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Standing in an unstable shoe increases postural sway and muscle activity of selected smaller extrinsic foot muscles

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ABSTRACT

Inactivity or the under-utilization of lower limb muscles can lead to strength and functional deficits and potential injury. Traditional shoes with stability and support features can overprotect the foot and potentially contribute to the deterioration of the smaller extrinsic foot muscles. Healthy subjects ($n = 28$) stood in an unstable MBT (Masai Barefoot Technology) shoe during their work day for a 6-week accommodation period. A two-way repeated measures ANOVA was used to determine (i) if unstable shoe wear increased electromyographic (EMG) activity of selected extrinsic foot muscles and increased postural sway compared to standing barefoot and in a stable control shoe and (ii) if postural sway and muscle activity across footwear conditions differed between a pre- and post-accommodation testing visit. Using an EMG circumferential linear array, it was shown that standing in the unstable shoe increased activity of the flexor digitorum longus, peroneal (PR) and anterior compartment (AC) muscles of the lower leg. No activity differences for the larger soleus (SOL) were identified between the stable and unstable shoe conditions. Postural sway was greater while standing in the unstable shoe compared to barefoot and the stable control shoe. These findings suggest that standing in the unstable MBT shoe effectively activates selected extrinsic foot muscles and could have implications for strengthening and conditioning these muscles. Postural sway while standing in the unstable MBT shoe also decreased over the 6-week accommodation period.

1. Introduction

Shoes are traditionally designed to improve stability and support the foot during locomotion, often with the goal of controlling such movements as pronation. It has been suggested in coaching circles and in the biomechanical community that (i) these shoe design features may lead to an overprotection and/or under-utilization of the smaller extrinsic foot muscles and (ii) training barefoot can be an effective method for strengthening foot and ankle muscles [1]. The under-utilization of muscles over time can result in reduced strength or weakness [2] and combined with muscle imbalances, can lead to increased injury susceptibility of the lower limb and back [3–7]. Unstable training devices such as wobble boards have proven effective in reducing injury in younger and older populations and this training enhances proprioception, improves muscle coordination and may even strengthen select muscles [8–10]. Recently, unstable shoes have been developed to simulate an effect similar to the wobble board, with the primary purpose of activating and strengthening muscles that may be relatively inactive and under-utilized while wearing a more stable shoe.

Masai Barefoot Technology (MBT) is an unstable shoe with a rounded sole that provides instability in the anterior–posterior direction and a cushioned heel sensor that provides instability in the medial–lateral direction. This design attempts to simulate an unstable surface, thereby requiring continual activation of important stabilizing muscles of the lower limb to maintain proper balance. Evidence exists that wearing the unstable MBT can contribute to a significant reduction in knee and low back pain [11,12].

The biomechanical and neuromuscular changes introduced by wearing unstable shoes have also been investigated [13–15]. Walking and standing in an unstable MBT shoe provides training to some of the larger extrinsic foot muscles crossing the ankle joint complex, specifically increasing activity of the gastrocnemius and tibialis anterior [14,15]. No study, however, has quantified muscle activity for some of the smaller extrinsic foot muscles important for stabilizing and controlling the foot, such as the peroneus longus and flexor digitorum longus.

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Most small extrinsic foot muscles (e.g. peroneus longus and brevis, flexor hallucis longus and tibialis posterior) have short moment arms about the talocrural joint (plantar- and dorsi-flexion) but more effective moment arms about the subtalar joint (inversion–eversion) [16]. A continuous engagement of these smaller muscles could lead to more effective control of movements and moments about the subtalar joint and potentially contribute to a reduction in joint loading and joint pain [1,17].

Quantification of activity of some smaller extrinsic foot muscles can be done invasively with indwelling electrodes [18] or non-invasively with a custom designed EMG circumferential linear array of several bipolar EMG electrode pairs adjacent to each. This array is capable of measuring individual activity of selected small extrinsic foot muscles and is suitable for studying the interplay between multiple muscles during tasks such as walking and standing [19].

The purpose of this study was to (i) quantify muscle activity of select small extrinsic foot muscles using a circumferential linear EMG array proximal to the ankle joint and (ii) quantify postural sway while standing barefoot, in an unstable MBT shoe and in a stable control shoe. Measurements were also compared before and after a 6-week accommodation period of wearing the unstable MBT shoe to determine if improvements in postural control occurred as a possible result of increased muscle training and strengthening.

The following hypotheses were tested:

H1. For selected smaller muscles including the peroneus brevis/longus and flexor digitorum longus, the initial muscle activity while standing in an unstable MBT shoe will be greater than standing barefoot or in a stable control shoe.

H2. After using the unstable MBT shoe for 6 weeks, the muscle activity for the same smaller muscles while standing in an unstable MBT shoe will remain greater than standing barefoot or in a stable control shoe.

H3. Initial postural sway while standing in an unstable MBT shoe will be greater than standing barefoot or in a stable control shoe.

H4. After using the unstable MBT shoe for 6 weeks, postural sway while standing in an unstable MBT shoe will be greater than standing barefoot or in a stable control shoe.

2. Methods

2.1. Subjects

Twenty-eight subjects (19 females, 9 males) participated in this study and meet the criteria in Table 1. The study was approved by the University of Calgary's Office of Medical Bioethics and all subjects signed a written consent form prior to testing. A priori power analysis ($\beta = 0.2$, $p = 0.05$) using previous Center of Pressure (CoP) excursion and EMG data [14] demonstrated adequate power would be achieved with 28 subjects.

Table 1
Subject descriptive data (mean and standard deviation in brackets) and subject selection criteria.

Gender	Number of subjects	Age [years]	Height [cm]	Mass [kg]
Female	19	53.2 (6.9)	162.3 (6.0)	76.0 (14.3)
Male	9	53.6 (10.2)	171.7 (4.5)	85.8 (15.3)

Selection criteria
(a) Able to wear unstable shoe a minimum of 30 h/week while walking or standing at work
(b) No previous experience with unstable shoes
(c) Between 40 and 70 years of age
(d) No arthritis, diabetes or neuromuscular condition
(e) No lower extremity injury or major pain in past 6 months
(f) No previous major surgeries to lower extremity or back
(g) No regular exercise routine involving the lower leg

2.2. Testing protocol overview

The study was completed in the Human Performance Laboratory (HPL) and Stephenson Cardiovascular Magnetic Resonance (MR) Center at the University of Calgary. Before and after a 6-week accommodation period wearing unstable shoes, a custom designed EMG circumferential linear array measured activity of selected extrinsic foot muscles during quiet standing. CoP excursion data was also collected with a force plate. All EMG measurements were performed on the left leg for a barefoot, stable control shoe and unstable MBT shoe condition. The control shoe was a relatively stable one that the subject previously owned and wore at work. The unstable MBT shoe (M. Walk model, Masai Barefoot Technologies, Switzerland) had a rounded sole in the anterior–posterior direction to provide anterior–posterior instability and a cushioned heel sensor to provide medial–lateral instability.

Subjects made two visits of approximately 2 h to the HPL to participate in the standing tests. During the first visit and prior to initial testing, subjects were instructed on how to use the unstable shoe and were given 5–10 min to stand and walk in the shoe under supervision. Following the initial test, subjects were instructed to wear the unstable shoes for 1 h on that day and gradually increase wear to approximately 8 h per day by the end of 1 week. Subjects also visited the MR Center before and after the accommodation period for an MRI of the lower leg to help with EMG array placement.

2.3. Standing tests

Subjects were instructed to focus their vision on a target directly in front of them and stand erect and steady on a force plate (Kistler Instrumente. AG, Winterthur, Switzerland), with hands by their side and feet spaced 15 cm apart and aligned in the anterior–posterior direction of the force plate [14]. Three 30 s trials were performed for each footwear condition in a randomized order. CoP excursions and the activity of select extrinsic foot muscles were quantified during the standing trials before and after the accommodation period.

2.4. Muscles and array position

The optimal array position was the level proximal to the ankle where a number of smaller extrinsic foot muscles were prominently arranged directly under the surface of the skin and where the flexor digitorum longus (FDL) was least obstructed by the soleus (SOL) near the surface of the skin (Fig. 2C).

The location of the FDL was identified through palpation during manual muscle testing and later verified using MR images. The optimal array position was approximately 1/4 to 1/3 the distance from the lateral malleolus to the lateral tibial plateau. The first electrode pair of the array was positioned along the medial edge of the tibia adjacent to the FDL. At this position, muscle activities for the SOL, FDL, an anterior compartment (AC) muscle group (tibialis anterior, extensor hallucis longus and extensor digitorum longus) and a peroneus (PR) muscle group (peroneus brevis and peroneus longus) were all selectively quantifiable, as has been described previously [19].

2.5. CoP/EMG protocol

Force plate data (forces and moments) captured at 2400 Hz and filtered with a zero-lag 4th order low-pass Butterworth filter (cut-off frequency of 50 Hz) were exported into Kintrak software (Human Performance Laboratory, Calgary AB, Canada) to calculate the range of CoP excursion data in the anterior–posterior and medial–lateral directions [14].

Using a Samsung Q1 wireless PC tablet connected to a USB 16 channel Biovision EMG measuring unit (Biovision system, Weinheim, Germany), surface EMG was recorded at 2400 Hz with a signal amplification of 2K. Bipolar surface Ag/AgCl electrodes were incorporated into a custom designed circumferential linear array (Fig. 1A and B), with 15 pairs of electrodes (10 mm diameter) inserted between two bands of double-sided adhesive tape with a dimension of 270 mm long and 30 mm wide. The distance between each pair of electrodes and between two adjacent electrode pairs was 11 mm and the perforated hole for each electrode was 2 mm in diameter [19]. An accelerometer, attached to the EMG measuring unit, synchronized the EMG data with the kinetic data captured with another computer. Before applying the electrodes, hair was removed with a razor and the skin cleaned with alcohol. The contact surface of each electrode on the EMG array was coated with a small amount of conducting gel.

For each measurement session, the location of the EMG array was marked on the skin to allow accurate repositioning of a second array for MR imaging. The second array had contrasting elements visible during the MRI that represented the positions of each electrode pair on the array.

2.6. MRI protocol

Using a 1.5-T MRI scanner (Avanto, Siemens Medical Solutions, Erlangen, Germany), MR images were taken of the lower left leg. The purpose of the MR

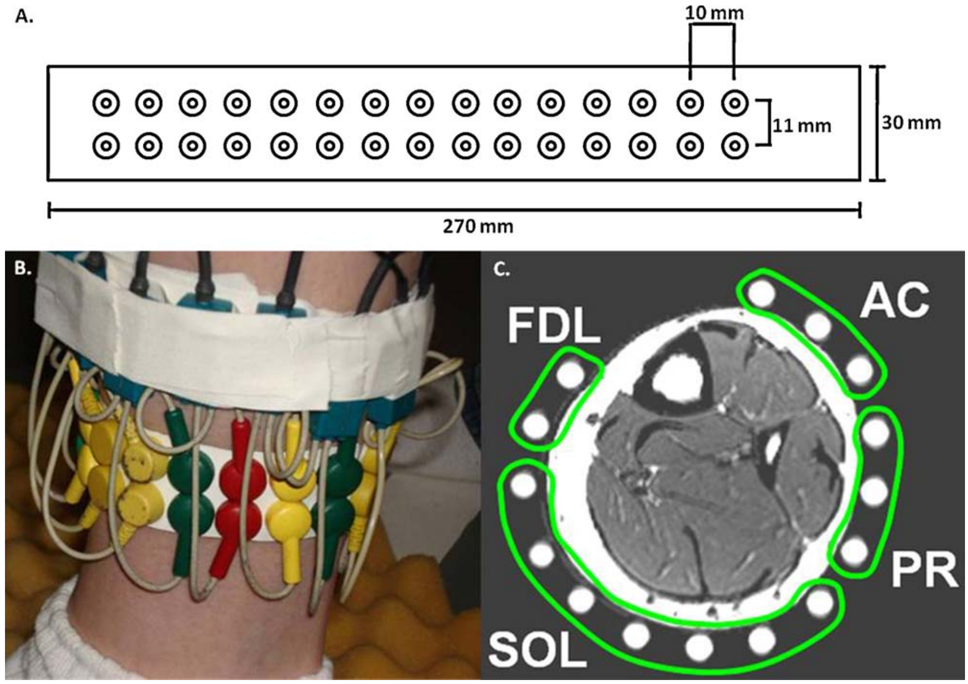

Fig. 1. (A) EMG circumferential linear array schematic showing the 15 pairs of electrodes along with the dimensions of the array. (B) EMG array positioned on the leg during standing tests. (C) EMG array visible in an MRI scan with the four muscles/muscle groups illustrated. (FDL: flexor digitorum longus; SOL: soleus; PR: peroneus group; AC: anterior compartment group.)

images was to (i) aid in the positioning of the EMG array between the two visits and (ii) to determine the muscle or muscle group each electrode pair was positioned over. Subjects were placed in a supine position with the left foot held at 90° and stabilized while positioned within an extremity coil using a series of spacers, tape and sponges. 120 cross-sectional images spaced 4 mm apart were captured and inspected by a trained radiography technologist to ensure no noise or movement artifact was present.

2.7. EMG processing

EMG signals were resolved into time–frequency space using a wavelet analysis technique [20] and averaged across the three standing trials for each shoe condition. A filter bank of 13 wavelets with a center frequency ranging from 7 Hz (wavelet 0) to 542 Hz (wavelet 12) determined the intensity of each wavelet. The total EMG intensity was defined as the sum of the EMG wavelet intensities for

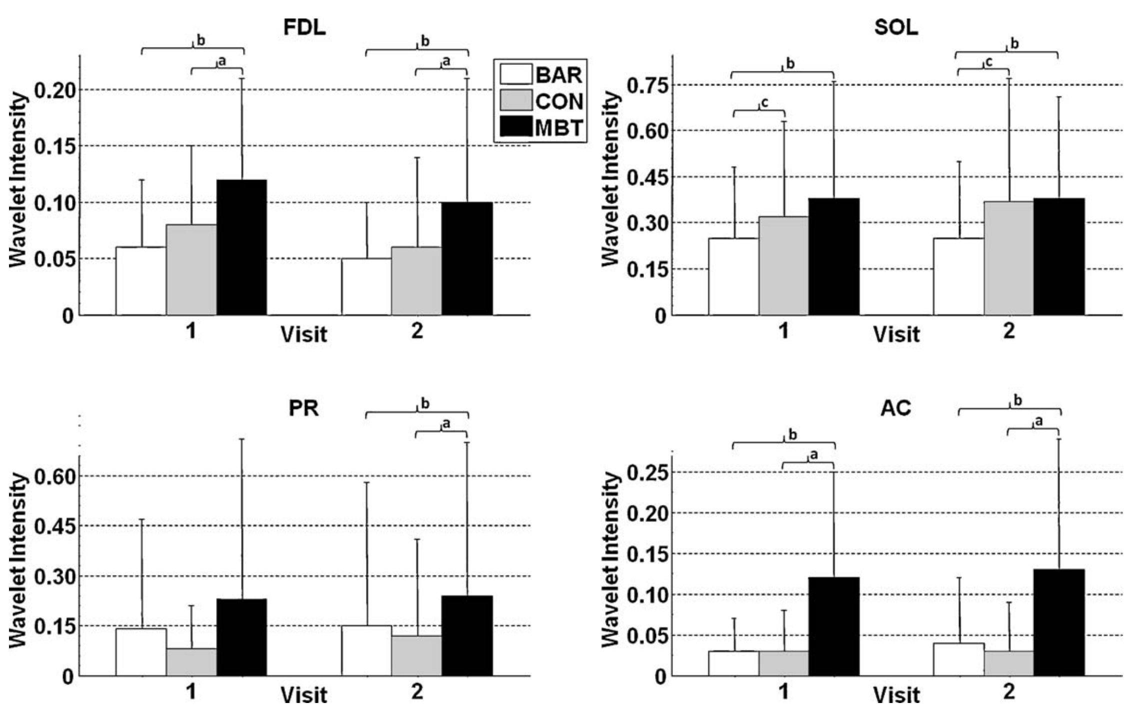

Fig. 2. Integrated EMG wavelet intensity group means with standard deviations while standing Barefoot (BAR), with the unstable MBT shoe (MBT) and with the stable control shoe (CON) for four muscle groups and both visits. (FDL: flexor digitorum longus; SOL: soleus; PR: peroneus group; AC: anterior compartment group.) 'a' MBT significantly different from CON ($p < 0.05$). 'b' MBT significantly different from BAR ($p < 0.05$). 'c' BAR significantly different from CON ($p < 0.05$).

wavelet domains 1 through 13 and this provided the signal power for a specific instance of time, similar to the traditional root mean square (RMS) value [14]. The integrated wavelet intensity was determined for the middle 15 s of the 30 s standing period. The intensities for all electrodes associated with one specific muscle or muscle group were averaged to give one total intensity value for that muscle or muscle group. This was done on an individual basis for each muscle group and for each individual subject.

2.8. Statistical analysis

All statistical tests were performed using the Statistical Package for the Social Sciences version 16.0 (SPSS Inc., Chicago IL, USA). The effects of the three footwear conditions on CoP excursion ranges and muscular activity intensities and the effects across pre- and post-accommodation testing visits were analyzed using a 3×2 two-way repeated measures ANOVA. An alpha level of $p < 0.05$ indicated significant statistical differences for a shoe, visit and/or interaction effect and when a main or interaction effect was identified, Bonferroni corrected pairwise post hoc comparisons were made between individual shoe conditions and visits.

3. Results

3.1. EMG-activity intensities

Comparing activity wavelet intensities, neither visit (pre- and post-accommodation testing) nor interaction effects were identified for all muscle groups (Table 2 and Fig. 2). A shoe effect was evident for the four muscle groups and based on the small p-values, Bonferroni pairwise comparisons were performed (Table 3). For both testing visits, the unstable MBT shoe produced larger intensities compared to the other two footwear conditions for the FDL and AC muscle group. No differences were identified between the barefoot and stable control shoe conditions for both of these muscles.

During the first visit, no differences were identified between shoe conditions for the PR muscle group. For the second visit, however, greater activity intensities for the unstable MBT shoe condition compared to the other two shoe conditions were identified.

Shoe differences for the SOL were similar across visits, with the barefoot condition having smaller activity intensities than both the stable control and unstable MBT shoe conditions. No differences were identified between the stable control and unstable MBT shoe conditions.

Table 2
Two-way repeated measures ANOVA results indicating shoe (barefoot, stable control and unstable MBT), visit (pre-accommodation or Visit 1 and post-accommodation or Visit 2) and interaction effects for EMG wavelet intensities of the four extrinsic foot muscle groups and CoP excursion ranges in both directions.

	Effect p-values		
	Shoe	Visit	Interaction
EMG wavelet intensities			
FDL	<0.001	0.17	0.93
SOL	<0.001	0.79	0.50
PR	0.08	0.77	0.79
AC	<0.001	0.66	0.89
CoP excursions			
Medial–lateral	<0.001	0.46	0.07
Anterior–posterior	<0.001	0.86	0.05

FDL: flexor digitorum longus; SOL: soleus; PR: peroneus group; AC: anterior compartment group. Post hoc Bonferroni pairwise comparisons, presented in Table 3, were performed when one of the p-values for a specific effect (shoe, visit or interaction) was less than 0.1.

3.2. Center of pressure (CoP) excursions

A shoe effect was identified for CoP excursion ranges in the anterior–posterior and medial–lateral direction (Table 2) and pairwise comparisons indicated greater excursions for the unstable MBT shoe compared to the other footwear conditions for both visits (Table 3). Based on the small p-values for the interaction effect, pairwise comparisons indicated a significant decrease in CoP excursions for the unstable MBT shoe in both directions when comparing the pre (Visit 1) and post (Visit 2) accommodation period testing. Visit differences did not exist for the other two footwear conditions.

4. Discussion

Several shoe companies have recently developed so called "barefoot" shoes [1] with the purpose of providing some of the

Table 3
Mean and standard deviations, including significant Bonferroni corrected post hoc pairwise comparisons, for EMG wavelet intensities of the four extrinsic foot muscle groups and CoP excursion ranges for the three shoe conditions (barefoot, control and MBT) during both visits (pre- and post-accommodation testing).

	Mean (±SD)			Significant pairwise comparisons
	Barefoot	Control	MBT	
Visit 1 (pre)				
EMG wavelet intensities				
FDL	0.06 (0.06)	0.08 (0.07)	0.12 (0.09)	a ($p = 0.01$), b ($p = 0.004$)
SOL	0.25 (0.23)	0.32 (0.31)	0.38 (0.38)	b ($p = 0.02$), c ($p = 0.04$)
PR	0.14 (0.33)	0.08 (0.13)	0.23 (0.48)	
AC	0.03 (0.04)	0.03 (0.05)	0.12 (0.13)	a ($p < 0.001$), b ($p = 0.001$)
CoP excursions (mm)				
Medial–lateral	11.94 (8.22)	11.12 (6.44)	22.82 (8.49)	a ($p < 0.001$), b ($p < 0.001$)
Anterior–posterior	26.40 (15.69)	25.50 (10.87)	51.60 (17.65)	a ($p < 0.001$), b ($p < 0.001$)
Visit 2 (post)				
EMG wavelet intensities				
FDL	0.05 (0.05)	0.06 (0.08)	0.10 (0.11)	a ($p = 0.005$), b ($p = 0.01$)
SOL	0.25 (0.25)	0.37 (0.40)	0.38 (0.33)	b ($p = 0.02$), c ($p = 0.007$)
PR	0.15 (0.43)	0.12 (0.29)	0.24 (0.46)	a ($p = 0.05$), b ($p = 0.02$)
AC	0.04 (0.08)	0.03 (0.06)	0.13 (0.16)	a ($p < 0.001$), b ($p = 0.001$)
CoP excursions (mm)				
Medial–lateral	12.84 (13.56)	11.36 (9.67)	18.78 (15.09)	a ($p < 0.001$), b ($p = 0.01$), d ($p = 0.05$)
Anterior–posterior	26.88 (12.97)	26.24 (10.31)	44.69 (17.33)	a ($p < 0.001$), b ($p < 0.001$), d ($p = 0.02$)

FDL: flexor digitorum longus; SOL: soleus; PR: peroneus group; AC: anterior compartment group. 'a' MBT significantly different from control ($p < 0.05$). 'b' MBT significantly different from barefoot ($p < 0.05$). 'c' Barefoot significantly different from control ($p < 0.05$). 'd' MBT post-accommodation testing (Visit 2) significantly different from MBT pre-accommodation testing (Visit 1).

suggested benefits of barefoot locomotion. Being conceptually similar to wobble board training during injury rehabilitation, the unstable MBT shoe is one of these "barefoot" shoes designed to train or activate some of the smaller extrinsic foot muscles while standing or walking. Evidence for the effectiveness of wobble board training does exists [9,10,21], however, such evidence for the effective training of the smaller extrinsic foot muscles by an unstable shoe has not been previously provided. The results of this study, provide for the first time, evidence that an unstable shoe condition may increase muscle activity of select extrinsic foot muscles, supporting hypotheses H1 and H2. The increases in muscle activity while standing in the unstable shoe compared to the stable control shoe persisted even after the 6-week accommodation period. Whether training of the smaller muscles occurs during activities such as walking still has to be investigated. The authors speculate, however, that the training effect of unstable shoes on the smaller muscles would be less during walking and running than during standing, based on the design of the unstable shoe's sole.

Many of the smaller extrinsic foot muscles have an advantageous geometrical position with larger relative lever arms for controlling movements about the subtalar joint [22]. A conceptual model suggests that these muscles sense changes in position about the subtalar joint axis "quicker" than the larger extrinsic foot muscles (e.g. triceps surae with the Achilles tendon). By reacting earlier, these muscles may maintain balance more effectively with less force through the joint [1,17]. This concept is one of the proposed advantages of strong smaller extrinsic foot muscles (e.g. flexor digitorum longus, peroneus brevis/longus), along with other important functional roles previously described at the foot and ankle [23,24]. Because it is thought that the smaller extrinsic foot muscles are particularly vulnerable to inactivity or overprotection while wearing stable and supportive shoes, it is proposed based on the findings from this study that training with an unstable shoe could have training and/or strengthening benefits. Further support for the use of unstable shoes, muscle changes that were once believed to be solely caused by aging are now understood to be the result of disuse and therefore potentially reversible [25].

Generating ankle torques and activating muscles at the ankle help stabilize the body during quiet standing and control postural sway [26,27]. Standing in the unstable MBT shoe demonstrated greater postural sway for both the pre- and post-accommodation period testing, satisfying H3 and H4. This provides support that the MBT was effective in inducing an unstable environment that helped to train or increase activity of the smaller extrinsic foot muscles during standing. While activity for the FDL, PR and AC groups remained greater after 6 weeks for the unstable shoe compared to barefoot and the stable shoe, postural sway did decrease between visits for the unstable shoe only. This implies that muscle coordination may have been improved to reduce postural sway. Increased activity levels while standing in the unstable shoe continued after the 6-week period, suggesting that the training effect of the unstable shoe remains even after extended use of the unstable shoe.

A limitation of this study was that a 6-week accommodation period for a separate group of subjects wearing a stable control shoe was not carried out to confirm that reduction in postural sway from the pre to post visits was due solely to the 6 weeks of unstable training in the MBT shoe. It is not expected; however, that wearing a stable control shoe for 6 weeks would reduce postural sway.

In summary, the custom designed EMG array combined with the MRI data permitted the successful detection of increased muscle activity of select smaller extrinsic foot muscles while standing in an unstable MBT shoe. It appears that the unstable MBT shoe is effective in activating some of the smaller extrinsic foot muscles that could be relatively inactive or under-utilized while standing in a more stable shoe. Postural sway also improved with MBT usage and it is recommended that a methodology be developed to directly quantify strength changes in the smaller ankle muscles with prolonged usage of the unstable MBT shoe.

Conflict of interest statement

While Masai Barefoot Technology (MBT) provided the unstable shoes and financial support, they had no role in (i) the study design, (ii) the collection, analysis and interpretation of the data, (iii) the writing of the manuscript or (iv) the decision to submit the manuscript for publication.

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