Kinematic and Electromyographic Analysis of the Trunk and Lower Limbs During Walking in Negative-Heeled Shoes

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Background: We investigate kinematic adaptation and muscle activities in the trunk and lower extremities of healthy subjects during treadmill walking in negative-heeled sports shoes *versus* normal sports shoes.

Methods: Thirteen healthy female university students participated in the study. We analyzed sagittal-movement kinematics and electromyographic findings from the erector spinae, rectus abdominus, rectus femoris, biceps femoris, tibialis anterior, and lateral gastrocnemius muscles of the dominant side in two shod conditions.

Results: Negative-heeled gait is characterized by faster cadence, shorter stride length, increased maximal extension angles in the trunk and hip, increased flexion angle in the knee, larger dorsiflexion in the stance phase, and a larger range of motion of the ankle joint. Negative-heeled gait resulted in a significantly larger integrated electromyographic value, a longer duration of electromyographic activity, and a higher mean amplitude of electromyographic activity in the tibialis anterior, lateral gastrocnemius, and biceps femoris muscles.

Conclusions: Negative-heeled gait compared with normal gait places a higher physiologic demand on the tibialis anterior, lateral gastrocnemius, and biceps femoris muscles when walking on a level surface. Thus, negative-heeled shoes could be of value if used in an exercise rehabilitation or training program where inclined walking is not available owing to a flat terrain. (J Am Podiatr Med Assoc 97(6): 447-456, 2007)

The strength of the muscles across the ankle and knee joints is important in maintaining stability and in reducing the likelihood of injury. For patients with ankle and knee joint injuries, many approaches have been developed to enhance the muscular strength around these joints as part of rehabilitation, one of which is graded walking.[1] Negative-heeled shoes, also known as earth shoes, were designed to mimic uphill walking so as to build up and exercise the muscles in the trunk and lower limbs. In normal sports shoes, the heel is approximately 1.5 cm higher than the toe part.[2] In contrast, in negative-heeled shoes the toe part is 1.5 cm higher than the heel, which tilts the foot into approximately 10° of dorsiflexion.

Previous studies[3] in trunk and lower-extremity kinematics have shown that gait adaptation on uphill treadmill inclination during walking is characterized by an increasingly flexed posture of the hip, knee, and ankle at initial foot contact and by a progressive forward tilt of the pelvis and trunk. An earlier report[4, 5] showed a significant decrease in walking speed and cadence when walking up a steep ramp of greater than 9°. A reduction in step length was also observed during descent walking.[6] Electromyographic studies[1, 7-9] regarding muscle activation in uphill treadmill walking and ramp ground walking have found a modifying level of activation of the relevant flexor and extensor muscles in the lower extremity.

Some studies show the influence of shoe heel height on locomotor adaptation. It was found that walking in high-heeled shoes produced shorter stride lengths and higher stance time percentage than walking in normal sports shoes.[10] Kinematically, gait while wearing high-heeled shoes, compared to gait while wearing low-heeled shoes, was characterized by significantly increased knee flexion at heel strike and during the stance phase and significantly lower knee flexion and hip flexion during the swing phase.

Studies that present the kinematics of the trunk and lower limbs when walking in negative-heeled

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shoes are limited, and the kinematic changes that occur when walking in these shoes are not consistent. The earliest study[11] of negative-heeled shoes stated that there were no changes in the gait pattern of subjects walking barefoot, in tennis shoes, or in negative-heeled shoes. However, comparison of the flexion and extension of the back, hip, knee, and ankle joints of subjects when standing and walking in negative-heeled shoes, positive-heeled shoes, and bare feet suggested that the greatest compensation for heel height occurs distally.[12] Another study[13] reported that walking speed was significantly reduced while walking in negative-heeled shoes as a consequence of a shorter stride length combined with an increased cadence. Walking patterns differed drastically at the ankle joint, but no significant difference was found at the knee and hip joints. Kinematic adaptation in different walking conditions is attributed to the changes in muscle activity in the trunk and lower extremities. However, for negative-heeled shoes, no study about muscle activity in the trunk and lower extremities has been reported.

The purpose of the present investigation was to establish a basic understanding of the activity levels of the muscles of the erector spinae, rectus abdominus, rectus femoris, biceps femoris, tibialis anterior, and lateral gastrocnemius and to evaluate the kinematic adaptation of the trunk and lower extremities when walking in negative-heeled shoes. This knowledge will provide a basis for the recommendation of walking in negative-heeled shoes to strengthen the muscles of the trunk and lower extremities through locomotion adaptation, which could be of value if used in an exercise rehabilitation or training program where inclined walking is not available owing to a flat terrain.

Materials and Methods

Subjects and Shoes

A total of 13 female subjects (mean ± SD age, 23.08 ± 3.9 years; body weight, 50.18 ± 5.3 kg; and height, 1.63 ± 0.05 m) volunteered to participate in the study. All of the subjects were in good health and had no experience walking in negative-heeled shoes. They had no previous history of muscle weakness, neurologic disease, or any drug therapy. All of the subjects were fully informed of the purpose and the procedures involved in the study, to which they gave informed consent according to the guidelines of the Chinese University of Hong Kong's ethics committee. All of the subjects were provided with two types of shoes: normal sports shoes and negative-heeled shoes. Both types of shoes were similar in construction and materials except for heel height. Normal sports shoes tilted the sole into approximately 10° of plantarflexion, whereas negative-heeled shoes tilted the sole into 10° of dorsiflexion. Because heel heights vary according to the sizes of shoes, in this study, only size 37 (European) shoes were selected.

Data Collection and Analysis

Each subject participated in two walking trials wearing negative-heeled shoes and normal sports shoes. The order of the shoes was randomly assigned for each trial. In each trial, subjects walked on a treadmill at a constant speed of 1.33 m/sec, a comfortable speed for adults.[14] Before the start of the trial, lightweight spherical (diameter = 2 cm) reflective markers were attached to the right side of the subject at anatomical positions (acromion, greater trochanter, lateral epicondyle of the femur, lateral malleolus, calcaneus, and head of the fifth metatarsal) to facilitate the later video digitization (Fig. 1A).

Walking movement was recorded with a 3-CCD video camera (50 Hz) set at a 1/500-sec shutter speed starting from the time the subject felt comfortable or had achieved a steady stance. The camera was positioned lateral to the subject, perpendicular to the movement plane, at a distance of 5 m. For each trial, 10 consecutive strides recorded at 1, 4, and 6 min were digitized and analyzed with a video motion analysis system (APAS; Ariel Dynamics, Trabuco Canyon, California). As shown in Figure 1B, the hip joint angle was determined by the acromion, greater trochanter, and lateral epicondyle of the femur; the knee joint angle was determined by the greater trochanter, lateral epicondyle of the femur, and lateral malleolus; and the ankle joint angle was determined by the lateral epicondyle of the femur, lateral malleolus, and head of the fifth metatarsal. All of the joint angles at the erect standing position were defined as 0°. The positive angle value of each joint was associated with hip flexion, knee flexion, and ankle dorsiflexion, respectively. In addition, the sagittal orientation of the trunk segment was measured with respect to the horizontal axis in the anterior direction. Higher values indicated extension. A Butterworth low-pass filter was used to smooth the position-time data for anatomical landmarks. The maximum and minimum trunk, hip, knee, and ankle joint angles, range of motion, stride cycle time, cadence, and stride length were calculated.

The electromyographic signals of the erector spinae, rectus abdominus, biceps femoris, rectus femoris, tibialis anterior, and lateral gastrocnemius muscles were examined for each subject's dominant side. Two pregelled (silver-silver chloride) diaphoretic surface elec-

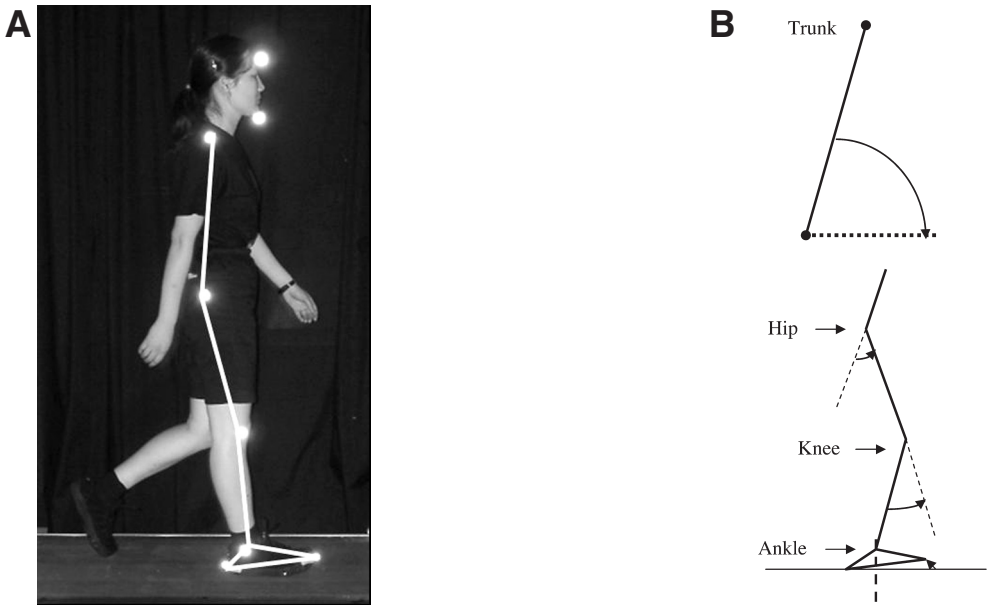

Figure 1. A, Lateral view of the kinematic model. B, Segment and joint angle definitions are illustrated for the sagittal plane. For every segment and joint angle, the arrow direction indicates the positive angle from neutral.

trodes were placed, 3 cm apart, over prepared muscle sites. A single ground electrode was placed on the anterior superior iliac crest of the pelvis. The raw electromyographic signals were sampled at 1,000 Hz using a software program (LabVIEW; National Instruments Corp, Austin, Texas) and were stored in a computer for postevent analysis. Video filming and electromyographic signal collection were synchronized with an external light trigger. The raw electromyographic data were high-pass filtered digitally at 20 Hz, full-wave rectified, and linear enveloped, with a cutoff frequency of 5 Hz. The electromyographic parameters used in this study included the average integrated electromyographic value in 1 sec, the mean amplitude of electromyographic activity, and the duration of electromyographic activity in each muscle during a stride cycle. The corresponding time point at which electromyographic amplitude exceeded or went below 2 SD of the mean amplitude of the electromyographic activity of the muscle was set as the criterion of the onset and offset of the electromyographic activity, respectively.

To reduce small variations in the duration of each gait cycle between subjects, the time of the gait cycle was normalized (0% to 100%). For each subject, the kinematic and electromyographic parameters at the same normalized time point of each stride were averaged across the ten consecutive strides and further averaged across the three time points for each shod condition. The parameters were finally averaged across all of the subjects for each shod condition.

Statistical Analysis

Differences in the measured parameters between negative-heeled shoes and normal sports shoes were examined with a paired-sample t test, with the level of significance set at $P < .05$.

Results

Kinematic Parameters

Table 1 shows the mean and standard deviation of each variable and statistical comparisons between the two shod conditions during walking on a treadmill. Walking in negative-heeled shoes induced a shorter stride cycle time and stride length compared with walking in normal sports shoes ($P < .001$). Because walking speed was the same, the decrease in stride length when walking in negative-heeled shoes resulted in a faster cadence ($P < .001$).

For trunk posture, significant differences in the maximum flexion and extension angles were found between the two shod conditions ($P < .01$). The range of motion of the trunk during walking in negative-heeled shoes tended to be slightly increased but did not show any statistical significance. Wearing negative-heeled shoes had less impact on trunk posture despite producing a slight backward (0.95°) posture.

At the hip joint, maximum flexion and extension angles showed significant differences between the two shod conditions ($P < .05$), but no significant dif-

Table 1. Comparison of Kinematics Variables Between Normal Sports Shoes and Negative-Heeled Shoes During Treadmill Walking

Variable	Normal Sports Shoes	Negative-Heeled Shoes	*t* test	*P* Value
Temporal measurement				
Stride cycle time (sec)	1.05 (0.04)	1.02 (0.04)	5.16	<.001
Cadence (steps/min)	114.40 (1.99)	116.80 (2.02)	–5.36	<.001
Stride length (cm)	140 (4.90)	137 (5.00)	4.84	<.001
Trunk position (°)				
Maximum flexion angle	88.95 (3.78)	89.90 (3.91)	–3.46	.005
Maximum extension angle	80.15 (3.67)	80.82 (3.83)	–2.90	.013
ROM during stride cycle	8.81 (1.84)	9.07 (1.81)	–0.91	.380
Hip joint (°)				
Maximum flexion angle	21.87 (3.27)	20.34 (3.27)	–2.49	.028
Maximum extension angle	–10.82 (4.07)	–11.98 (3.75)	–2.97	.012
ROM during stride cycle	32.69 (5.17)	32.32 (4.22)	0.70	.495
Knee joint (°)				
Angle at touchdown	7.53 (3.39)	7.92 (3.45)	–0.702	.496
Maximum flexion angle during stance	18.66 (4.64)	19.13 (3.34)	–0.698	.498
Maximum extension angle during stance	0	1.58 (1.34)	–4.25	.001
ROM during stride cycle	66.03 (2.83)	65.28 (2.96)	0.969	.352
Ankle joint (°)				
Angle at touchdown	7.89 (2.31)	13.86 (2.46)	–18.99	<.001
Maximum PF angle during stance	–3.29 (2.40)	4.85 (2.28)	–25.19	<.001
Maximum DF angle during stance	10.39 (2.74)	15.86 (2.58)	–18.71	<.001
ROM during stride cycle	28.01 (3.19)	28.70 (2.98)	–2.52	.027

Abbreviations: ROM, range of motion; PF, plantarflexion; DF, dorsiflexion.
Note: Data are given as mean (SD).

ferences were found in range of motion. At the knee joint, a difference of 1.58° in the maximum extension angles between the two shod conditions in the stance phase was found to be a significant difference ($P < .001$). However, no significant differences were found between the two shod conditions in the angle at touchdown, the maximal flexion angle during stance, and the range of motion during the stride cycle. At the ankle joint, the angle at touchdown, the maximum dorsiflexion and plantarflexion angles, and the range of motion of the joint all showed significant differences between the two types of shoes ($P < .05$). The difference in maximum dorsiflexion during the stance phase between the two walking conditions was 5.47°. In normal sports shoes, 3.29° of maximum plantarflexion was observed during the stance phase. In negative-heeled shoes, the foot was always dorsiflexed during the stance phase. Figure 2 shows the mean angular changes of the hip, knee, and ankle joints during a complete stride cycle in all of the subjects, with differences in the ankle joint being the most pronounced.

Electromyographic Activities

Table 2 lists the means and standard deviations of the average integrated electromyographic activity, electromyographic activity duration, and mean amplitude of electromyographic activity of each muscle and statistical comparisons between the two shod conditions. The average integrated electromyographic value increased by 13.0% for the tibialis anterior muscle, 21.7% for the lateral gastrocnemius muscle, and 11.3% for the biceps femoris muscle when walking in negative-heeled shoes ($P < .01$) (Fig. 3). Moreover the duration of electromyographic activity was longer by 83.4% in the tibialis anterior muscle and 35.8% in the lateral gastrocnemius muscle during walking in negative-heeled shoes ($P \leq .001$). The duration of electromyographic activity of the biceps femoris and erector spinae muscles for negative-heeled shoes was longer (21.9% and 16.4%, respectively) than that observed for normal sports shoes, but no statistical difference was noted. The mean amplitudes of electromyographic activity of the tibia-

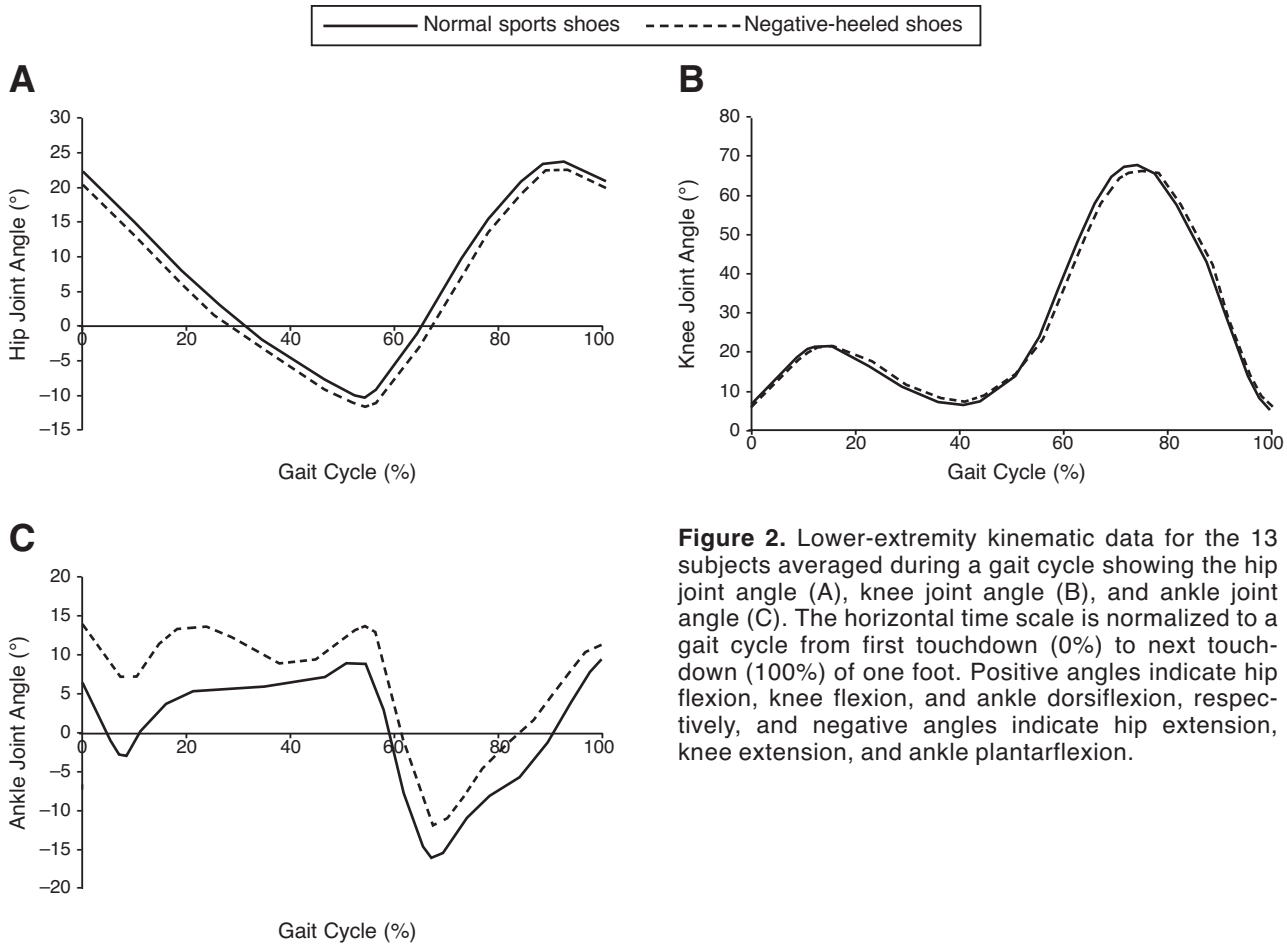

Figure 2. Lower-extremity kinematic data for the 13 subjects averaged during a gait cycle showing the hip joint angle (A), knee joint angle (B), and ankle joint angle (C). The horizontal time scale is normalized to a gait cycle from first touchdown (0%) to next touchdown (100%) of one foot. Positive angles indicate hip flexion, knee flexion, and ankle dorsiflexion, respectively, and negative angles indicate hip extension, knee extension, and ankle plantarflexion.

lis anterior, lateral gastrocnemius, and biceps femoris muscles during walking in negative-heeled shoes were higher by 12.7%, 21.3%, and 11.4%, respectively ($P < .01$ or $P < .05$). No statistically significant differences in electromyographic measurements were found in the rectus femoris and rectus abdominis muscles between the two walking conditions. Electromyographic analysis revealed that the calf and biceps

Table 2. Comparison Across Subjects of Electromyographic (EMG) Variables Between Normal Sports Shoes (NSSs) and Negative-Heeled Shoes (NHSs) During Treadmill Walking in a Gait Cycle

	Average Integrated EMG Activity (per sec)		Duration of EMG Activity (% of a gait cycle)		Mean Amplitude of EMG Activity in a Gait Cycle (μV)	
Muscle	NSS	NHS	NSS	NHS	NSS	NHS
Tibialis anterior	0.40 ± 7.24	0.47 ± 7.61	20.92 ± 6.30	38.38 ± 11.32[a]	40.17 ± 7.33	45.28 ± 7.86[a]
Lateral gastrocnemius	0.33 ± 7.04	0.40 ± 9.62	24.92 ± 5.02	33.85 ± 12.41[a]	32.68 ± 7.61	39.65 ± 9.84[a]
Rectus femoris	0.21 ± 8.40	0.20 ± 5.64	28.62 ± 9.53	28.38 ± 9.91	21.42 ± 8.59	19.74 ± 5.77
Biceps femoris	0.29 ± 0.10	0.31 ± 9.95	29.54 ± 13.83	36.00 ± 16.35	29.25 ± 1.00	32.59 ± 1.00[b]
Erector spinae	0.18 ± 6.80	0.17 ± 6.18	30.00 ± 9.75	29.23 ± 3.37	18.52 ± 7.18	17.38 ± 6.32
Rectus abdominus	0.12 ± 5.29	0.11 ± 5.56	60.62 ± 19.19	70.54 ± 14.28	11.48 ± 5.56	11.50 ± 5.60

Note: Data are given as mean ± SD.
[a] $P \leq .01$.
[b] $P < .05$.

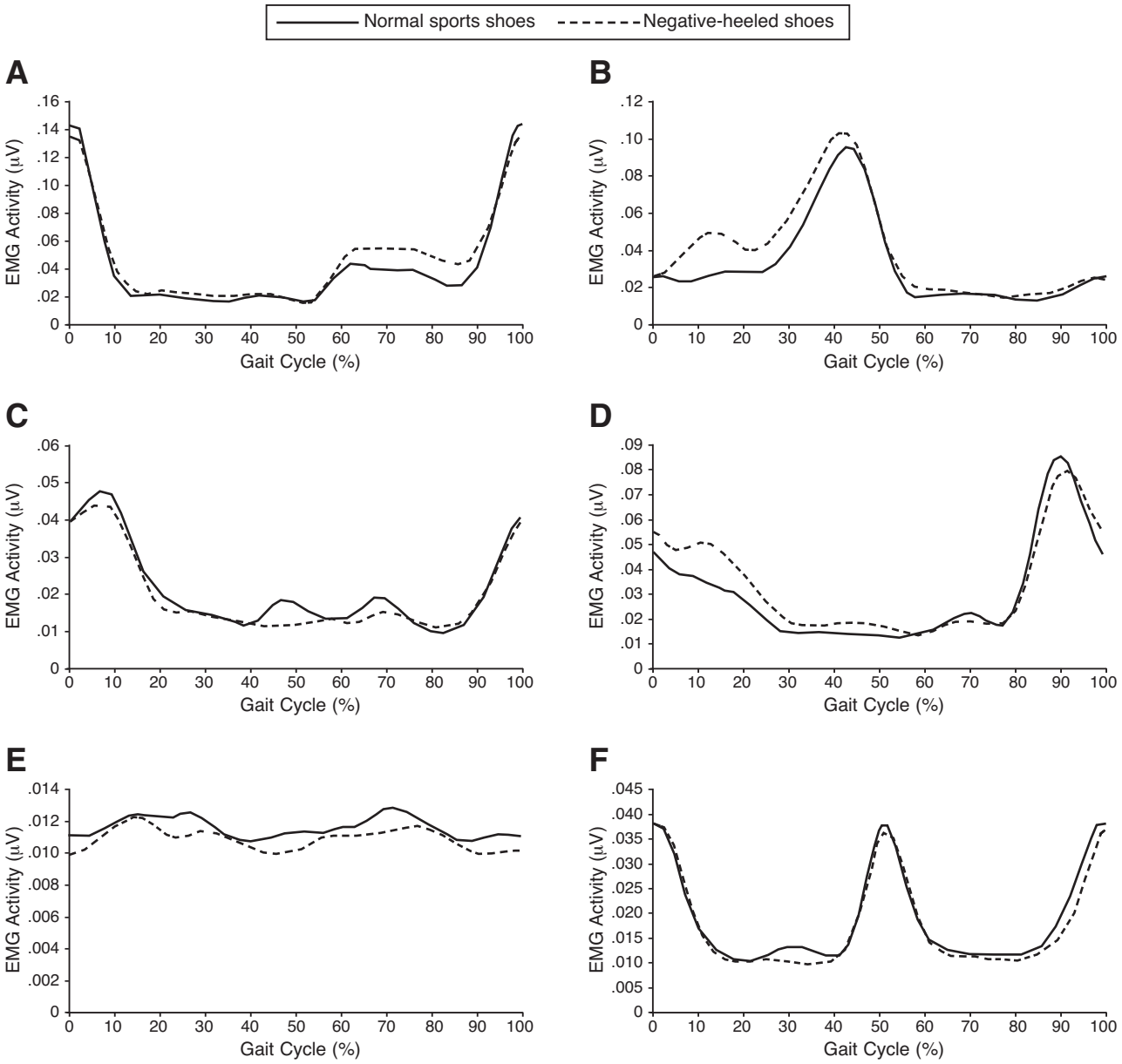

Figure 3. Electromyographic (EMG) patterns of the six muscles in the trunk and lower extremities for the 13 subjects averaged during a gait cycle: tibialis anterior (A), lateral gastrocnemius (B), rectus femoris (C), biceps femoris (D), rectus abdominus (E), and erector spinae (F) muscles. The horizontal time scale is normalized to a gait cycle duration from first touchdown (0%) to next touchdown (100%) of one foot.

femoris muscles were more sensitive to walking in negative-heeled shoes.

Discussion

Kinematic Changes

According to Winter,[15] during a completed stride cycle when walking with natural cadence, the ranges of motion of the hip, knee, and ankle joints were 32.79°, 64.86°, and 29.39°, respectively. The ranges of motion of walking in negative-heeled shoes observed in the present study were 32.32°, 65.28°, and 28.70° for the hip, knee, and ankle, respectively, which were close to the ranges observed by Winter. Thus, negative-heeled gait is a normal gait.

With walking speed being controlled at a constant 1.33 m/sec in both walking modes, wearing negative-

heeled shoes showed a significantly shorter stride cycle time, associated with faster cadence and shorter stride length. In studying uphill walking, Leroux et al[3, 7] found that as the treadmill slope increased, the stride length progressively increased and, consequently, the stride cycle duration increased. These authors found that the increase in hip flexion was important, in direct association with the increase in stride length. The present results show a decrease in hip flexion, which may have been due to the increase in dorsiflexion of the ankle joint and the difference between the tasks of level and uphill walking, which may have consequently resulted in the decrease in stride length and a shorter stride-cycle duration. In addition, the maximum extension angle of the knee joint at take-off when walking in negative-heeled shoes was significantly smaller than when walking in normal sports shoes (Table 1), which possibly contributed to shortening of the stride length.[16] To keep a constant speed, subjects had to increase their cadence to compensate for the decrease in stride length.

While walking in normal sports shoes, initial contact was followed by plantarflexion (–3.29°) by placing the forefoot completely on the ground during the earlier stance phase. The ankle joint changed again to dorsiflexion (10.39°) from midstance through take-off. While walking in negative-heeled shoes, the ankle joint was held in less dorsiflexion (4.85°) after initial contact, then changed gradually to the greatest dorsiflexion (15.86°) at take-off. The range of motion of the ankle joint was significantly greater in negative-heeled shoes than in normal sports shoes, probably because of the structure of the negative-heeled shoe, with the heel being lower than the toe.

Leroux et al[3, 7] and Lange et al[1] reported that increasing the treadmill gradient induced an increasingly flexed posture of the hip, knee, and ankle at initial contact and a progressive forward tilt of the pelvis and trunk. A similar result occurred when walking in negative-heeled shoes: the foot could not retain the plantarflexed position owing to the slope of the shoes. Therefore, the ankle joint maintained dorsiflexion throughout the stance and swing phases. In this regard, it could be said that greater ankle joint dorsiflexion would lengthen muscles such as the gastrocnemius and soleus and increase the duration of contact,[3, 7] facilitating power generation during the propulsion phase of walking. The findings of the electromyographic analysis also confirmed the longer working duration of muscle in a gait cycle. Yamamoto et al[17] found that walking exercise in negative-heeled shoes at a moderate speed induced an increase in blood flow in the calf. As the ankle became more dorsiflexed, the length of the moment arm of the Achilles tendon increased, thus promoting the ability of this tendon to produce active propulsion. The opposite result has been found with walking in high-heeled shoes.[2]

After an injury to or surgical operation on the gastrocnemius and soleus muslces or Achilles tendon, the common rehabilitation exercise protocol involves dorsiflexion stretching with a towel or strap, standing on an inclined plane, performing an initial toe raise on a box or step, lifting the body to maximum ankle plantarflexion and then lowering it to ankle dorsiflexion, and walking on a treadmill with a slight incline.[18] The purpose of these exercises is to increase the range of motion of the ankle joint and the strength of the calf muscle and the Achilles tendon. Similarly, during sports the highest stress on the Achilles tendon occurs during eccentric contraction of the gastrocnemius soleus complex, for example, when pushing off the weightbearing foot and simultaneously extending the knee in uphill running. Eccentric exercise is recommended for rehabilitation of those who undergo these stresses in their sports.[19] As described previously herein, walking in negative-heeled shoes caused dorsiflexion that could increase the range of motion of the ankle joint and improve the strength of the calf muscle and Achilles tendon. Therefore, walking in negative-heeled shoes might be a viable alternative method of exercising to those previously described herein during postsurgical rehabilitation of the calf muscle and the Achilles tendon.

For the knee joint, the only significant difference was exhibited in the maximum extension angle at take-off. The results for extension angle in the present study were consistent with the suggestion that extension of the knee contributes to an increase in stride length.[16] This was confirmed in the present study where the stride length of walking in normal sports shoes was significantly greater than that of walking in negative-heeled shoes (Table 1). The knee joint would achieve a greater extension angle in negative-heeled shoes than in uphill walking before the foot makes contact with level ground. However, the difference between the tasks of level and uphill walking might require different mechanisms of posture control at the knee joint.

Trunk orientation, therefore, plays an important role in maintaining balance in walking. The maximum hip flexion angle, extension angle, range of motion and trunk flexion angle implied that the whole trunk moved posteriorly, causing the center of gravity to shift backward while wearing negative-heeled shoes compared with walking in normal sports shoes. This finding agreed with the results of previous studies,[2, 20] which reported that the center of gravity was shifted forward when walking in high-heeled shoes. Leaning

the trunk forward facilitates movement of the center of gravity outside the area of support and assists the lower limbs in generating more momentum during take-off in uphill walking[1, 3, 7] and level walking.[21, 22] From this point of view, walking in negative-heeled shoes induced the upper body to tilt backward, which may be disadvantageous in the propulsion phase compared with walking in normal sports shoes.

In this kinematic analysis, walking in negative-heeled shoes enabled the ankle to maintain dorsiflexion, which benefited active propulsion. However, the increase in ankle dorsiflexion resulted in the center of gravity shifting backward, which may cause difficulty in generating active propulsion. These adverse aspects may compensate each other so that an adapted walking pattern can be sustained. This posture may be helpful in keeping the upper body in an upright position, thereby achieving a more graceful posture. In terms of imitating uphill walking, similar ankle dorsiflexion was found in both walking modes. However, owing to the different tasks associated with the two walking modes, the postural adaptation in the knee and hip joints and the trunk orientation showed considerable differences. Therefore, a follow-up study is needed to determine whether postural adaptations show similar patterns in walking in negative-heeled shoes for a relatively long period.

Electromyographic Changes

The electromyographic activity of the quadriceps, hamstring, tibialis anterior, and gastrocnemius muscles during level walking has previously been profiled.[23, 24] Studies have demonstrated that during level walking, the tibialis anterior muscle shows two peaks of electromyographic activity: first at the swing-stance transition and second at the stance-swing transition. The gastrocnemius muscle shows a single peak of activity recorded during push-off, and the hamstring muscle shows its greatest activity during deceleration in the swing phase. The quadriceps muscles achieve peak activity at heel strike and are relatively inactive by midstance until the next heel strike. Electromyographic activity patterns observed in these muscles while wearing normal sports shoes in this study were the same as those observed by previous researchers. Other studies[1, 7, 9, 25] have included the electromyographic activities of the thigh and calf muscles in graded walking. Brandell[25] examined the effects of speed and 5° and 10° upward grades on electromyographic activity of the quadriceps and calf musculature. The author concluded that increases in speed and grade resulted in increased electromyographic activity of the vasti and calf muscles, with a consistently greater increase in the vasti muscles. Tokuhiro et al[9] studied electromyographic activities of the lower-limb muscles during slope walking at 3°, 6°, 9°, and 12°. They found that in upslope walking, the duration of electromyographic activity in the tibialis anterior, semitendinosus, and gastrocnemius muscles was longer and that of the rectus femoris muscle was shorter than in level walking. Leroux et al[7] provided further evidence of increased electromyographic activity in thigh and calf muscles during uphill walking at 5°, 10°, and 15° of treadmill grade. The peak amplitude of electromyographic activity of the vastus lateralis, medial hamstring, soleus, medial gastrocnemius, and tibialis anterior muscles was progressively increased during uphill walking in healthy subjects. The changes in peak amplitude of electromyographic activity in the thigh and calf muscles were consistent with the results obtained by Brandell.[25]

The present electromyographic results show that during walking in negative-heeled shoes, electromyographic activity patterns in the thigh and calf muscles are similar to the patterns observed in uphill walking, which showed significantly longer duration of electromyographic activity in calf muscles, observable slightly shorter duration in the rectus femoris muscle, and significantly higher peak amplitude of integrated electromyographic activity in the calf and biceps femoris muscles. Changes in mean amplitude of electromyographic activity of the rectus femoris muscle when walking in negative-heeled shoes were consistent with the findings reported by Leroux et al,[7] which not only showed a significant increase but actually recorded a slight decrease. This finding indicates weaker muscle activity during walking in negative-heeled shoes. Figure 3 shows that walking in negative-heeled shoes induced higher muscle activity in the biceps femoris muscle, which contributed to more knee flexion, as observed in the kinematic analysis. The hamstring and quadriceps muscles are important to normal knee function. The hamstring muscles provide dynamic stability to the knee by resisting mediolateral and anterior translational forces on the tibia.[26] The coactivation of the antagonist muscles about the knee aid the ligaments in maintaining joint stability, equalizing articular surface pressure distribution, and controlling tibial translation.[27, 28] The electromyographic activity of the hamstring muscle during level walking has shown that the hamstring muscles decelerate the leg before heel contact and then act synergistically with the quadriceps muscles during the stance phase to stabilize the knee.[29] The electromyographic activity patterns in the rectus femoris and biceps femoris muscles during walking in negative-heeled shoes seemingly enhanced the co-contrac-

tion of these two muscles. Therefore, walking in negative-heeled shoes might be helpful in exercising these two muscles.

Significant changes in electromyographic activity were found in calf muscles when walking in negative-heeled shoes. The tibialis anterior and gastrocnemius muscles showed longer duration and higher mean amplitude of electromyographic activity, which indicates that walking in negative-heeled shoes had higher demand on calf muscle activity. Except for the longer duration and higher mean amplitude of electromyographic activity, tibialis anterior muscle electromyographic activity showed relatively higher activity in the swing phase. This change was attributed to less plantarflexion of the ankle joint at the swing phase. Gastrocnemius muscle electromyographic activity when walking in negative-heeled shoes was characterized by the changes in the stance phase, where a two-peak activity pattern was observed. The first peak occurred after touchdown, and the second peak appeared at push-off. After touchdown, the foot rolled forward and tended to full stance. Because of the structure of negative-heeled shoes, the ankle joint at the stance phase underwent larger dorsiflexion, and the gastrocnemius muscle had to work harder to roll forward to reach full stance. Because the forefoot part was tilted upward by 10°, it needed more effort to lift the heel and move the body forward, thus increasing the amplitude and duration of electromyographic activity during push-off. This finding was not observed in the electromyographic activity pattern when walking in normal sports shoes.

The significant increases in electromyographic activities of the thigh and calf muscles are encouraging but do not necessarily support a strengthening effect. The mean amplitude of electromyographic activity increased from 11.3% to 21.7%, and electromyographic activity duration was raised from 35.8% to 83.4%. These increases in electromyographic activity demonstrate greater muscular involvement, and, thus, there could be a training effect of negative-heeled shoes if used in exercise rehabilitation. It is possible that negative-heeled shoes might also be a good form of training for persons prone to shin splints that are thought to be related to a weak tibialis anterior muscle and a short gastrocnemius muscle. However, it is not well understood what level of electromyographic activity is required to achieve a strengthening effect, and this level may differ depending on the population.

Conclusion

The findings of this study indicate that walking in negative-heeled shoes alters trunk and lower-extremity kinematics and results in higher muscle activities of the tibialis anterior, lateral gastrocnemius, and biceps femoris muscles. These changes represent an adaptation of human gait by which posture and limb stability are maintained, as the ankle joints are forced into a dorsiflexion position. To compensate for the changed ankle joint posture, the trunk was postured slightly backward, the hip more extended, and the knee joint more flexed. Kinematic changes in the lower limb and trunk were realized through increased muscle activities in the ankles with the tibialis anterior and lateral gastrocnemius muscles and in the knee flexor biceps femoris muscle. Negative-heeled gait is a normal gait, but it generates higher muscle activities in the lower limbs. Thus, walking in negative-heeled shoes might be considered good training for the enhancement of these muscles.

Financial Disclosures: This study was supported by grants from the Chinese University of Hong Kong.
Conflict of Interest: None reported.

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