initial offsets to highlight between and within group differences. Extension moments and extended joint angles are defined as positive.

Absolute fascicle lengthening during stance ($t = 34.069$, $P < 0.001$) and peak fascicle strain ($t = -4.321$, $P < 0.01$) were both greater in heels, with mean strain values of $3.8 \pm 1.4\%$ (barefoot) and $12.9 \pm 4.0\%$ (heels). In heels, ankle ROM was smaller ($t = 2.260$, $P = 0.041$) and the ankle was more plantar

flexed at ground contact ($t = 7.282$, $P < 0.01$). Knee ROM did not differ statistically between conditions ($t = 1.731$, $P = 0.122$), but the knee was more flexed at ground contact in heels ($t = 4.116$, $P = 0.029$). Compared with barefoot walking, walking in heels resulted in similar peak ankle dorsifl-

exor moments ($t = 1.198$, $P = 0.313$), smaller peak plantar flexor moments ($t = 3.569$, $P < 0.01$), larger peak knee extensor moments ($t = -3.849$, $P < 0.01$), and smaller peak knee flexor moments ($t = -2.432$, $P = 0.038$; Fig. 1).

DISCUSSION

The main finding of this study was that the muscle fascicles of habitual HH wearers exhibited substantially larger strains when walking in heels than when walking barefoot, despite the smaller range of ankle rotation in the high heels condition. This finding is consistent with the notion of increased Achilles tendon stiffness after long-term HH use (9) and supports our first hypothesis. Conversely, in barefoot walking, habitual HH wearers exhibited higher MG muscle activation but similar fascicle strains and joint kinematics relative to controls, thus partially refuting our second hypothesis, possible reasons for which are discussed below. The results of this study may have important implications for muscle efficiency and injury risk during common movements such as walking.

Comparisons between Habitual HH Wearers and Controls

In accordance with the findings of Csapo et al. (9), the habitual HH group in the present study had shorter muscle fascicles during standing than controls, suggesting that they had experienced chronic adaptations in muscle-tendon architecture related to HH use. Furthermore, the average participant age in our study (25 ± 7 yr) was considerably lower than in the study of Csapo and colleagues (42.9 ± 11 yr), indicating that long-term HH use can induce structural adaptations at an earlier age than previously reported. Csapo et al. (9) suggested that the reduction of fascicle length observed in regular HH wearers may represent a long-term adaptation of the plantar-flexor muscles, whereby the number of in-series sarcomeres decreases in an attempt to reset a normal sarcomere operating range.

Despite similar joint kinematics and moments, the HH group exhibited higher muscle activation in MG but not TA or SOL during the stance phase of barefoot walking, suggesting that this group required different neural strategies to compensate for alterations in muscle-tendon architecture. Higher MG activity may increase the likelihood of fatigue in prolonged walking in nonheeled shoes and decrease muscle efficiency (19). The HH group also showed similar MG fascicle strains compared with controls. In light of the finding that chronic HH use leads to a stiffening of the Achilles tendon (9), it might be expected that fascicle strains would be larger in this group, as was the case when walking in heels. One possible explanation for this apparent contradiction could be that following habitual HH use, the MTU strains imposed during barefoot walking are somewhat unfamiliar and the response is to stiffen the muscles during stance. If this were correct, it would suggest that MTU stretch was largely taken up by the aponeurotic tissues in this group, although we are unable to confirm or refute this hypothesis on the basis of our data.

Comparisons within the HH-Wearing Group

In agreement with previous research (17), HH wearers exhibited an increase in muscle activation of the TA and soleus when walking in heels, indicating an increase in coactivation. Furthermore, although average MG EMG activity was un-

changed, the MG muscle appeared to be activated over a larger portion of the stance phase when walking in heels (see Fig. 1), as reported previously (5). These changes are presumably related to the decrease in stability caused by wearing heels and are consistent with the increased energetic cost of transport associated with walking in heels (13, 22).

As expected, the MG fascicles were shorter in the HH condition attributable to the ankle being in a more plantar flexed position. During walking, the muscle fascicles lengthened and strained significantly more (and at a higher rate) in heels compared with barefoot. In fact, estimated fascicle strains were approximately three times higher ($\sim 13\%$ in heels vs. $\sim 4\%$ in barefoot walking), and fascicle strain rate was approximately six times higher. This represents a potential injury risk and may partly explain the fact that HH shoes are often associated with discomfort and muscle fatigue (1, 23). These results are also consistent with the notion that habitual HH use results in an increase in Achilles tendon stiffness (9), which, in combination with a smaller ankle range of motion during stance, could explain the shift of MTU stretch away from tendinous tissues and toward the muscle fascicles when walking in heels. If appreciable energy is stored in the tendinous tissues during walking, as is known to occur in running (2), distribution of stretch to the muscle fascicles would decrease the effectiveness of this mechanism in HH, as well as altering the muscle's force producing capacity and increasing the amount of active muscle shortening during late stance. All of these changes could increase muscle energy requirements.

Walking in heels resulted in larger peak vertical GRFs, as shown previously (13, 26). Csapo et al. (9) suggested that this implies an increase in the relative muscle forces acting on the tendon-aponeurosis complex in the HH group, which could eventually lead to tendon hypertrophy, based on their finding of a larger Achilles tendon cross-sectional area in experienced HH wearers. However, it should be noted that the peak plantar flexor moment decreased in heels. Simonsen et al. (26) reported the same trend and suggested that this can be explained by the more plantar flexed foot position, which decreases fascicle length and Achilles tendon moment arm, while also ensuring that the GRF vector passes closer to the ankle joint center, decreasing the moment requirement. The smaller ankle moment appears to be at least partly compensated by an increase in the peak knee flexion moment, as shown here and by Simonsen et al. (26).

Methodological Considerations

A strength of this study was that HH participants were habitual HH wearers and performed the testing protocol in HH to which they were accustomed. This design eliminates the possibility of learning effects, which is a potential limitation of asking all participants to wear a standardized shoe to which they are not accustomed (23). Furthermore, the standard deviation of heel height relative to participant height was only 1%, suggesting that the chosen shoes induced similar relative alterations in MTU length between individuals. A limitation of this study was the use of surface EMG electrodes in the HH group. When walking in heels, the muscle geometry is altered, so the sample of motor units from which the surface electrodes recorded will have differed between the barefoot and heels conditions. Therefore, comparisons of EMG data between

conditions rest on the assumption that spatial activation is homogeneous throughout the muscle, which may not be the case in human walking (16).

Conclusions

In long-term HH wearers, walking in HH is associated with substantial increases in muscle fascicle strains and muscle activation during the stance phase compared with barefoot walking. Adaptations attributable to long-term HH use may compromise muscle efficiency in both barefoot and HH walking. The observed neuromuscular behavior is consistent with the reports that HH wearers often experience discomfort and muscle fatigue and suggests that HH use may increase the risk of strain injuries.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: N.J.C., R.S.B., and C.P.C. conception and design of research; N.J.C. and C.P.C. performed experiments; N.J.C. and C.P.C. analyzed data; N.J.C., R.S.B., and C.P.C. interpreted results of experiments; N.J.C. prepared figures; N.J.C., R.S.B., and C.P.C. drafted manuscript; N.J.C., R.S.B., and C.P.C. edited and revised manuscript; N.J.C., R.S.B., and C.P.C. approved final version of manuscript.

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