

Evaluating the Fatigue Rate of Lower Leg Muscles during Prolonged Standing: A Comparison between Stable and Unstable Footwear

ZANYAR KARIMI¹, MAHMOOD REZA AZGHANI², TEIMOUR ALLAHYARI^{3*},
HAMIDREZA KHALKHALI⁴

¹*Department of Occupational Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran;*

²*Department of Biomechanics, Faculty of Mechanical Engineering, Sahand University of Technology, Tabriz, Iran;*

³*Department of Occupational Health, School of Health, Urmia University of Medical Sciences, Urmia, Iran;*

⁴*Department of Epidemiology and Biostatistics, School of Health, Urmia University of Medical Sciences, Urmia, Iran.*

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ABSTRACT

It is well established that unstable footwear with a rounded sole design has the potential to alter lower limb muscle activity during standing and walking activities. Thus, the main objective of this study was to compare lower leg muscles fatigue rates between stable and also unstable footwear during prolonged standing. This study was conducted in Urmia, northwest Iran (2015) and participants included ten young healthy male. During 2 h of continuous standing with two footwear conditions (stable and unstable shoes), surface electromyographic (EMG) data of bilateral tibialis anterior (TA) and medial gastrocnemius (MG) muscles were continuously recorded. The probability of muscle fatigue was identified through recording simultaneous increase in the EMG amplitude and shift in the EMG frequency spectrum towards lower frequencies. According to analysis of EMG recordings, standing with stable shoe yielded significantly higher rates of muscle fatigue for bilateral MG muscles ($p < 0.05$). Furthermore, no significant differences were observed for the fatigue rates of TA muscles between two footwear conditions. However, none of monitored muscles were indicated fatigue during standing with unstable shoe. The results suggested that unstable footwear, compared to stable one, is more efficient to prevent the occurrence of muscle fatigue which seems to be advantageous for the musculoskeletal system. Therefore, unstable footwear can be recruited as an ergonomic intervention for individuals who stand for prolonged periods.

KEYWORDS: *Muscle fatigue, Prolonged standing, Unstable shoe, Electromyography (EMG)*

INTRODUCTION

Standing for prolonged periods may be seen as dominant working posture for many of industrial and service work forces, including health care staff, supermarket workers, school teachers,

and inspection and assembly workers. The relationship between prolonged standing and adverse health outcomes, such as low back pain and lower extremity problems, has been well documented previously [1].

Corresponding author: Teimour Allahyari

Email: Allahyari@umsu.ac.ir

Regarding underlying mechanisms of leg discomfort during standing, it should be noted that beside the blood pooling and insufficient circulation [2], postural control activities also may lead to increased load on the muscular system, particularly in lower leg region [3]. Postural control is facilitated by postural movements such as the sway of the whole body around the ankle joint, called ankle strategy, or the motion around the hip joint, called hip strategy [4]. In conditions of high stability such as bipedal quiet standing, postural sway is normally lower than 0.5 Hz, so the body can be compared to a simple inverted pendulum (ankle strategy) with a very low level of sustained contractions [5-6]. In this line, several studies have reported increase in lower leg muscles fatigue as a source of discomfort in courses of prolonged standing [7-11].

Muscle fatigue is characterized by a decrease in the maximal force/tension that the involved muscles can produce, and it develops gradually soon after the onset of the sustained physical activity [12]. Different metabolic or neurologic factors have been introduced to the onset of fatigue, which are controlled peripherally and centrally by the neuromuscular system [13]. Furthermore, it can be measured as 1) a reduction in muscle tension/force, 2) a change in electromyographic (EMG) activity or 3) as subjectively perceived localized muscle fatigue [14]. However, a more feasible and reliable means of assessing muscle fatigue in ergonomic studies is EMG recordings analysis [8]. Common fatigue induced changes of EMG signals during sustained or repetitive muscle contractions can be observed as an increase in the amplitude or a shift in the frequency spectrum towards lower frequencies [15].

Preventing musculoskeletal disorders (MSDs) in the workplace has become a top priority in many countries. In this sense, an increased emphasis has been placed on ergonomic interventions. Of the different factors attributed to MSDs precipitation, muscle fatigue plays a significant role [16]. Accordingly, several solutions have been introduced to alleviate muscle fatigue during prolonged standing, including anti-fatigue mats, foot rests, sit/stand chairs, and footwear modifications [1, 17-18]. Regarding footwear interventions, application of shoe insoles is one of the popular ones. Despite the popularity, controversial and predominantly negligible positive effects have been reported for insoles [1, 10-11]. Unstable shoe, with a rounded sole design in the anterior-posterior direction, is another type of footwear modifications which is frequently recommended [19-20].

The main goal for the use of unstable shoes is to change static standing situation into a

more dynamic ones (active standing) [21]. A stable posture is achieved when the center of mass (CoM) is within the base of support and is aligned with the center of pressure (CoP) [5]. Any external or internal perturbation that changes the projection of the CoM to the limits of the base of support, and also changes the alignment between CoM and CoP, may lead to postural challenge which can be defined as instability [5]. In this line, it has been indicated that unstable shoes can induce significant instability to standing posture through substantial increase in CoM movements [19]. In addition, it has been reported that active standing can be useful for venous return from the legs which is also accompanied with lower rates of muscle fatigue [8, 22]. In this regard, significant increase in the lower leg muscle activity level has been reported during short-term and also long-term standing with unstable shoe [20, 23-24]. Furthermore, increased activity variation and decreased antagonist co-contraction of lower leg muscles have also been reported [23, 25]. Alongside with the muscular activity changes, improved venous return and blood circulation was also seen during standing on unstable shoe [20, 24-25]. However, the main issue that may be questioned here and also overlooked in all related previous studies is the fatigue state of lower leg muscles during prolonged standing on unstable shoe; is unstable shoe an alleviating intervention for muscle fatigue during prolonged standing?

We hypothesized that the unstable footwear would result in lower rates of muscle fatigue due to creating a more dynamic standing posture, compared to stable footwear condition. Therefore, the main purpose of this study was to examine the effects of unstable footwear, compared to stable footwear, on the lower leg muscles fatigue rates during prolonged standing through analyzing EMG recordings in the time and frequency domains. It should be notified that in order to satisfy the purpose of this survey, we have done further processing on EMG signals obtained from a previous study recorded during a 2-h simulated continuous standing with stable/unstable footwear in the laboratory settings [25].

MATERIALS AND METHODS

Subjects: The study protocol was approved by the Ethics Committee of Urmia University of Medical Science, Urmia, Iran - 2015. All volunteers also read and signed an informed consent form before participation. Ten paid healthy males were recruited for this experiment from a university student population (mean age= 25.3 yr, SD = 1.49, mean height = 1.77 m, SD = 0.02, mean weight = 74.8 kg, SD = 2.69). None of the subjects were engaged in work that requires prolonged standing and all of them were free from any lower

limb problems. To evaluate a single shoe size, during selection process of subjects, wearing the shoe with size of 42 by the participants in their daily activities was the primary criterion.

Footwear: Unstable and stable (flat-bottomed) footwear, used in this experiment, were constructed by a certified orthopedic shoe technician in a medical shoe center. The materials used for construction of footwear were the same in both of upper (soft natural leather) and lower (ethyl-vinyl-acetate (EVA) foam) shoe parts. The only difference between the two shoes was the outsole design, which was characterized by a rounded sole design in the anterior-posterior direction for unstable shoe and a flat design for stable shoe (Fig. 1).

Instrumentation: The EMG data from two bilateral muscles, tibialis anterior (TA) and medial gastrocnemius (MG), were collected using four circular Ag/AgCl bipolar surface electrodes (SX230, Biometrics Ltd., Gwent, UK) which were connected to the DataLINK system (DLK900, Biometrics Ltd., Gwent, UK). The diameter of each electrode and the center-to-center inter electrode distance was 1 cm and 2 cm, respectively. The raw EMG signals were acquired at a sample rate of 1000 Hz, pre-amplified at the electrode site, and also were amplified using a single differential amplifier with an input impedance of 1000 M Ω , a common mode rejection ratio of 110 dB, and a gain of 1000. The signals were filtered with a bandwidth of 15-500 Hz.

Experiment: The study used a within-subject experimental design in which each participant completed a 2-h simulated continuous standing test session in the laboratory for each of two footwear conditions: stable shoe and unstable shoe (random assignment).

In the beginning of each test session, lower legs of participants were prepared for surface EMG electrode placement. Skin surface of the belly area of the interested muscles were shaved and the dead cells and non-conductor elements were removed by alcohol and abrasive pad, respectively. For the application of surface electrodes the recommendations of SENIAM were followed [26]. The electrodes then were applied over two bilateral muscle groups: TA (in 20% of the distance from the tibial tuberosity to the inter-malleoli line) and MG (in 25% of the distance from the medial side of the popliteus cavity to the calcaneal tubercle). The reference electrode was placed on the medial malleolus. To avoid movement and to ensure homogeneous and constant pressure, the electrodes were fixed to the skin using adhesive tape.

After electrode placement, to obtain maximal voluntary contractions (MVC) the

following positions were used: plantar flexion through single leg toe standing with provided balanced support (strong manual resistance was given downward at the shoulders) for MG, and ankle dorsiflexion while standing (manual resistance was given downward at the foot) for TA muscle. Following EMG electrodes placement and maximum voluntary contraction (MVC) tests for each muscle, participants entered into the prolonged standing task as its experimental set-up is shown in Fig. 1. During standing in a confined area, light assembly and mental tasks were completed by participants. For further details regarding experiment protocol please see Karimi et al (2016) study [25]. EMG data were collected continuously for the 2-h standing in 15-min blocks for all the muscles in the quiet bipedal anatomical standing position (nine of 30-s EMG recording for each muscle).

Data processing: Raw EMG signals (MVC and nine of 30-s recordings for each muscle) were analyzed using Matlab software (Matlab R 2009, ver 7.8.0.347, The Mathworks, Inc., Natick, USA). Since electrodes possessed band-pass filter of 15–500 Hz, no software filters were manually applied to the data. To smooth raw data, a time window of 200 ms was passed for every batch of 30 000 data taken for every muscle within every 30 s recording (30 s \times 1000 Hz) and the root mean square (RMS) was computed for each window. This protocol was also applied for MVC data. To normalize the RMS data, all of the RMS data was subtracted from the RMS of the rest data and divided by the maximum RMS value from the MVC test minus the RMS of the rest data. RMS values were computed over 30 \times 1 s non-overlapping windows for each collection period. Normalized RMS of EMG signals is the most reliable parameter in the time domain [8]. Furthermore, mean power frequency (MPF) values in the frequency domain were separately extracted from the each 30-s EMG signals recorded in 15 min intervals. Power spectrum was computed over the frequency range of 20–230 Hz using fast Fourier transformation on the band-pass filtered signals. In addition, signal spectrum was smoothed with a hamming window of 50% overlap. MPF values were computed in epochs of 1 s for each 30-s recording.

Finally, computed RMS and MPF values were linearly regressed and the corresponding slopes were determined for each muscle in both footwear conditions. Fatigue rate can be identified for each muscle if EMG analysis yielded a negative slope for MPF and positive slope for RMS [15].



Fig. 1. Subjects standing for 2 h in each of footwear conditions while completing light assembly and mental tasks - Stable shoe (upper) and unstable shoe (lower) also illustrated here.

Statistical analysis: Slopes of RMS and MPF extracted from EMG signals during 2 h of standing on each of footwear conditions (stable shoe and unstable shoe) were statistically analyzed. SPSS software version 19.0 (SPSS, Inc. 2010) was used for all statistical analyses. As normality test on slopes data yielded a negative result, the Wilcoxon signed rank test (a nonparametric test) was used to analyze differences between conditions. The alpha level of equal to or less than

0.05 was accepted as significant for all statistical tests.

RESULTS

As shown in *Fig. 2*, the signs of muscle fatigue (negative slope for MPF vs time and positive slope for RMS vs time) are predominantly evident for bilateral MG and TA muscles during 2 h of standing on stable shoe compared to unstable shoe (excluding MPF positive slopes for bilateral TA muscles in the stable footwear condition).

Regarding slopes of MPF, Wilcoxon signed rank test results revealed a significant difference between stable and unstable shoe conditions for both of right ($p=0.037$) and left ($p=0.044$) MG muscles. However, there was no such significant difference for right and left TA muscles in the MPF slopes between two footwear conditions.

At the same time, during 2 h of standing with unstable shoe, slopes of RMS for bilateral MG (right: $p= 0.009$, left: $p=0.005$) and TA (right: $p= 0.028$, left: $p=0.046$) muscles were also significantly different from standing on stable shoe. Thus, for these set of muscles, which are one of the main controller of balance and posture during standing [5], the results implies lower rates of muscle fatigue during prolonged standing on unstable shoe in comparison with stable shoe.

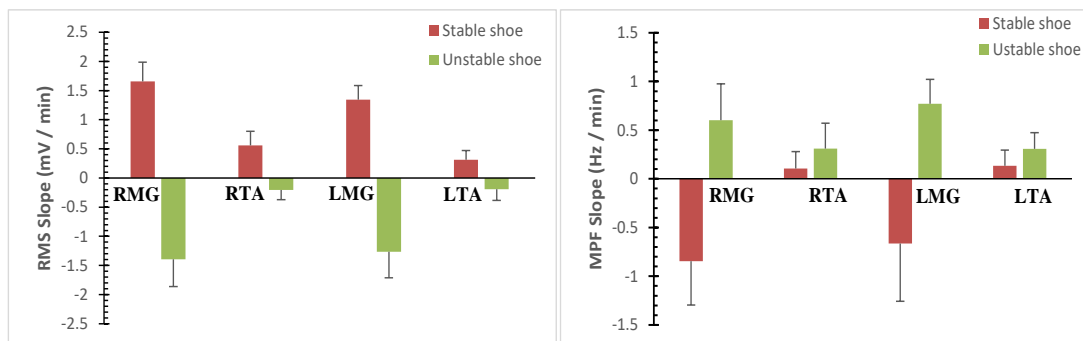


Fig. 2. The average and standard errors of the slopes of MPF (right) and RMS (left) during 2 h of standing with stable/unstable shoes. Muscles: right medial gastrocnemius (RMG), left medial gastrocnemius (LMG), right tibialis anterior (RTA), left tibialis anterior (LTA).

DISCUSSION

All EMG-based fatigue analyses follow a fundamental assumption: “the change in the mechanical performance capacity is reflected in corresponding changes in the myoelectrical signal of the muscle under test” [12]. Accordingly, in occupational settings during sustained or repetitive muscle contraction typical changes in surface EMG signals, such as an increase in the amplitude (RMS) or a shift in the frequency spectrum (MPF) towards lower frequencies, have been interpreted as signs of muscular fatigue and reduced mechanical capacity

[15]. It has been reported that the frequency based EMG variables are more sensitive to fatigue-related changes than amplitude based EMG ones. This preference is due to the less dependence of frequency domain parameters on the instantaneous force level of a muscle [15]. Nevertheless, decrease in frequency domain variables coupled with a concomitant increase in time domain parameters would be a more reliable indicator of muscle fatigue rate. According to this rationale, the present study focused on evaluating the influence of

footwear stability on the fatigue state of lower leg muscles, through conducting a comparison between stable and unstable shoes during 2 h of continuous and stationary standing test.

Findings of this study demonstrate that fatigue rates for bilateral MG and TA muscles, based on the positive slope of RMS values, are significantly higher during standing on stable shoe than standing on unstable shoe (*Fig. 2*). Furthermore, regarding negative slope of MPF values as another indicator of muscle fatigue, significant elevated rates of fatigue state were only seen for bilateral MG muscles on standing with stable shoe (*Fig. 2*). Therefore, these results provide more evidences for an association between elevated rates of lower leg muscle fatigue (conclusively for MG muscles) during 2 h of standing with stable shoe and perceived higher leg discomfort in stationary standing periods which is frequently reported by previous studies [1-2, 8-9, 22].

To meet further explanation regarding higher fatigue rates of MG muscles it should be noted that of the all dominant maintainers/controllers of upright posture, the posterior calf muscles group (including MG) play a significant role [5]. Besides, intermittent activation of related muscles also is critical for venous return from the legs [8, 22]. During static standing situations such as standing with stable shoe, the stillness of legs may be accompanied with more low-level and sustained muscle contractions [5], and such case may cause restriction of the blood circulation and yield leg swelling and edema. Therefore, metabolic wastes tend to accumulate within the muscles because of the reduced blood flow and potentially it can contribute to an increase in muscle fatigue rate [27].

Another major finding is the positive effects of unstable shoe on fatigue state of lower leg muscles. None of the monitored muscles in the current experiment indicated fatigue during 2 h of continuous standing with unstable shoe (*Fig. 2*). The underlying mechanism to prevent muscle fatigue during standing on unstable shoe potentially backed to creation a more active standing posture [19]. There are some experimental evidences confirms that dynamic standing significantly inhibit the occurrence of muscle fatigue and discomfort [1, 8, 22]. In this line, it has been reported that unstable shoe construction produces higher activities of muscles encompassing the ankle joint during standing and walking compared to regular and stable shoes [4, 19-20, 23, 28]. In addition, higher variability in lower limb kinematic variables [29-30], postural sway [31] and also lower leg muscle activity [25] have been found during standing on unstable shoes compared to conventional shoes. The instability and increased muscle activity level and variation induced by

unstable shoes could eventually lead to increased venous return from the legs [24-25]. Furthermore, improved blood circulation and also eliminated low-level and sustained muscle contractions through more dynamic and alternating ones in the lower leg region would be more advantageous to prevent muscle fatigue; as such outcomes were reported in the present research.

It is worthwhile to note that both right and left TA muscles indicated positive slope for RMS values in standing on stable shoe which means occurrence possibility of muscle fatigue; in the same time positive slope for MPF values were recorded for related muscles that reflects no sign of muscle fatigue (*Fig. 2*). However, with regard to the EMG amplitude (RMS) it has been experimentally indicated that the amplitude increases with increasing force as well as with the occurrence of fatigue [15]. Thus, each EMG recording which shows a simultaneous increase (positive slopes) in RMS and MPF values over time may be interpreted as an increase in muscle force than increase in fatigue rate.

CONCLUSION

Overall, the results of the present study demonstrates that wearing unstable shoe during 2 h of prolonged standing significantly eliminates lower leg muscles fatigue, potentially due to more dynamic/active standing posture compared to standing on stable shoe (static standing). Therefore, these findings encourage the use of unstable footwear as a beneficial/practical ergonomic intervention which can diminish the negative effects of prolonged standing on musculoskeletal system, namely muscle fatigue. Furthermore, these types of solutions can result in increased performance and effectiveness during upright standing and also can contribute to better occupational health [32]. However, there are some limitations here that should be considered in future studies which evaluates the unstable footwear for standing workers, including (1) recruiting greater number of participants, (2) using longer time limit of standing tests, (3) conducting the experiment in the real work environments, (4) monitoring other dominant leg muscles, and (5) taken into account other kinematic and kinetic variables.

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