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Analysis of muscular fatigue and foot stability during high-heeled gait

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Abstract

Plantar pressure measurements and surface electromyography (EMG) were used to determine the effects of muscular fatigue induced by high-heeled gait. The medio-lateral (M/L) stability of the foot was characterized by measuring the M/L deviations of the center of pressure (COP) and correlating these data with fatigue of lower-limb muscles seen on EMG. EMG measurements from habitual high-heeled shoe wearers demonstrated an imbalance of gastrocnemius lateralis versus gastrocnemius medialis activity in fatigue conditions, which correlated with abnormal lateral shifts in the foot-ground or shoe-ground COP of these women.

Keywords: Body balance; Contact stress; Foot stability; Muscle fatigue; Plantar pressure; Surface EMG

1. Introduction

High-heeled shoes worn by women have been shown to affect gait kinematics adversely, particularly at the ankle joint [1–3], which is excessively plantar flexed. This has been shown to increase the metabolic cost of gait and result in accelerated muscle fatigue. These, in turn, may impair foot stability and cause ankle sprains and/or falls [4,5]. Safe placement of the swing foot at initial contact and adequate evolution of the foot–ground pressure (FGP) maintains balance and so avoids falls [6,7]. The tibialis anterior and extensor hallucis longus muscles contract immediately after initial contact and again towards toe-off, to assist ankle stabilization and arch support, while the peroneus longus muscle acts to stabilize the ankle from midstance to push-off [8]. Increased activity of the foot evertors moves the center of pressure (COP) medially and the body center of mass laterally to maintain body balance. Similarly, increased invertor activity moves the COP laterally and the body center of mass medially. Because of the relatively small width of the foot, a fine active control of its medio-lateral (M/L) stability is required [9]. Winter [7] showed that any generated by the invertors and evertors greater than 10 N m would cause the foot to roll over on its medial or lateral aspects. One common result of deficient foot–ground interaction during the stance phase is a rapid inversion motion of the foot, producing an ankle sprain, which may possibly lead to a fall [10,11].

Muscular fatigue can be defined as an inability of muscles to maintain a reasonably expected force output. In fatigue conditions reduced muscular control of the foot–shank joints may impair the ability to resist dynamically inversion or eversion. Foot stability in stance can be measured from abnormal deviations in the COP trajectory [12,13]. A useful approach for 'developing' lower-limb muscle fatigue in a laboratory is to design exercises of repetitive eccentric–concentric muscle contraction that have been shown to reflect muscular endurance to fatigue, rather than strength [14,15]. Each lower-limb muscle has been shown to be characterized by different contractile and metabolic properties [15] and thus, may respond differently to fatigue. Localized muscle fatigue can be quantified by following the shift in the electromyography (EMG) spectral density

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towards lower frequencies, using the median frequency (MF) of the power spectrum as a guiding parameter [16]. The shift towards the lower band has been correlated with several physiological reactions of muscle tissue to fatigue [17]. Mannion and Dolan [18] have shown a nearly linear relation between a decrease of MF and the force output of skeletal muscles during fatigue.

We wished to clarify the changes in muscle activity from fatigue induced by high-heeled shoes in controlling the foot and shank, and to determine the biomechanical effects on foot stability. In this study, surface EMG and FGP measurements were integrated to analyze the effects of muscular fatigue induced by high-heeled gait on the structural stability of the foot.

2. Methods

Eight female subjects (average age 26 years, S.D. = 4, average weight 55 kg, S.D. = 5) volunteered to follow the fatiguing protocol. Four of these women were regular wearers (approximately 8 h/day for the last 2 years) of high-heeled shoes of approximately 5 cm, while the other four women habitually wore flat-heeled shoes.

A 'fatigue test' was designed to study the effects of high-heeled gait. It consisted of two sets of ankle flexion exercises, (1) 'voluntary contraction' tasks that simulated muscular loading of the foot structure during the swing phase; and (2) 'forced contraction' tasks that loaded the subject's foot as occurring at midstance and push-off (Fig. 1). The tests were conducted barefoot for standardization. In the 'voluntary contraction' phase of the test, the subject was seated while one leg was placed on a supporting surface, with its foot free to perform dorsal and plantar flexion cycles. In the 'forced contraction' phase of the test, the subject was instructed to stand on one foot, while maintaining balance using the opposite hand for support. The subject was then instructed to perform the following cycles, (1) to raise the heel gradually until only the forefoot was in contact with the ground; (2) to maintain a maximal heel rise at this position for approximately 1 s; and (3) bring the entire surface of the foot to make contact with the ground. This heel rise test is a generally accepted exercise for analysis of the lower-limb muscle endurance to fatigue in simulated walking [15]. Subjects were instructed to perform 40 voluntary dorsal and plantar flexion cycles of the foot. Immediately after completing the voluntary contractions, they were then instructed to conduct 40 cycles of the forced contraction maneuver, or alternatively, to terminate the test earlier due to self-reported exhaustion. The criterion of Lunsford and Perry [14], recommending 25 repetitions of heel-rise as normal for both genders from 20 to 59 years of age, was used as a minimal standard for inclusion of subjects in the study group.

The EMG data were acquired simultaneously from both heads of the gastrocnemius, soleus, tibialis anterior, extensor hallucis longus, and peroneus longus using a six-channel portable system of EMG amplifiers connected in parallel (EMG 100, BIOPAC System, CA, USA). After shaving and scrubbing the skin with alcohol, disposable Ag/AgCl surface electrode discs with a diameter of 9 mm (EL 503, BIOPAC System) were attached to the subject's skin at locations recommended by Perotto and Delagi [19]. For each muscle, two electrodes were placed at a distance of approximately 30 mm in the direction of the muscle fibers. A reference electrode, shared by the six measurement channels, was placed on the bony part of the lateral aspect of the knee joint. Cables and interfaces were shielded to eliminate interferences.

EMG signals from the six muscles were acquired and recorded for 5 s, starting at every tenth voluntary and every tenth forced ankle flexion, until 40 ankle flexions of each type were completed. The EMG data were also acquired simultaneously with the FGP evolution during gait carried out on a 7.5-m long contact pressure display (CPD) gait platform (The Biomechanics Laboratory, Tel Aviv University, Israel). These EMG/CPD simultaneous measurements were carried out before and immediately after the fatiguing exercise, to test its effect on the pattern of muscular activity and the evolution of the FGP during gait. The EMG/CPD measurements during gait that had been carried out before and following the fatiguing test were repeated three times with the subjects wearing their own shoes and for an additional three times while they were barefooted, to test the repeatability of the results. During gait, the EMG system was carried over the subject's shoulder (Fig. 1a). The internal clocks of the PCs connected to the EMG and CPD systems were synchronized before each measurement and time was digitally recorded at both the EMG signal channels and the CPD video channel to allow accurate agreement of timing between the muscular EMG and plantar pressure data. The EMG data acquired during the fatiguing test were used to evaluate the fatigue-induced decrease in MF of the spectrum of each of the muscles.

EMG signals were pre-amplified by factors in the range of 2000–5000 (depending on the subject) and captured by a 12-bit A/D board (PLC 818, Scientific Solution Lab, USA) at a sampling rate of 1 kHz. The evolution of the power spectrum function of each of the six muscles of interest was calculated off-line by means of a signal processing software package.

A Hanning window was used to modify a time frame window of 0.5 s before a fast Fourier transform (FFT) was applied to obtain the spectra of the EMG burst that was generated by each forced contraction maneuver lasting approximately 1 s. The time frame window for the FFT analysis ranged between -0.25 and $+$

0.25 s from the mid-time of the duration of the burst signal. Signal envelopes were calculated (Fig. 2a) using a digital band, fourth-order Butterworth 7–11 Hz filter [20] to evaluate the activity time frames of the EMG bursts and to locate the mid-time values of their duration. The power spectrum functions that were calculated by using the FFT analysis were smoothed with a ‘moving average’ filter of 21 points and normalized with respect to the maximal value achieved during exercise (Fig. 2b). The evolution of the MF of each muscle was then derived from its set of power spectra in terms of percent decrease from the initial value. Plantar pressures were acquired using the optical CPD method, which enabled simultaneous, fast imaging of a large contact area using a sensitive birefringent integrated optical sandwich [6,21–23]. Dimensionless parameters quantifying the M/L eccentricity of the COP under the heel and forefoot regions were determined based on the dynamic FGP pattern to allow for inter-subject evaluation of M/L shifts in the COP as a response to fatigue. The dimensionless representations of the eccentricities of the COP under the heel (e_h) and metatarsal heads (e_{mh}) are defined as follows.

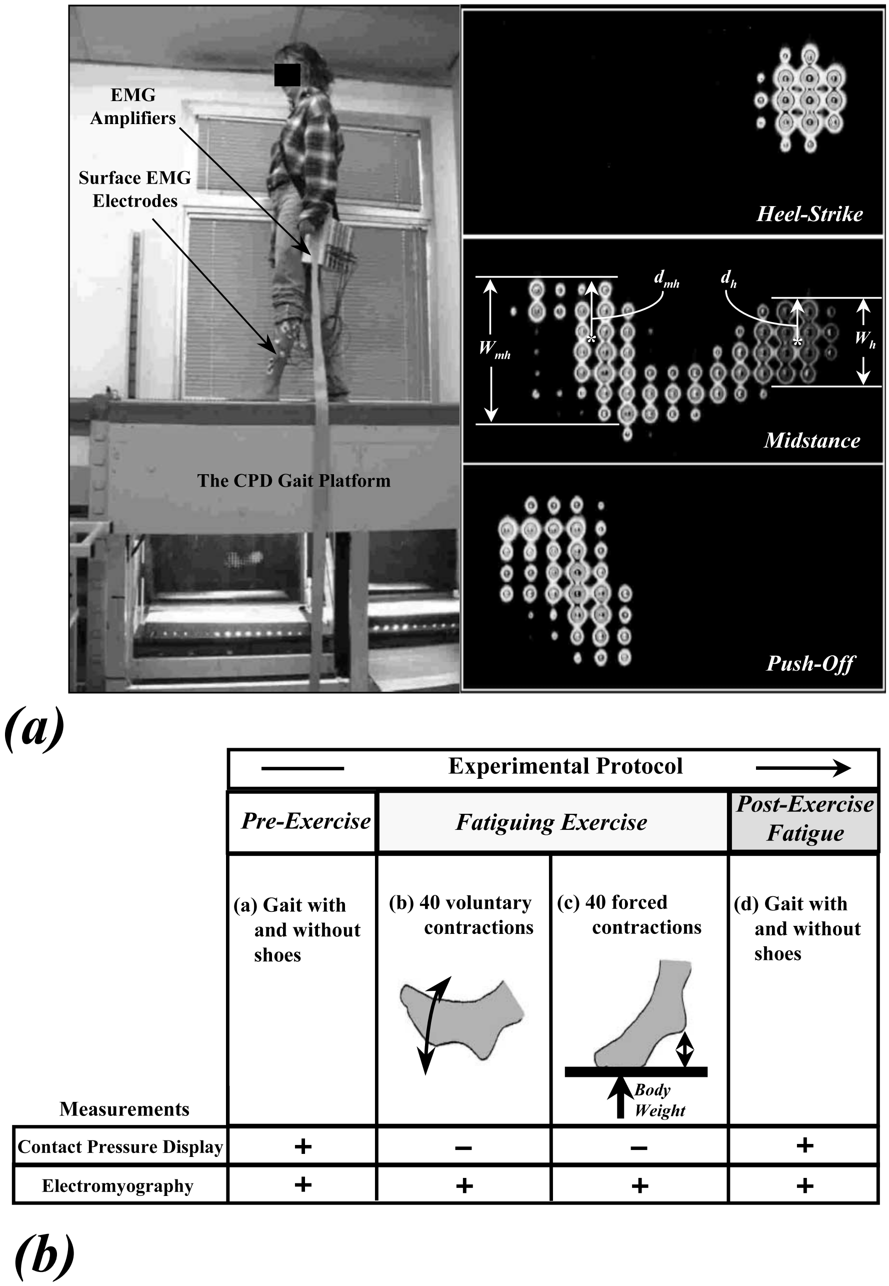

Fig. 1. Analysis of lower-limb muscular fatigue, (a) recording of gait data (left) and typical high-resolution CPD images (right) of the FGP during heel strike, midstance (with the parameters defining the eccentricities of the COP under the heel and metatarsal heads) and push-off; (b) schematic description of the experimental procedure.

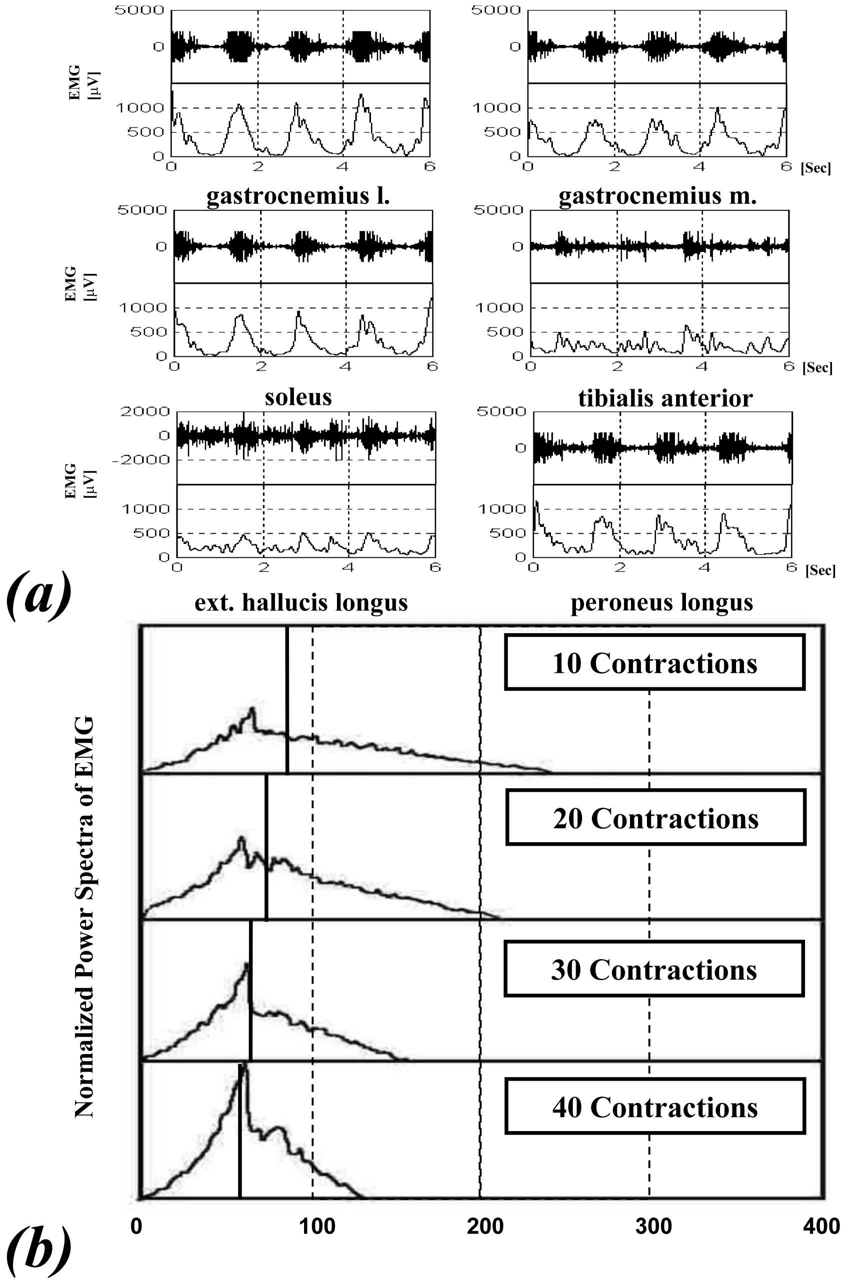

Fig. 2. Quantification of lower-limb muscular fatigue, (a) example of four cycles of raw electromyographic (EMG) data (top) and processed signal envelopes (bottom) for the muscles of interest during forced contractions and (b) example of the evolution of the power spectra function of the soleus muscle. The MF is marked on each power spectrum by a solid line.

$$e_h = \frac{1}{2} - \frac{d_h}{w_h} \quad (1)$$

$$e_{mh} = \frac{1}{2} - \frac{d_{mh}}{w_{mh}} \quad (2)$$

where, w_h and w_{mh} are the transverse widths of the contact areas under the heel and metatarsal heads, respectively, while d_h and d_{mh} are the transverse distances of the COP from the medial boundaries of the contact areas under the heel and metatarsal heads, respectively (Fig. 1a). Hence, positive values for e_h and e_{mh} indicated medial eccentricities while negative values indicated lateral eccentricities.

3. Results

Representative evolutions of the raw EMG data and signal envelopes and MF values for the gastrocnemius medialis and gastrocnemius lateralis muscles during the fatiguing test in a woman with no experience in wearing high-heeled shoes are shown in Fig. 3.

Spectral analysis of the EMG data acquired during the fatiguing tests revealed differences in muscular endurance of the habitual versus non-habitual high-heeled shoe wearers. The peroneus longus and the gastrocnemius lateralis muscles of women who regularly wore high-heeled shoes were less able to endure fatigue compared with these muscles in women who did not wear high-heeled shoes (see Fig. 4 for comparison of EMG data of flat-heeled and high-heeled shoe users). The MF of the EMG signal of the peroneus longus of high-heeled shoe wearers was shown to decrease gradually throughout the fatiguing exercise, until it reached an average value of $65 \pm 7\%$ of its initial magnitude. However, for women wearing flat-heeled shoes, the decrease in the MF of the peroneus longus signal was substantially lower, to $85 \pm 9\%$ of its initial value.

The relative MF of the gastrocnemius lateralis decreased more rapidly than that of the gastrocnemius medialis during fatiguing of every regular high-heeled shoe wearer. The average difference between the relative MF values of these two muscles among the habitual high-heeled shoe wearers was $36 \pm 8\%$ at the end of the forced contraction phase of the exercise. In contrast, differences in the relative MF of the gastrocnemius medialis versus gastrocnemius lateralis were significantly lower ($7 \pm 3\%$, Fig. 5a) in all women who were not habitual wearers of high-heeled shoes.

The imbalance in gastrocnemius lateralis versus gastrocnemius medialis activity in habitual high-heeled shoe wearers during fatigue was also seen in the EMG/CPD gait tests (Fig. 5b). Comparison of the relative MF magnitudes of the gastrocnemius medialis versus the lateralis muscles during gait, pre- and post-exercise of habitual high-heeled shoe wearers, similarly revealed an average difference of $30 \pm 5\%$ in endurance. This pattern of an imbalanced EMG activity of the gastroc-

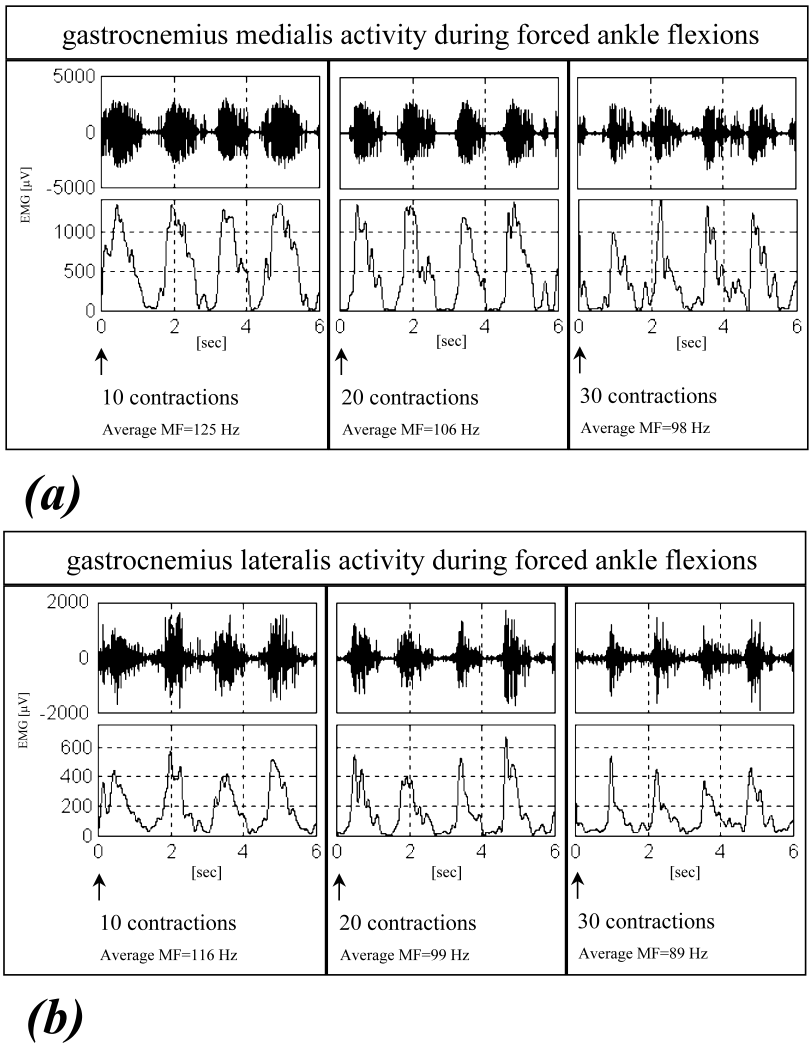

Fig. 3. Evolution of the raw (top) surface electromyogram and signal envelope (bottom) for the (a) gastrocnemius medialis and (b) gastrocnemius lateralis muscles during forced ankle flexion contractions in a woman with no experience in wearing high-heeled shoes. MF, median frequency (values of MF are averaged for ten contraction cycles).

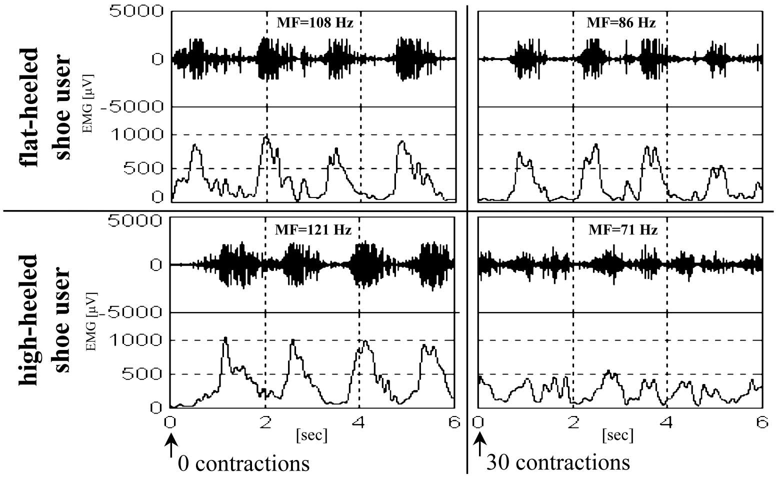

Fig. 4. Representative evolutions of the raw surface electromyogram, signal envelopes and MF values for the peroneus longus muscle during forced ankle flexion contractions in a woman with no experience in wearing high-heeled shoes (top) and a women who regularly wears high-heeled shoes having heels 5-cm high (bottom). Values of MF are averaged for ten contraction cycles.

nemius muscles in fatigue conditions was observed in all the habitual high-heeled shoe wearers each time they repeated the gait test while wearing their own shoes.

The average eccentricity values of the COP under the heel and metatarsal heads (calculated using Eqs. (1) and (2)) for the two subject groups during barefooted walking in fatigue conditions are given in Table 1. For all flat-heeled shoe wearers in fatigue conditions, the average eccentricities of the COP under the heel and metatarsal heads during midstance were substantially medial. For women who habitually wear high-heeled shoes, however, the respective heel and metatarsal heads COP eccentricities during midstance in fatigue conditions were abnormally orientated laterally, indicating a lack of M/L foot stability (Table 1). In the latter group, the lateral deviation of the COP of the shoe–ground contact pressure was even more pronounced (Fig. 5b), especially under the shoe heels where it reached a value of $e_h = -0.25$.

4. Discussion

This study was aimed to relate fatigue of specific muscles during high-heeled gait to the foot's tendency towards M/L instability. We found differences in muscle response to fatigue between regular and non-regular wearers of high-heeled shoes in this small sample of women. One important difference between heel rise tests and high-heeled gait in real life is that, while the subject carrying out the heel raises is pushing up his bodyweight, a subject who walks in high-heels will resist a slightly higher load, of about 1.08–1.14 times his body weight during push-off, due to the dynamic effects [4].

The peroneus longus and the gastrocnemius lateralis muscles of women who regularly wore high-heeled shoes were shown to be more vulnerable to fatigue compared with these muscles in women who did not wear high-heeled shoes. A pattern of imbalanced EMG activities of the gastrocnemius medialis versus the gastrocnemius lateralis under fatigue conditions was observed repeatedly in habitual high-heeled shoe wearers. The eccentricities of the COP under the heel and metatarsal heads in this group were found to be abnormally shifted to the lateral aspect during gait whilst fatigued.

It is very likely that the lateral tendency of the COP in high-heeled shoe wearers is related to the imbalanced activity of the fatigued gastrocnemius lateralis and gastrocnemius medialis. The deviation of the resultant force generated by these muscles and transferred via the Achilles tendon to the calcaneus could result in an inverting moment that acted to incline the foot's skeleton laterally. The peroneus longus, which normally acts to protect the foot from sudden inversion, was also observed to be more vulnerable to fatigue among high-heeled shoe wearers, further decreasing the stability of their feet. These differences in the endurance of the gastrocnemius lateralis and peroneus longus muscles among the habitual and non-habitual high-heeled shoe wearers appear to be caused by adaptation of the lower-limb's muscular system to habitual use of high-heeled shoes, as suggested by Lee et al. [1].

One possible explanation as to why the two heads of the gastrocnemius respond differently to fatiguing plantar flexions of the foot is based on the alteration in their length as a result of heel rise. When no heel lift is present, both the gastrocnemius medialis and the gastrocnemius lateralis muscles are positioned at their resting lengths. When a heel raise is introduced, the muscle fiber length shortens and the active tension that is generated upon the contraction of the muscles is less consistent with their characteristic length–tension relations. When high-heeled shoes are habitually being used, one of the gastrocnemius muscles may act more intensively to produce the forces required to raise the foot from midstance to push-off leading to asymmetric muscle activity.

Regular wearers of high-heeled shoes have reported a feeling of lack of foot stability after heel strike, unlike women who try to walk in high-heeled shoes for the first time [1]. This may relate to our observation that there was a lower endurance of the peroneus longus to fatiguing contractions amongst the regular high-heeled shoe wearers. The peroneus longus could be less active during high-heeled gait and consequently, less trained in its role to stabilize the ankle.

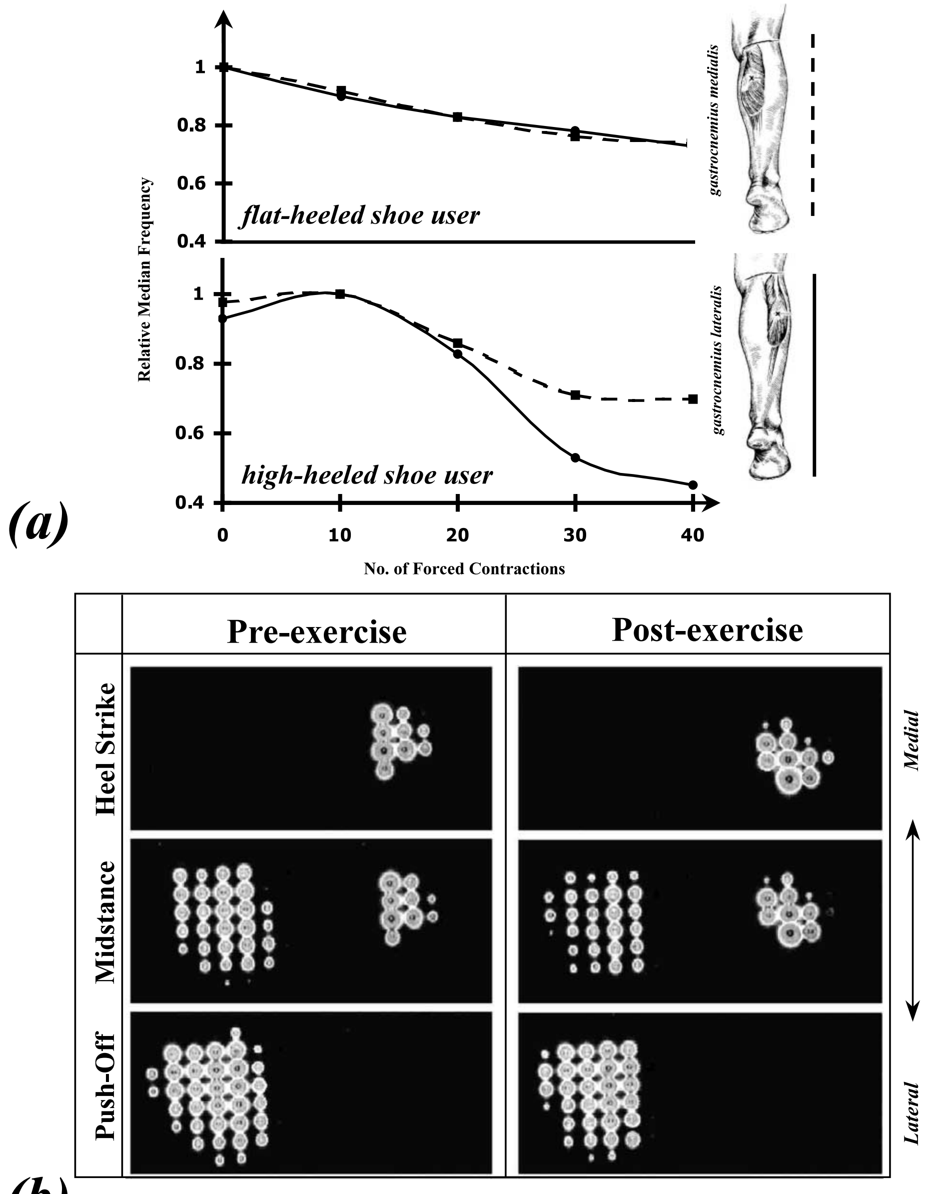

Fig. 5. Effect of fatigue on muscular activity and FGP, (a) typical MF reductions of the gastrocnemius medialis and gastrocnemius lateralis in response to fatiguing contractions in (top) a woman with no experience in wearing high-heeled shoes (initial MF values for the gastrocnemius medialis and lateralis were 134 and 127 Hz, respectively) and (bottom) a woman who regularly wears high-heeled shoes having heels 4.5 cm high (initial MF values for the gastrocnemius medialis and lateralis were 126 and 110 Hz, respectively); (b) effect of fatigue on the shoe–ground contact pressure evolution when wearing high-heeled shoes: representative CPD images during heel-strike, midstance and push-off acquired from a regular high-heeled shoe wearer, pre- and post-exercise. A significant shift of COP toward the lateral aspect post-exercise is clearly shown, particularly under the heel during heel strike and midstance.

Table 1
Average eccentricity values of the COP under the heel (e_h) and metatarsal heads (e_{mh}) during the midstance sub-phase of the barefooted gait of flat-heeled shoe wearers and habitual high-heeled shoe wearers in fatigue conditions

COP eccentricities	Flat-heeled shoe wearers	High-heeled shoe wearers
e_h	0.05 ± 0.02	-0.09 ± 0.02
e_{mh}	0.20 ± 0.06	0.11 ± 0.06

Each group included four subjects, and each subject repeated the EMG/CPD gait test three times. Values are averaged accordingly.

The above factors may all contribute to the experimentally observed abnormal deviations of the COP locations following intensive, prolonged use of high-heeled shoes. These deviations indicate clearly a lack of body balance, which, together with the less stable nature of the high-heeled shoe, increase the likelihood of accidental injury. The results suggest that, to maintain comfort and reduce the risk of injury, women should be advised to select shoes with a moderate heel height and to refrain from wearing high-heeled shoes for long periods. Shoe manufacturers may consider the use of integrated ankle constraints and enlarged support areas of the shoe heels to protect the foot from ankle sprains.

A decreased length of the calf muscle–tendon complex, reducing the normal foot's range of motion, is associated with normal aging in both men and women [5]. It is possible that this deterioration is accelerated in habitual high-heeled shoe wearers, since this shoe type constrains the gastrocnemius–soleus muscle length to be shorter than the usual. When the resulting limited passive motion is combined with decreased muscle force due to fatigue, it may limit the ability to respond to postural perturbations and to generate the forces needed to control the center of mass. Therefore, such changes may partly be responsible for the mechanism of falls among elderly women who also habitually use high-heeled shoes, and this could be investigated in future studies.

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