

Masai Barefoot Technology

2004

**Effect of an
Unstable Shoe Construction
on
Lower Extremity Gait Characteristics**

**Human Performance Laboratory
University of Calgary
Calgary, Canada**

A project report for Masai Switzerland
comparing selected biomechanical
characteristics of the MBT and a
control shoe.

Submitted June 30, 2004

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Kinematics, kinetics, muscle activity, soft tissue vibrations and oxygen consumption for stable & unstable shoes

Executive Summary

Introduction

Two strategies are available to improve stability during locomotion, constructing shoes that provide support and/or strengthening lower extremity muscles. However, when using shoes that provide stability, the muscles contributing to static and dynamic stability get weaker because they are not used. For this reason, many people train these under-activated muscles, using unstable situations (e.g. a wobble board). Conceptually, it does not seem logical to separate the functions of static and dynamic stability and muscle training. One may suggest that training of lower extremity muscles should be combined with the actual locomotion activities. Such a training device has recently been developed by Masai Barefoot Technologies (MBT). The MBT shoe (Figure 1) has a rounded sole in the anterior-posterior direction, thus providing an unstable base. It is speculated and supported by anecdotal evidence that these shoes act as a training device for lower extremity muscles and that the frequent use of this shoe is associated with several positive medical and health benefits.



Fig 1 Lateral view of the unstable MBT shoe used in the study, indicating the rounded sole constructed in the a-p direction.

The theoretical concept behind this unstable shoe construction is to strengthen the muscles close to the movement axes because strong forces close to the joint axes substantially reduce the resultant joint loading (Fig. 2).

Reduced joint loading also has a beneficial effect on lower extremity joint pain. Thus, it seems important to understand the mechanics of devices like the MBT shoe, which can be used to train these muscles acting close to the joint axes. Theoretical consideration and initial experimental results indicate that an unstable shoe design may be beneficial for human locomotion and possibly for the reduction of joint pain and discomfort. However, a comprehensive analysis of the kinetic, kinematic and muscle activity differences has, to the knowledge of the authors, not been done yet.

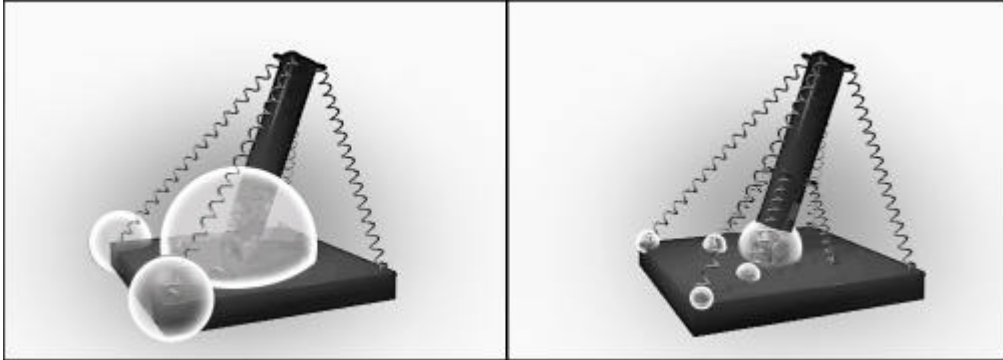


Fig. 2 Illustration of the calculated effect of the inclusion of strong forces close to the joint axis (right picture) on the joint and insertion loading for a mast with large and small springs, oscillating around its equilibrium position. The spheres at the insertion of the springs and at the joint of the mast indicate the magnitude of the forces at these locations.

The purpose of this investigation was to compare kinematics, kinetics, muscle activity, soft tissue vibrations and oxygen consumption during standing and locomotion for healthy subjects using an unstable MBT shoe and a conventional stable control shoe.

Methods

Eight subjects participated in this study performing tests in a control shoe (Adidas SuperNova) and the illustrated MBT shoe (Fig. 1). A first test battery was performed during quiet standing, quantifying the movement of the center of pressure and the corresponding muscle activity. A second test battery was performed during walking, quantifying kinematics, kinetics, muscle activity (EMG), soft tissue vibrations and oxygen consumption for the two shoe conditions for walking in an initial testing session at the start of the project and two weeks later in a second session. Subjects were asked to wear the unstable test shoe as much as possible for the two weeks (9.5 ± 2.1 h) as suggested by the manufacturer.

Results and Discussion

Standing quietly

The center of pressure excursions were significantly greater while standing in the MBT shoe compared to the control shoe. This increased wobbling “instability” was accompanied by an increased tibialis anterior and gluteus medius muscle activity during the initial measurement (with little change in the other muscles). After two weeks, all muscles showed an increase in EMG activity with a significant difference between MBT and control shoe of 70% in the tibialis anterior (Table 1).

The increase in the movement of the center of pressure is a logical result of the construction of an unstable shoe sole and was expected.

At the beginning of the use of the MBT shoe, selected muscles showed an increase in EMG activity. Over time, however, increased EMG activity was observed in all muscles of the lower

extremity when standing in the MBT shoe compared to the control shoe (Table 1). Thus, muscle training does occur during standing in all muscles to balance the standing position.

Conclusion: *Standing quietly: The MBT shoe produced substantial increases in the movement of the center of pressure and demands, therefore, more muscle activity to balance the standing position. This demand increases with prolonged use of the MBT shoe. Thus, for standing, the MBT shoe acts as a muscle training device.*

Table 1 Summary of the differences between the MBT and the control shoe for session 1 (ΔX_1) and session 2 (ΔX_2). Significant differences between MBT and control shoe in bold and italic.

Variable	Specifics	ΔX_1 (MBT-Control) [%]	ΔX_2 (MBT-Control) [%]
Center of pressure	Medio-lateral	+ 138	+ 114
Center of pressure	Anterior-posterior	+ 130	+ 59
EMG intensity	Tibialis anterior	+ 79	+ 70
EMG intensity	Gastrocnemius	- 9	+ 38
EMG intensity	Vastus medialis	+ 10	+ 37
EMG intensity	Biceps femoris	- 3	+ 11
EMG intensity	Gluteus medius	+ 51	+ 28

Walking

Kinematics:

The lower extremity kinematics were similar for the MBT and the control shoe with one exception: The plantar-dorsiflexion angle showed substantial differences in the first part of ground contact for the MBT shoe compared to the control shoe. The difference in the plantar-dorsiflexion angle was primarily due to changes during the landing in the MBT shoe. The landing in the control shoe occurred at the heel. The landing in the MBT shoe occurred more towards the midfoot. The fact that the lower extremity kinematics did not change with the exception of the plantar-dorsiflexion angle is in agreement with the concept that the joint movements are primarily determined by the actual movement task (walking in this experiment) and that each joint has a “preferred movement path”. It is positive to see that the MBT shoe construction did not affect the other joint movements.

Kinetics:

For the first half of ground contact, the resultant rotational joint impulses (integral under the resultant joint moment curve) showed a substantial and significant increase for ankle plantar flexion and ankle inversion, a significant decrease for knee extension and small decreases (on the average 19%) for all but one of the knee and hip impulses (Table 2).

The significant increases in the first half of ground contact can be explained with changes in the walking technique. The foot landed in a slightly dorsiflexed position with the MBT shoe and stayed in this position throughout the first half of ground contact. Therefore, there is no dorsiflexion moment in the initial phase. The relative increase in plantarflexion impulse was large. However, the actual ankle plantar-flexion moments in the first half were small and, therefore, this change is no reason for concern for excessive ankle joint loading. The increase in

the rotational inversion impulse is a result of the construction of the MBT shoe, which guides the foot initially into an everted position.

The small decreases in all but one other rotational joint impulse are probably associated with the changes of the center of pressure location during the first half of ground contact. Due to the construction of the MBT shoe, the point of application is more towards the center of the foot, which reduces the resultant joint moments. Typically, a reduction in the resultant joint moment and rotational joint impulse is associated with a reduction in joint loading.

The changes for the second half of ground contact are smaller and less systematic.

Conclusion: The MBT shoe produced an increase in the ankle plantar-flexion and inversion rotational impulse and a decrease in most other rotational joint impulses. The reduction in all rotational knee impulses may be associated with a reduction in the knee joint loading.

Table 2 Summary of the relative differences in resultant rotational joint impulses between the MBT and the control shoe for the first measurements for the first (Δ_{0-50}) and the second (Δ_{50-100}) half of ground contact.

Variable	Specifics	Δ_{0-50} (MBT-Control) [%]	Δ_{50-100} (MBT-Control) [%]
Rot. Impulse ankle	Dorsi-plantar	+ 80	+ 3
Rot. Impulse ankle	In-eversion	+ 105	- 18
Rot. Impulse ankle	Ab-adduction	- 9	+ 34
Rot. Impulse knee	Flexion-extension	- 47	+ 1
Rot. Impulse knee	Ab-adduction	- 12	+ 9
Rot. Impulse knee	Int-ext. rotation	- 21	- 6
Rot. Impulse hip	Flexion-extension	- 6	- 10
Rot. Impulse hip	Ab-adduction	+ 2	+ 1
Rot. Impulse hip	Int-ext. rotation	- 30	- 10

Muscle activity:

Muscle activity for the 100 ms before and after first ground contact showed few differences between the MBT and the control shoe. However, the tibialis anterior had a 33% reduction in the pre-activation and a 58% reduction in the activation right after heel strike when walking in the MBT shoe. These reductions were a result of low frequency EMG contributions. The reduction in initial activation is related to the change in the landing position with the MBT shoe and was to be expected. In addition, the biceps femoris had a 50% reduction in the pre-activation when walking in the MBT shoe. These reductions were a result of high and low frequency EMG contributions.

Conclusion: Due to the change in landing position, the MBT shoe produced a reduction of tibialis anterior activity shortly before and after heel strike and a reduction of biceps femoris activity shortly before heel strike.

Preferred movement path:

It has been proposed that each joint has a preferred movement path for a given task. If a shoe counteracts to this preferred movement path the joint moments and/or the muscle activity should increase. If the joint moments and/or the muscle activity decreases one can conclude

that this shoe intervention produces a movement that is closer to the preferred movement path. The results for the ankle joint show an increase in two of the three joint moments and a decrease in the tibialis anterior EMG activity. Thus the indications for changes in the preferred movement path with the MBT shoe are not conclusive. The results for the knee joint show a slight decrease of all three knee joint moments. The results for the hip joint show a slight decrease of two of the three hip joint moments. Additionally the biceps femoris EMG activity showed a decrease.

Conclusion: *The MBT shoe produced a movement for the knee and hip joint which was closer to the preferred movement path than the movement path produced by the control shoe. This corresponds to a reduction of knee and hip joint loading during walking.*

Soft tissue vibrations:

The soft tissue vibrations showed small and not significant changes in the vibration amplitude as predicted by the muscle tuning paradigm. The time to maximum acceleration was delayed for all three soft tissue packages (significantly for the hamstrings). The resonance frequency showed the biggest changes (around 30%); the quadriceps showed an increase and the hamstrings and gastrocnemius showed a decrease. These results indicate that the MBT shoe has an effect on muscle tuning with two of the three tested soft tissue packages reducing the frequency.

Table 3 Summary of the relative differences in vibration amplitude, time of maximum vibration acceleration and frequency of vibration for three soft tissue packages, quadriceps, hamstrings and gastrocnemius.

Variable	ΔX (MBT-Control) quadriceps [%]	ΔX (MBT-Control) hamstrings [%]	ΔX (MBT-Control) gastrocnemius [%]
a(max)	+ 6	- 7	- 14
time to a(max)	+ 4	+ 29	+ 16
frequency	+ 26	- 32	- 33

Oxygen consumption:

Walking in the MBT shoe required a significant 2.5% increase in oxygen consumption with an unchanged heart frequency. The muscle activity did not change significantly during walking, with the exception of a reduction in the tibialis anterior and biceps femoris activity. However, the reductions were small and should not affect the oxygen consumption results substantially. Therefore, the reason for this increase in oxygen consumption must be found elsewhere. The most important difference between the tested MBT and control shoe was in their mass. The mass difference was 292 g. A mass difference of 100 g corresponds to between 0.5 and 1.0% in oxygen consumption. Thus, the difference in oxygen consumption is caused primarily by the difference in shoe mass. Subjects using the MBT shoe will use more energy, which may be associated with a training effect. However, if this effect is not desired, the shoe construction should be made lighter.

Conclusion: *The oxygen consumption in the MBT shoe was 2.5% higher than in the control shoe. This difference was primarily caused by the difference in the shoe mass.*

Summary

The results of this study showed the following results:

- Standing in the MBT shoe produced more movement of the center of pressure and required more muscle activity in the lower extremity to balance the body. Thus, during standing, the MBT shoe acts as a muscle training device.
- The general walking kinematics were not changed by the MBT shoe except for the landing kinematics (flat foot) and the stride frequency (higher) and stride length (shorter).
- The rotational ankle joint impulse for plantar-flexion for the first half of stance is higher for the MBT shoe. However, the actual plantar flexion moments are small during the first half of contact time. Thus, this increase should not be of any concern.
- The rotational ankle joint inversion impulse for the first half of stance is substantially higher for the MBT shoe. Small changes in shoe construction could change this situation if desired.
- The rotational ankle joint impulses for all other joints and axes are slightly decreased with the MBT shoe. The reduction is consistent for the knee joint and is on the average for all axes 19%. This result and the results for the reduced or maintained muscle activity during walking are evidence that the MBT shoe produces movement close to the preferred movement path.
- The muscle activity of the major muscle groups shortly before and after heel strike was not changed with the MBT shoe with the exception of reduction of the tibialis anterior and biceps femoris muscles.
- The MBT shoe required 2.5% more oxygen consumption for the same walking task, a difference that can be explained primarily by the additional weight of the MBT shoe.
- The onset and the frequency of the soft tissue vibrations were influenced by the MBT shoe.
- It is speculated that the MBT shoe strengthens the small muscles with small levers with respect to the rotational axes. This would reduce the joint loading which could explain some anecdotal results of less pain and discomfort.

***In summary,
the results of this study showed that the MBT shoe***

⇒ acts as a muscle training device during standing and quasi-static activities and

⇒ reduces knee and hip joint loading during walking.

INTRODUCTION

Stability is an important aspect of human locomotion for any group of people. Stability is important for children as they learn to walk, for athletes to perform well, and for the elderly to be mobile as long as possible. There are two major strategies to improve stability during locomotion (a) constructing shoes that provide support and/or (b) strengthening lower extremity muscles.

Shoes for walking and other locomotion activities are typically constructed to provide stability for the user (e.g. stability shoes, movement control shoes, rehabilitation shoes for ligament injuries, etc.). However, it is possible that by using such shoes, the muscles that would usually contribute to static and dynamic stability may get weaker over time because they are not used. For this reason, many people train these under-activated muscles, using unstable situations. One frequently used device for stability training is the wobble board. Several studies have shown that using balance training devices, such as a wobble-board or an unstable surface, can significantly improve ankle and knee proprioception (Waddington et al., 2000, Waddington and Adams, 2004) and possibly improve muscle preparation prior to touchdown during walking in healthy individuals. Standing balance training has also been reported to be effective for rehabilitation training following ankle ligament injury (Wester et al., 1996). In addition, several studies have reported that standing balance training is beneficial in the prevention of lower extremity musculoskeletal injuries (Bahr et al., 1997; Caraffa et al., 1996; Wedderkopp et al., 1999).

Conceptually, it does not seem logical to separate the functions of static and dynamic stability and muscle training. One may suggest that training of lower extremity muscles should be combined with the actual locomotion activities. Such a training device has recently been developed by Masai Barefoot Technologies (MBT). The MBT shoe has a rounded sole in the anterior-posterior direction, thus providing an unstable base. It is speculated and supported by anecdotal evidence that these shoes act as a training device for lower extremity muscles and that the frequent use of this shoe is associated with several positive medical and health benefits.

The theoretical concept behind this unstable shoe construction is to strengthen the muscles close to the movement axes. A model calculation comparing the joint loading for a situation with no forces and with forces close to the joint axes (Fig. 3) reveals that the inclusion of strong forces close to the joint axis reduces the resultant joint loading substantially.

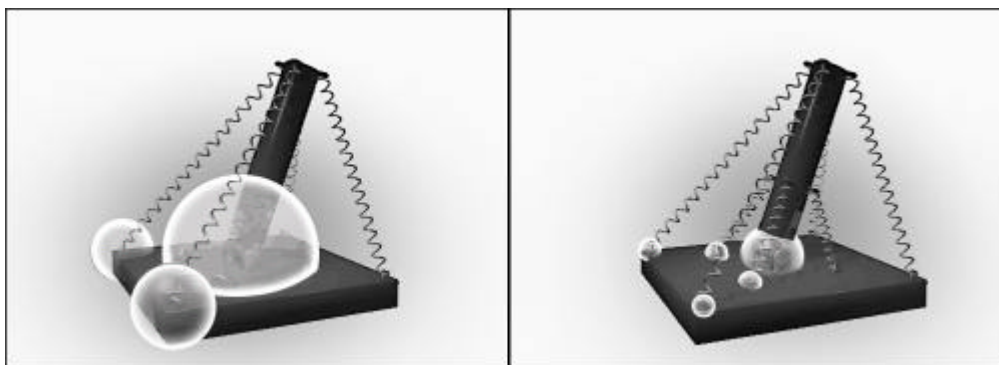


Fig. 3 Illustration of the calculated effect of the inclusion of strong forces close to the joint axis (right picture) on the joint and insertion loading for a mast on a joint with large and small springs, oscillating around its equilibrium position.

These model calculations illustrate that strong muscles with small lever arms reduce the joint loading substantially. Reduced joint loading would have a beneficial effect on lower extremity joint pain. Thus, it seems important to understand the mechanics of unstable training devices, which can be used to train these muscles, acting close to the joint axes.

The literature has few studies that discuss unstable shoes with rocker bottoms. Walking in shoes with a rocker-bottom has been shown to be a useful therapeutic intervention especially for people with insensitive or diabetic feet or following lower extremity surgery. The use of a full length rocker-bottom shoe has been reported to increase walking speed and other physiological functions for patients with diabetes mellitus and trans-metatarsal amputations compared to an ankle-foot orthosis or a short shoe design (Mueller and Strube, 1997). Furthermore, peak plantar pressure was significantly reduced in a rocker-bottom shoe compared to a regular walking shoe (Mueller et al., 1997). Based on these results it was suggested that peak pressure and the force-time integral were significantly reduced in a rocker-bottom shoe compared to a regular shoe design (Fuller et al., 2001). Additionally, plantar pressure measurements were quantified for healthy individuals for nine different rocker-shoe designs, differing in location of the axis and rocker height (van Schie et al., 2000). Peak pressure was reduced at most forefoot locations in the rocker shoe compared to a regular walking shoe with the maximal reductions in peak pressure being subject-specific.

Theoretical consideration and initial experimental results indicate that an unstable shoe design may be beneficial for human locomotion and possibly for the reduction of joint pain and discomfort. However, a comprehensive analysis of the kinetic, kinematic and muscle activity differences has, to the knowledge of the authors, not been done yet.

Thus, the purpose of this investigation was to compare kinematics, kinetics, muscle activity, soft tissue vibrations and oxygen consumption during standing and locomotion for healthy subjects using an unstable MBT shoe and a conventional stable control shoe.

METHODS

Subject population: Eight subjects volunteered for this study (5 male, 3 female; age: 28.0 ± 3.6 yr; mass: 70.1 ± 7.5 kg; height: 169.5 ± 6.4 cm). All subjects were free of lower extremity pain and injury for a minimum of 6 months prior to testing and had never used the shoe before. All subjects gave informed written consent corresponding to the guidelines of the University of Calgary Ethics Committee.

Shoe Condition: The control shoe tested in this study was the Adidas SuperNova running shoe (mass: 358 grams). The unstable shoe condition tested in the study was the MBT shoe (Masai Barefoot Technology, Switzerland: mass 650 grams). The MBT shoe is characterized by a round shoe sole design in the anterior-posterior direction, making the shoe unstable in this direction (Fig. 4).



Fig 4 Lateral view of the unstable MBT shoe used in the study, indicating the rounded sole constructed in the a-p direction.

Testing Procedure: Retroreflective markers were placed on the segments of the rearfoot, shank, thigh and pelvis of the right lower extremity. Markers were placed on both sides of the body over the greater trochanters, the medial and lateral femoral condyles and the medial and lateral malleoli. The three rearfoot markers were placed directly on the posterior and posterolateral aspect of the shoe heel counter. The position of the markers were determined for a standing neutral trial to define the same anatomical coordinate system for each segment for both shoe conditions, first for the control shoe and second for the unstable test shoe.

The first test consisted of three trials of 30 second each to determine movement of the center of pressure and the corresponding muscle activation during quiet standing. The second test consisted of 10 walking trials, first for the control shoe and second for the MBT shoe, at a walking speed of 5.0 ± 0.5 km/h. For the walking trials, the lower leg kinematic and kinetics, selected soft tissue vibrations and selected muscle EMG data were collected. Before testing with the MBT shoe, subjects were instructed on the proper walking methods by a person trained in the correct use of the shoe. Subjects completed approximately 5-10 minutes of walking in the laboratory until they felt comfortable walking in the MBT shoe. The quiet balance tests and the walking trials at the same pace were then repeated.

Subjects were asked to wear the MBT test shoe as much as possible for the next 2 weeks as suggested by the manufacturer. On average, the subjects wore the shoes for 9.5 hours (\pm 2.1 hours) each day over the 2 week period. After two weeks, subjects were retested. The same test protocol was used except the unstable test shoe was tested first followed by the control shoe.

Kinematic and Kinetic Data: Kinematic data were collected using an eight high-speed video camera system (Motion Analysis Corporation, Santa Rosa CA, USA) at a sampling rate of 240 Hz. The pre-determined criterion for tolerable error in space calibration was set at 0.06%, corresponding to a 0.6mm maximum error for a 1m³ volume. Three-dimensional marker traces were reconstructed using Expert Vision Three-Dimensional Analysis software (Motion Analysis Corporation, Santa Rosa CA, USA). Kinetic data were collected simultaneously with the kinematic data using a force platform (Kistler: Winterthur, Switzerland) that was placed in the center of the walkway level with the ground at a sampling rate of 2400 Hz. Kinematic and kinetic data were filtered using a zero-lag quadratic low-pass Butterworth filter with a cut-off frequency of 12 and 50 Hz, respectively. Linear and angular position, velocity and acceleration data were then calculated and exported for further analysis. Kintrak software (Human Performance Laboratory, Calgary, Canada) was used to calculate kinematic and kinetic variables of interest using an inverse dynamics technique. The angle, force, resultant joint moments and resultant joint power results were normalized to ground contact, resulting in 100 data points per trial. Peak joint angle, peak GRF values, and rotational impulse ($\int M dt$) determined from the joint moment data, were then determined for the first and second half of the stance phase for each trial and condition.

EMG Data: Myoelectric signals were recorded using round bipolar surface electrodes (Ag/AgCl: Biovision, Wehrheim, Germany). To achieve an optimal EMG signal and low impedance (< 5 k Ω) hair was removed and skin cleaned with isopropyl wipes prior to the electrodes being placed on the skin according to the techniques suggested by De Luca (1997). Each electrode was 10mm in diameter and had an inter-electrode spacing of 22mm and was placed midway between the motor end plate and distal myotendinous junction. A ground electrode was placed on the lateral condyle of the knee. Five EMG electrodes were placed on the skin overlying the muscle belly of the tibialis anterior (TA), medial gastrocnemius (GAS), biceps femoris (BF), vastus medialis (VM), and gluteus medius (GM) of the limb of interest. All raw EMG analog signals were on-line pre-amplified ($\times 7000$), and then converted into digital signals sampled at 2400 Hz simultaneously with the kinematic and kinetic data. Timing of touch-down for each trial were determined from kinetic data and EMG data were partitioned for 200 ms prior to touch-down until 500 ms after touch-down.

EMG signals were resolved into time-frequency space using wavelet analysis technique and then averaged across the 10 trials for each condition (von Tscharner, 2000). A set of 13 wavelets was used with a center frequency ranging from 7 Hz (wavelet 0) to 542 Hz (wavelet 12) and the intensity of each wavelet was calculated. Based on previous studies (von Tscharner, 2003; Wakeling et al., 2001; Wakeling et al., 2002), a high frequency band was defined as frequencies between 142 Hz and 300 Hz (wavelets 6-8) and a low frequency band was defined as frequencies between 25-85 Hz (wavelets 23). These frequency bands have been shown to correspond with slow and fast motor unit activation. The total EMG intensity was defined as the sum of EMG wavelet intensities for wavelet domains 1 through 8. The total intensity is a measure of the power of the signal contained within the given frequency bands. For the quiet standing condition, EMG data for each wavelet were normalized to the average total intensity of the control shoe condition. Total, low, and high intensities were averaged over the 30 sec quiet standing period. For the walking condition, EMG data for each wavelet were normalized to the peak total intensity of the control shoe condition. Total, low, and high

intensities were averaged over the pre-heel strike (100 ms before heel strike) and post-heel strike interval (100 ms after heel strike) resulting in six EMG variables per muscle.

Soft tissue vibration: Soft tissue vibrations were measured from the muscle bellies of the rectus femoris, biceps femoris (long head), and lateral gastrocnemius using skin-mounted tri-axial accelerometers (EGAX accelerometer, nominal frequency response 0-600 Hz; Entran devices). According to earlier studies (Wakeling et al., 2003), the axes of the accelerometers were oriented to be parallel to the long axis of the segment and were attached to the skin using Hollister medical adhesive glue and a stretch adhesive bandage to improve the congruence of motion of the accelerometer and the soft-tissue. The mean tissue acceleration during the standing-neutral trial was subtracted from the walking trials to reference the accelerations to a vertical standing posture. Soft tissue accelerations were quantified by their maximum peak following touch-down. The vibration frequency was estimated from twice the period between the inflection points prior to and following maximum acceleration.

Oxygen Consumption Testing: Following the 2 week accommodation period, subjects completed two economy testing sessions to determine oxygen consumption while walking in the unstable test shoe compared to the control shoe. All testing sessions were conducted on a treadmill at similar times of day to eliminate potential variation in VO_2 due to circadian rhythm. The walking speed was 5.0 km/h and was similar to the self-selected speed used for the biomechanical testing

The walking economy testing protocol consisted of a 5-10 minute warm up period consisting of a gradual increase in speed over time approaching and including the determined economy walking speed of the test. The subjects walked at the selected test speed for the final minutes of the warm up. The actual oxygen consumption tests consisted of four, five-minute walks with three-minute rest intervals between each walk to allow for changing shoes. During the walking economy test, the shoes were tested in either one of the following two protocols: C-U-U-C for one day and U-C-C-U for the other day. The protocols were randomly assigned to the subjects. During the oxygen consumption tests, which were completed on separate days, the subjects followed the opposite protocol to what they used in the first test.

The variables of interest were volume of oxygen consumption (VO_2), heart rate, and caloric expenditure. The measurement of VO_2 was averaged over 30 second intervals using a Truemax 2400 computerized metabolic system (ParvoMedics, Salt Lake City, UT, USA). Gases of known concentration were used to calibrate the metabolic cart immediately pre- and post-testing for all testing sessions. Heart rate was recorded using a Polar S610i monitor (Polar USA, Lake Success, NY, USA) and averaged over the same 30 second intervals as VO_2 . Caloric expenditure was calculated by first determining the respiratory exchange ratio (RER: the ratio of carbon dioxide produced to oxygen consumed measured by the metabolic system). The caloric equivalent of fuel utilized was then determined based on the RER (McArdle et al., 2001) and this value was multiplied by the VO_2 per minute of walking.

Statistical analysis: All statistical tests were performed using SPSS version 11.5.0 (SPSS Inc., Chicago, IL). The effects of the unstable test shoe on kinematics, kinetics, soft tissue vibration, and EMG were determined using repeated measures ANOVAs. Tukey post-hoc tests were used where appropriate with all tests considered significant at the $\alpha = 0.05$ level. For quiet standing, CoP and EMG variables of interest are presented as mean values over the 30 sec quiet standing period. For walking, kinematic, kinetic, and GRF variables, mean values are presented for the first and second half of stance with standard deviation. EMG during walking, total, low, and high frequency values are presented for the pre- and post-heel strike periods. Soft tissue vibration values are presented as the average frequency, maximum acceleration, and time to maximum acceleration after heel strike (Appendix A).

RESULTS

RESULTS DURING STANDING

Center of pressure during standing: Comparison MBT vs. control shoe: CoP excursion in the mediolateral and anteroposterior direction were significantly greater ($\Delta\text{CoP ML} = 9.13$ mm; $\Delta\text{CoP AP} = 16.67$ mm) when subjects stood as quietly as possible in the MBT shoe compared to the control shoe (Fig. 5; Table 4). Comparison between session 1 and session 2: There were no significant differences in CoP excursion between testing sessions for the control shoes or between testing sessions for the MBT shoes (Table 4).

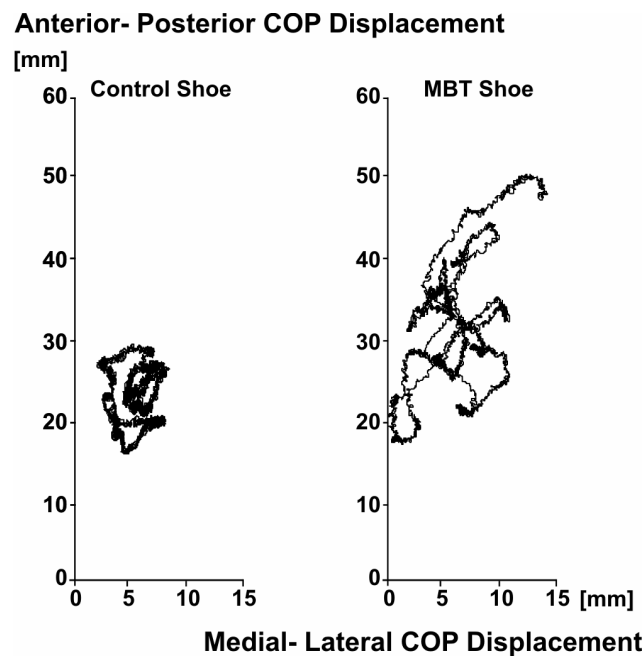


Fig. 5 Illustration of the difference in the movement of the center of pressure. The picture represents one representative trial for one subject of the center of pressure for the control shoe (left) and the MBT shoe (right) during quiet standing for 30 seconds.

Standing EMG: Comparison MBT vs. control shoe: When standing quietly in the MBT shoe, significantly greater tibialis anterior EMG intensity (low, high, and total; Fig. 6) and significantly greater gluteus medius EMG intensity (low and total: Fig. 7) was observed compared to standing in the control shoe (Table 5). Comparison between session 1 and session 2: All quantified muscles showed increased EMG activity compared to the control shoe condition (Table 5). Significantly greater gastrocnemius medialis EMG intensity (low, high, and total) and vastus medialis (low and total) was observed for the MBT shoe compared to the initial testing session in the MBT shoe (Table 5). The gluteus medius muscle exhibited significantly reduced EMG intensity (low, high, and total) when standing in the MBT shoe compared to the initial testing session (Table 5).

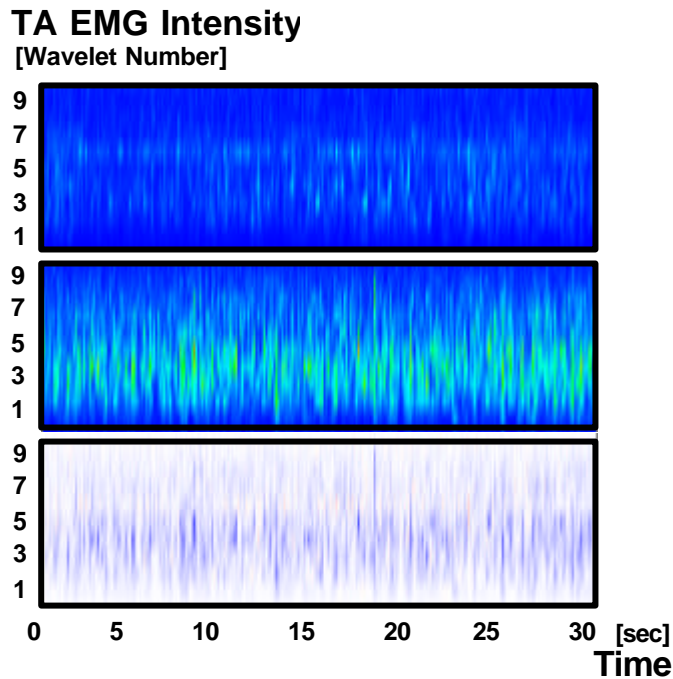


Fig. 6 Representative intensity pattern for the tibialis anterior muscle during quiet standing in the control shoe (top), MBT shoe (middle) and the difference between the two shoes (bottom). The color blue in the bottom figure indicates greater tibialis anterior EMG intensity for the MBT shoe.

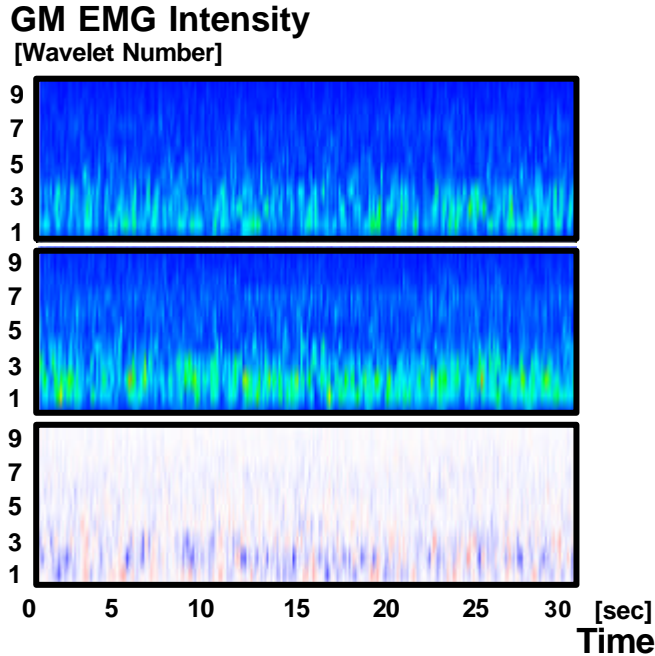


Fig. 7 Representative intensity pattern for the gluteus medius muscle during quiet standing in the control shoe (top), MBT shoe (middle) and the difference between the two shoes (bottom). The color blue in the bottom figure indicates greater gluteus medius EMG intensity for the MBT shoe. The color red indicates greater EMG activity for the control shoe.

RESULTS DURING WALKING

Kinematics: Comparison MBT vs. control shoe: The ankle joint was significantly more dorsiflexed during the first half of stance [$\Delta\text{Angle}(\text{dorsi}) = 10.13 \text{ deg}$] and remained in a more dorsiflexed position throughout the remainder of stance phase in the MBT shoe compared to the control shoe (Fig. 8; Table 6). No other differences in lower extremity joint kinematics were observed between the MBT and the control shoe condition (Table 6-8). Comparison between session 1 and session 2: The knee joint was significantly more adducted [$\Delta\text{Angle}(\text{add}) = 1.92 \text{ deg}$] for the second half of stance compared to the initial testing session in the MBT shoe (Fig. 9; Table 7). The hip joint was significantly more adducted [$\Delta\text{Angle}(\text{add}) = 3.40 \text{ deg}$] for the first and second half of stance compared to the initial testing session in the MBT shoe (Fig. 10; Table 8). There were no significant differences in joint kinematic variables of interest between testing sessions for the control shoe (Table 6-8).

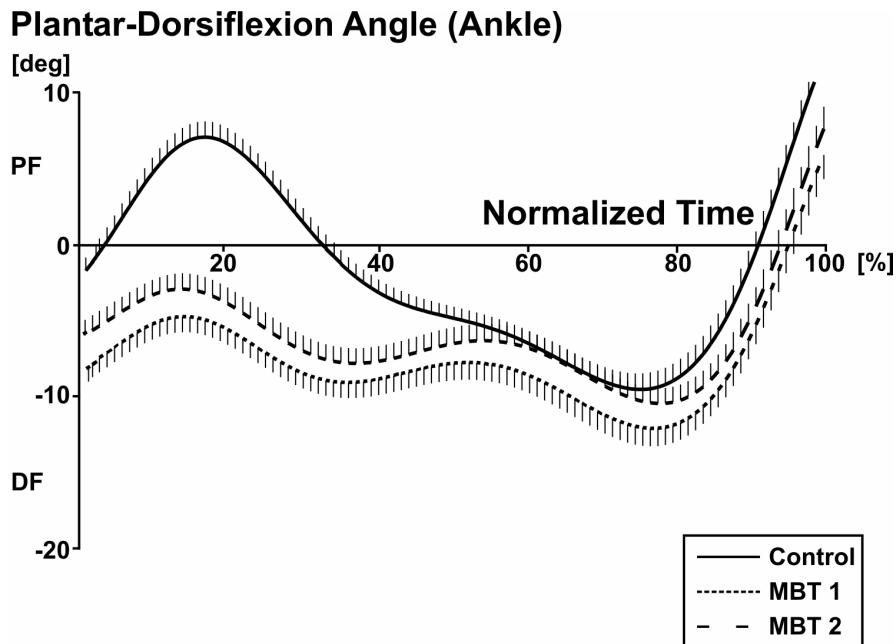


Fig. 8 Ankle plantar/dorsiflexion angle during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

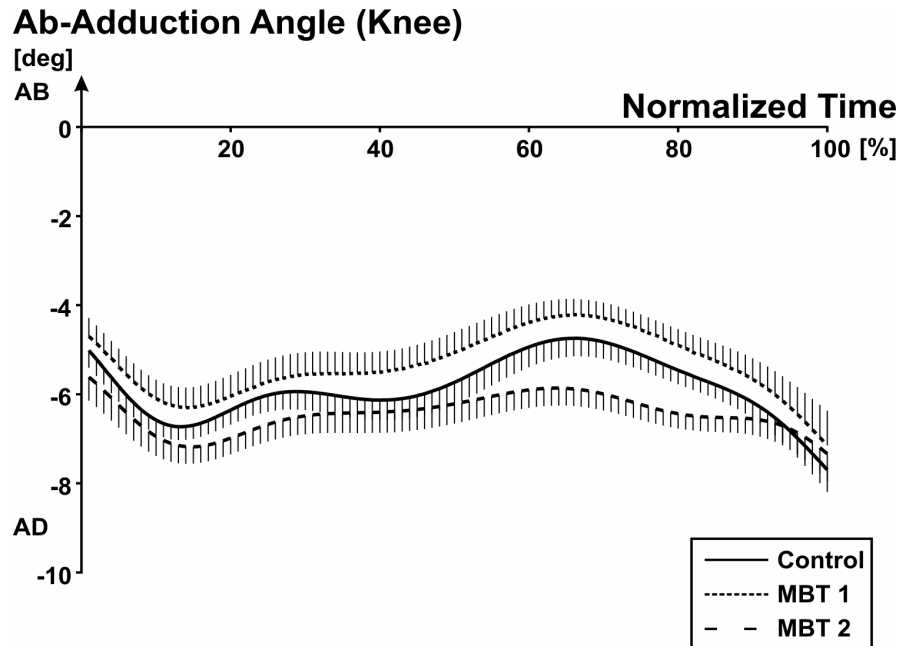


Fig. 9 Knee ab/adduction angle during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

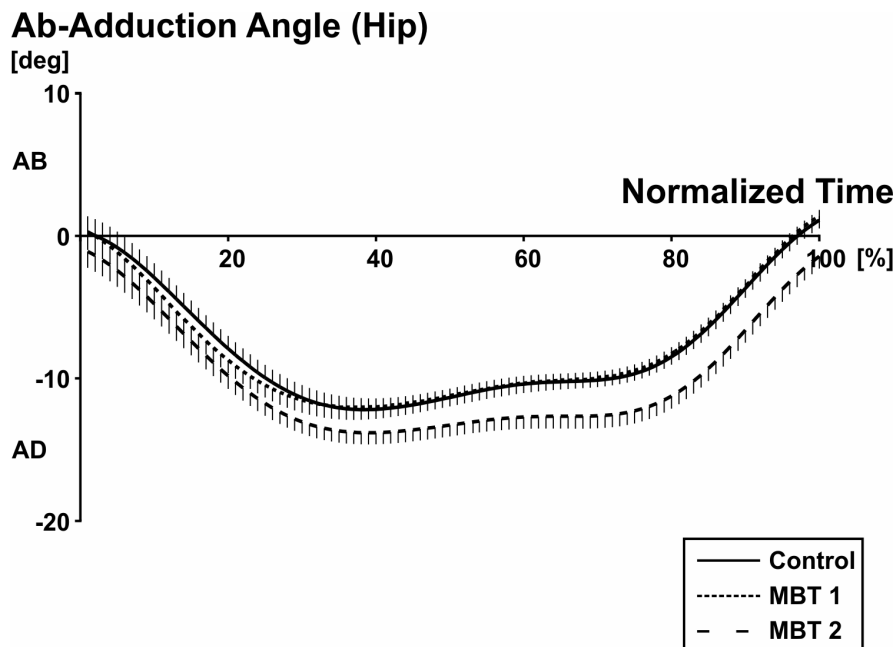


Fig. 10 Hip ab/adduction angle during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

Kinetics: Comparison MBT vs. control shoe: The ankle joint produced a sustained dorsiflexor moment and a significantly greater dorsiflexion rotational impulse [$\Delta I(\text{dorsi}) = 615.44 \text{ Nms}$] for the first half of stance when subjects walked in the MBT shoe compared to the control shoe (Fig. 11; Table 9). During the first half of stance, the ankle joint also produced a significantly greater inversion rotational impulse [$\Delta I(\text{invankle}) = 132.74 \text{ Nms}$] when walking in the MBT shoe compared to the control shoe (Fig. 12; Table 9). A significantly greater ankle adduction rotational impulse [$\Delta I(\text{addankle}) = 88.58 \text{ Nms}$] was observed during the second half of stance when walking in the MBT shoe compared to the control shoe (Fig. 13; Table 9). No other differences in lower extremity joint kinetics were observed between the MBT and the control shoe condition (Table 9-11). Comparison between session 1 and session 2: The ankle joint produced a significantly reduced dorsiflexion rotational impulse [$\Delta I(\text{dorsi}) = 249.04 \text{ Nms}$] and a significantly increased inversion rotational impulse [$\Delta I(\text{invankle}) = 93.95 \text{ Nms}$] for the first half of stance compared to the initial testing session in the MBT shoe (Fig. 11 & 12; Table 9). In addition, the hip produced a significantly greater adduction [$\Delta I(\text{addhip}) = 588.94 \text{ Nms}$; Fig. 14; Table 11] and external rotation rotational impulse [$\Delta I(\text{exrothip}) = 76.93 \text{ Nms}$; Fig. 15; Table 11] compared to the initial testing session in the MBT shoe. There were no other differences in joint kinetic variables of interest between testing sessions for the control shoe (Table 9-11).

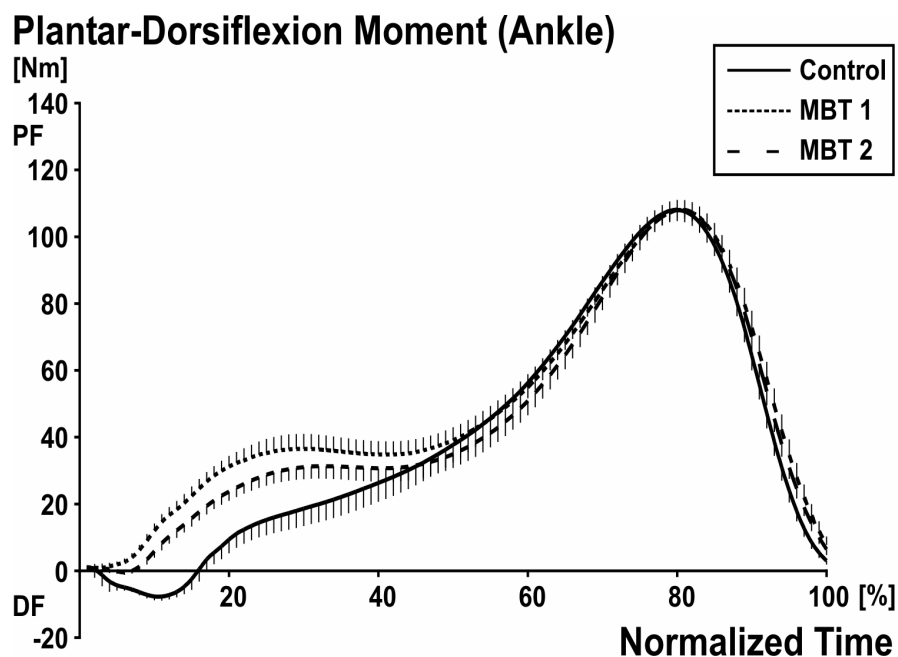


Fig. 11 Ankle plantar/dorsiflexion moment during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

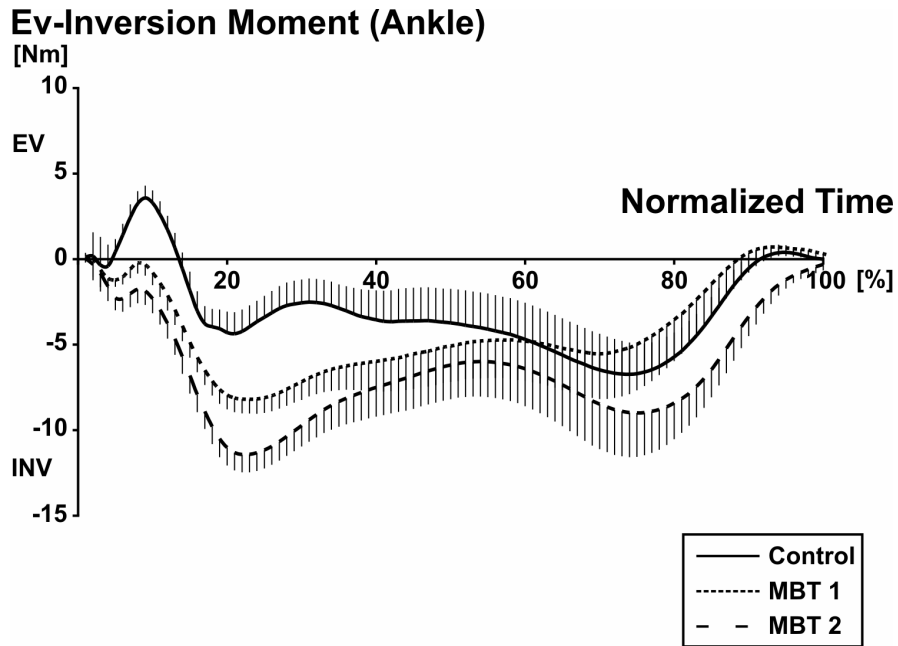


Fig. 12 Ankle inv/eversion moment during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

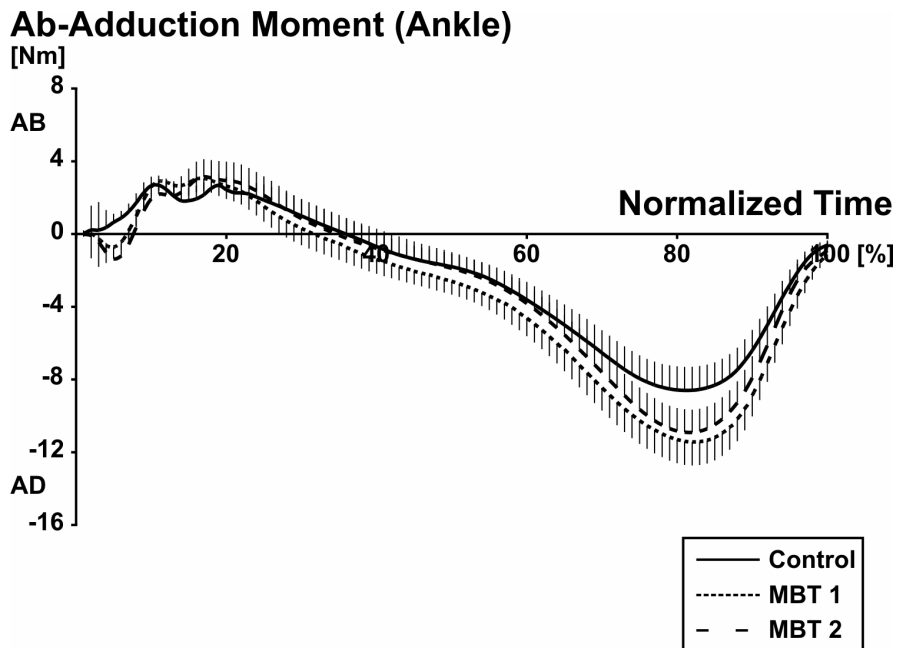


Fig. 13 Ankle ab/adduction moment during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

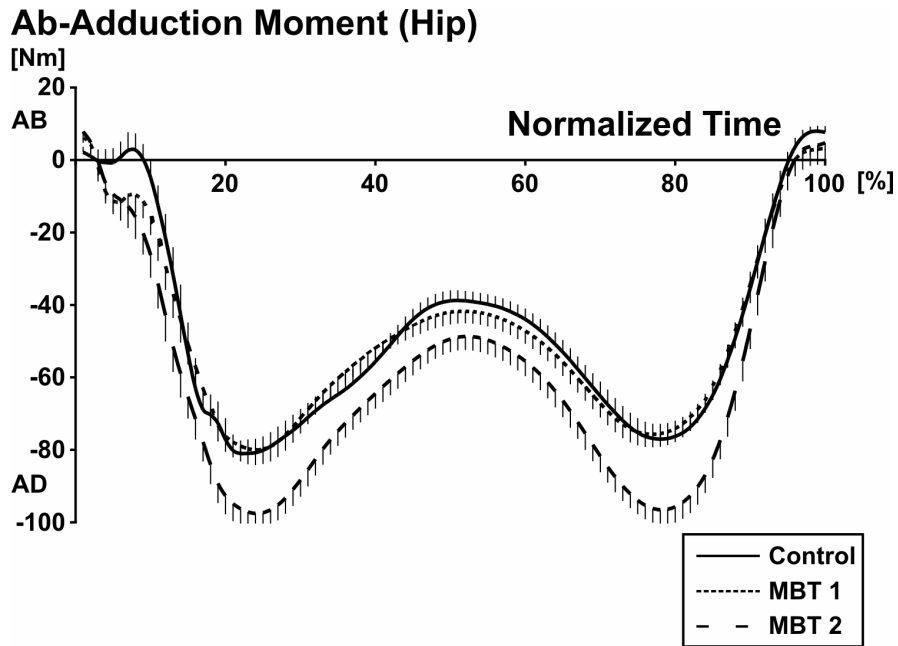


Fig. 14 Hip ab/adduction moment during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

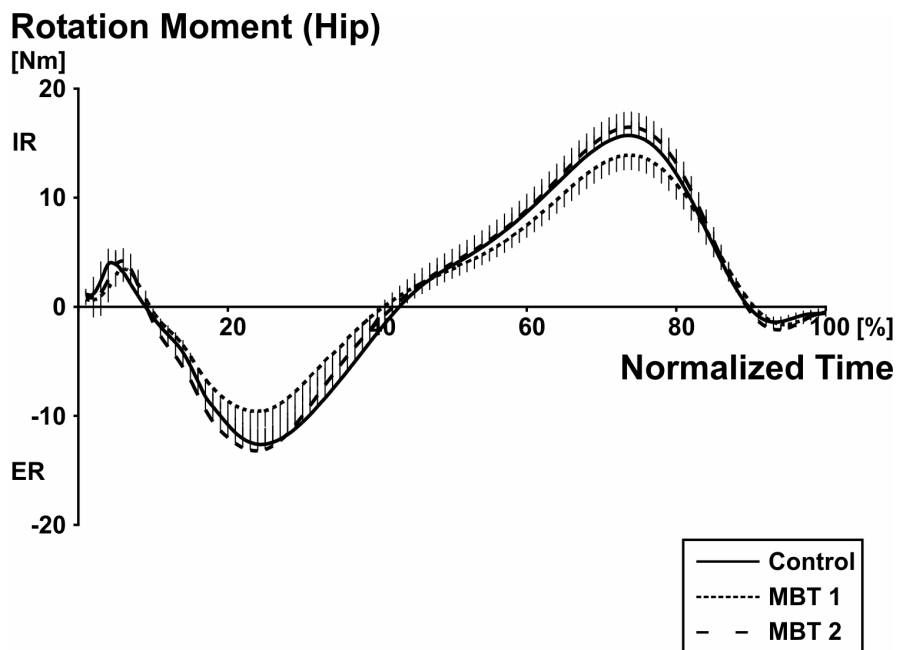


Fig. 15 Hip rotation moment during the stance phase of gait for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

GRF: Comparison MBT vs. control shoe: When walking in the MBT shoe, subjects demonstrated a significantly reduced peak lateral GRF [$\Delta N(\text{lat}) = 0.02 \text{ BW}$] during the first half of stance compared to the control shoe (Table 12). No other differences in GRF variables were observed between the MBT and the control shoe condition (Table 12). Comparison between session 1 and session 2: A significantly greater peak vertical GRF [$\Delta \text{GRF}(\text{lat}) = 0.18 \text{ BW}$] during the first half of stance was observed when subjects walked in the MBT shoe compared to the initial testing session (Table 12). There were no differences in GRF variables of interest between testing sessions for the control shoe (Table 12).

EMG: Comparison MBT vs. control shoe: The tibialis anterior muscle exhibited significantly reduced EMG intensity prior to (low, and total) and following (low, high, and total) heel strike compared to the control shoe (Fig. 16; Table 13-14). The biceps femoris muscle exhibited significantly reduced EMG intensity (low, high, and total) prior to heel strike compared to the control shoe (Fig. 17; Table 13-14). No other differences in muscle EMG were observed between the MBT and the control shoe condition (Table 13-14). Comparison between session 1 and session 2: The biceps femoris muscle exhibited significantly reduced EMG intensity (low and total) prior to heel strike compared to the initial testing session in the MBT shoe (Table 13-14).

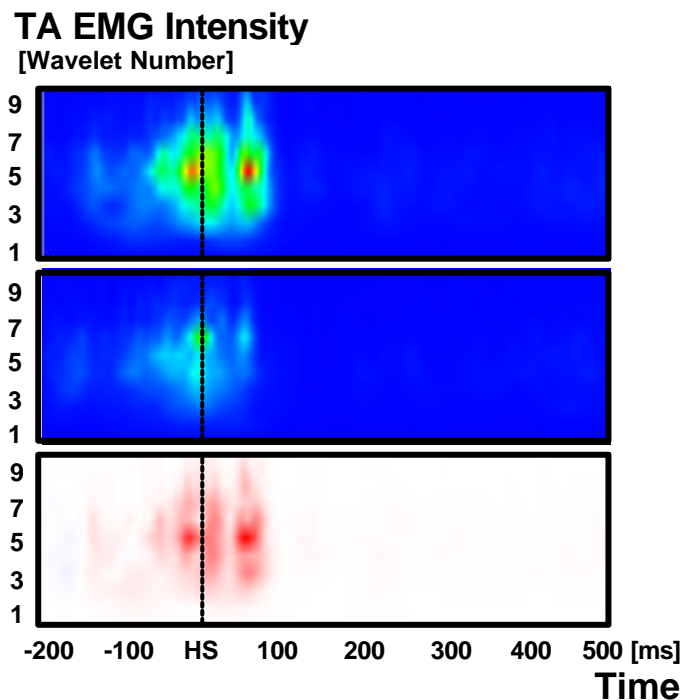


Fig. 16 Representative intensity pattern for one trial of one subject for the tibialis anterior muscle during locomotion in the control shoe (top), MBT shoe (middle) and the difference between the two shoes. The color red in the bottom figure indicates greater EMG activity for the control shoe.

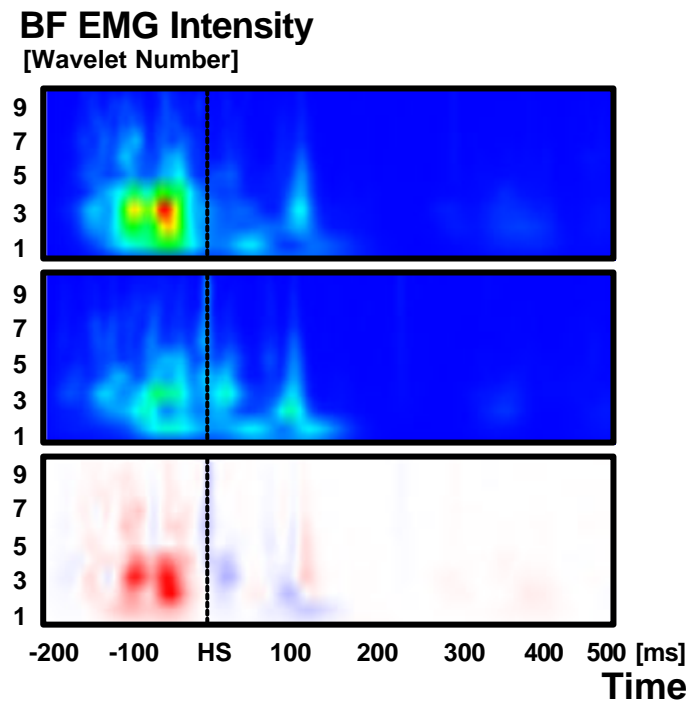


Fig. 17 Representative intensity pattern trial for one trial of one subject for the biceps femoris muscle during locomotion in the control shoe (top), MBT shoe (middle) and the difference between the two shoes. The color blue in the bottom figure indicates greater gluteus medius EMG intensity for the MBT shoe. The color red indicates greater EMG activity for the control shoe.

Vibration: Comparison MBT vs. control shoe: The hamstring soft tissue package exhibited a significantly reduced vibration frequency [Δf_c (ham) = 22.10 Hz] and a later time to peak acceleration [ΔT (ham) = 8.64 ms] compared to the control shoe (Fig. 18: Table 16). The gastrocnemius soft tissue package exhibited a significantly reduced vibration frequency (Δf_c (gas) = 26.70 Hz) compared to the control shoe (Fig. 19: Table 17). Comparison between session 1 and session 2: There were no differences in quadriceps, hamstring, or gastrocnemius soft tissue vibration or acceleration variables between testing sessions for the MBT shoe (Table 15-17). The hamstring and gastrocnemius soft tissue packages exhibited a significantly reduced vibration frequency [Δf_c (ham) = 22.10 Hz; Δf_c (gas) = 40.50 Hz] for the control shoe compared to the initial testing session (Table 16 & 17).

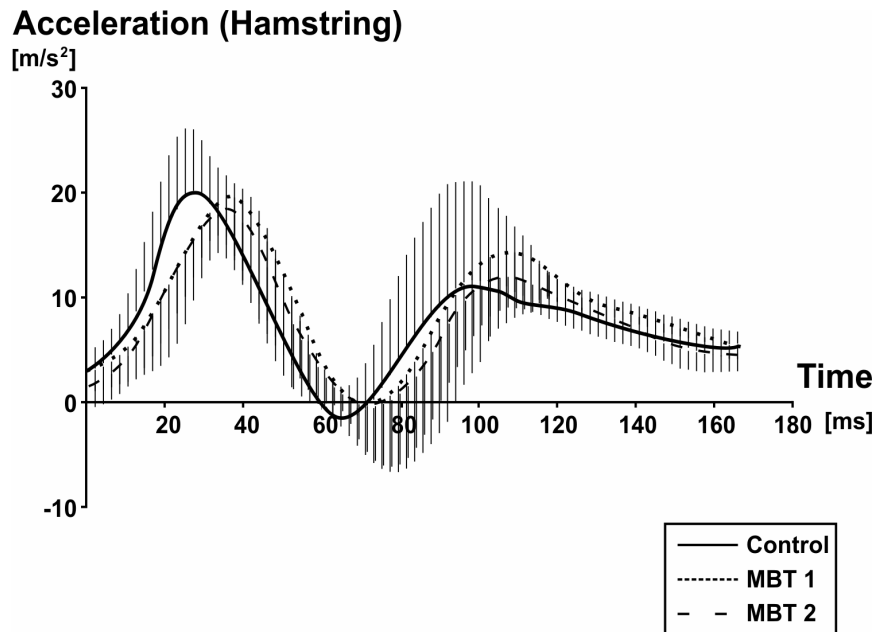


Fig. 18 Hamstring acceleration following heel strike for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

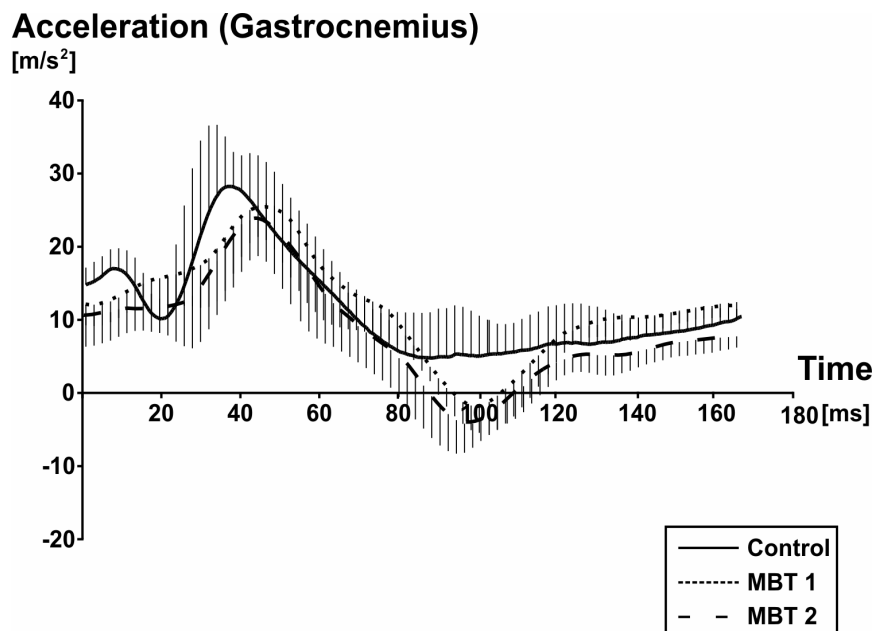


Fig. 19 Gastrocnemius acceleration following heel strike for the control shoe and MBT shoe during testing session 1 and the MBT shoe during the retest session. The standard error bars are depicted into one direction to allow for optimal reading of the graph.

Oxygen Consumption Testing: Comparison MBT vs. control shoe: When subjects walked in the MBT shoe, a significant increase in oxygen consumption ($\Delta L/\text{min}/\text{kg} = 2.5\%$) and caloric consumption ($\Delta \text{kcal}/\text{min} = 2.7\%$) was observed compared to the control shoe (Fig. 20; Table 18).

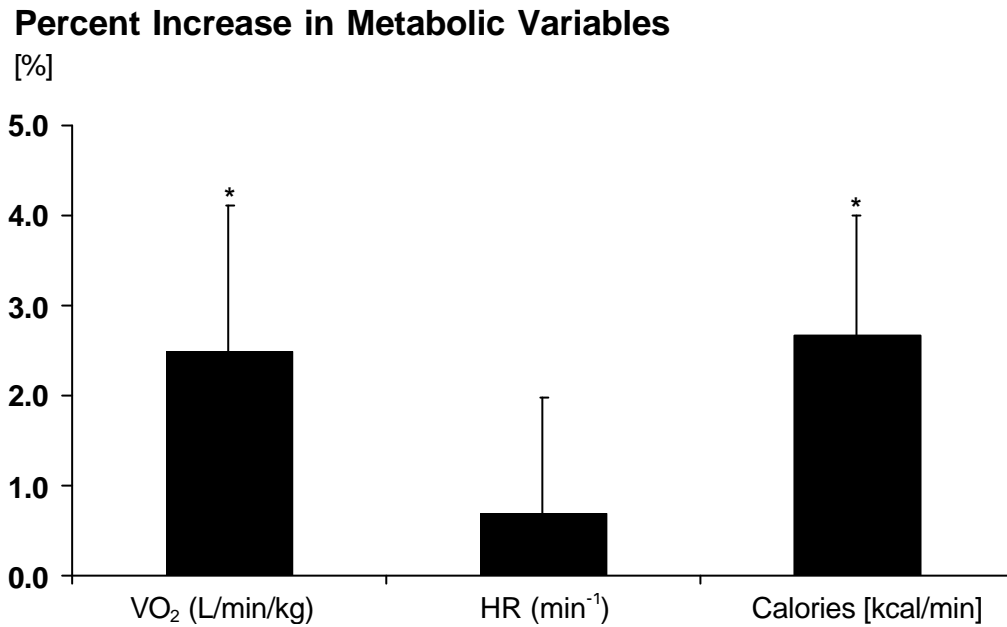


Fig. 20 Percent difference (mean and SD) from the control shoe in oxygen consumption, heart frequency and caloric demand when walking in the MBT shoe (positive values indicate increase in MBT shoe).

DISCUSSION

Eight subjects participated in the current study. According to an a priori power analysis based on pilot data, eight subjects were sufficient (Lieber, 1990). A coefficient of binomial distribution showed that for the 8 subjects used in the current investigation, 6 subjects would have to demonstrate a minimum 10% change from the control condition to gain statistical significance at a 95% confidence level. Therefore, the sample size was sufficient for the purposes of this study.

During quiet stance, stability is maintained by keeping the vertical projection of the body's centre of gravity within the area determined by the outside edges of the feet. Contractions of the muscles of the lower extremity keep the body balanced during this process, causing relative movement of various body segments. It is not surprising that the excursion of the center of pressure is larger for the relatively unstable MBT shoe than for the relatively stable control shoe. However, it is interesting that the muscle activity to provide this stability changed between the first and the second measurement.

It has been reported that subjects utilize an ankle strategy during low stability situations and then incorporate a hip strategy as stability requirements increase (Woollacott and Shumway-Cook, 2002). In the present study, when standing in the MBT shoe during the initial testing session, increased center of pressure excursion and increased ankle (tibialis anterior) and hip (gluteus medius) EMG activity were observed. These results suggest that the MBT shoe was more unstable compared to the control shoe and required both an ankle and hip strategy to stand as quietly as possible. However, during the retest session, a reduction in gluteus medius EMG activity was observed along with an increase in medial gastrocnemius, biceps femoris, and vastus medialis EMG activity concomitant with similar increases in center of pressure excursion compared to the control shoe. These results suggest that subjects no longer used a hip strategy and recruited other ankle and knee muscles to increase stability during quiet stance. These results suggest that the MBT shoe can be used effectively for stability training.

The lower extremity kinematics were similar for the MBT and the control shoe with one exception: the plantar-dorsiflexion angle showed substantial differences in the first part of ground contact for the MBT shoe compared to the control shoe. The difference in the plantar-dorsiflexion angle was primarily due to changes during the landing in the MBT shoe, which is a direct result of the MBT shoe construction. The landing in the control shoe occurs at the heel. The landing in the MBT shoe occurs more towards the midfoot with a foot position that is more dorsiflexed than in the control shoe. The fact that the lower extremity kinematics did not change with the exception of the plantar-dorsiflexion angle is in agreement with the concept that in normal situations, the joint movements are primarily determined by the "preferred movement path" in each joint (Nigg, 2001). However, the fact that the MBT construction did not affect the rest of the movement suggests that the "preferred movement path" could be maintained. The results of this study, however, do not allow one to conclude, which of the two tested shoe conditions allows a movement that is closer to the "preferred movement path".

The paradigm that the skeleton has a "preferred movement path" for a given movement task incorporates the idea that joint moments and/or muscle activity should be altered to maintain the "preferred movement path". If a shoe attempts to produce a movement that counteracts the "preferred movement path", muscle activity and/or joint moments must be increased. If the joint moments and/or the muscle activity are reduced in a shoe compared to another shoe, one must conclude that this first shoe approaches the "preferred movement path" of a joint more closely.

The results for the ankle joint show an increase in two of the three joint moments ($\int M dt$ for the first 50% of ground contact) and a decrease in the tibialis anterior EMG activity. Thus the indications for changes in the preferred movement path at the ankle joint with the MBT shoe are not conclusive. The results for the knee joint show a slight decrease of all three knee joint

moments. The results for the hip joint show a slight decrease of two of the three hip joint moments and the biceps femoris EMG activity showed a decrease. Thus, it can be concluded that the MBT shoe produced a movement for the knee and hip joint which was closer to the preferred movement path than the movement path produced by the control shoe. This corresponds to a reduction of knee and hip joint loading during walking.

In summary: Based on the results of the present study, it can be concluded that the MBT shoe produces a movement path, which is at least as close but probably closer to the preferred movement path for the knee and hip joint if compared to the control shoe. This conclusion can not be made for the ankle joint.

The concept of muscle tuning has been proposed recently (Nigg et al., 1995; Nigg, 2001; Nigg and Wakeling, 2001). It suggests that muscles are tuned to minimize soft tissue vibrations. This tuning occurs by keeping the vibration amplitude constant and changing the vibration frequencies if necessary; i.e. if the frequency of the input signal is close to the natural frequency of the soft tissue package (Wakeling et al., 2003). The results of this study showed that the vibration amplitudes were kept more or less constant and that the vibration frequencies were changed. Thus, the subjects using the MBT shoes tuned their muscles and some of the tuning was done significantly (hamstrings and gastrocnemius).

Walking in the MBT shoe required a significant 2.5% increase in oxygen consumption with an unchanged heart frequency. The muscle activity did not change significantly during walking, with the exception of a reduction in the tibialis anterior and biceps femoris activity. However, these reductions were small and should not affect the oxygen consumption results substantially. Therefore, the reason for this increase in oxygen consumption must be found somewhere else. The most important difference between the tested MBT and control shoe was in their mass. The mass difference was 292 g. A mass difference of 100 g corresponds to between 0.5 and 1.0 % in oxygen consumption. Thus, the difference in oxygen consumption is caused primarily by the mass difference. Subjects using the MBT shoe will use more energy, which may be associated with a training effect. However, if this effect is not desired, the shoe construction should be made lighter.

***In summary,
the results of this study showed that the MBT shoe***

- ⇒ ***acts as a muscle training device during standing and quasi-static activities and***
- ⇒ ***reduces knee and hip joint loading during walking.***

REFERENCES

1. Bahr, R, Lian, O, Bahr, I.A. A twofold reduction in the incidence of acute ankle sprains in volleyball after the introduction of an injury prevention program: a prospective cohort study. *Scand J Med Sci Sports*. 7(3):172-7, 1997.
2. Caraffa, A., Cerulli, G., Projetti, M., Aisa, G., Rizzo, A. Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc*. 4(1):19-21, 1996.
3. De Luca CJ: The use of surface electromyography in biomechanics. *J Appl Biomech* 13: 135-163, 1997.
4. Fuller, E., Schroeder, S., Edwards, J. Reduction of Peak Pressure on the Forefoot with a Rigid Rocker-Bottom Postoperative Shoe. *J Am Podiatr Med Assoc*. 91(10): 501-507, 2001.
5. Lieber RL. Statistical significance and statistical power in hypothesis testing. *J Orthop Res*. 8(2):304-9, 1990.
6. McArdle W.D., Katch, F.I., Katch, V.L. (2001). Exercise Physiology: Energy, Nutrition & Home Performance. Williams & Wilkins, NY, USA.
7. Mueller, M.J., Strube, M.J. Therapeutic footwear: enhanced function in people with diabetes and transmetatarsal amputation. *Arch Phys Med Rehabil*. 78(9):952-6, 1997.
8. Mueller, M.J., Strube, M.J., Allen, B.T. Therapeutic footwear can reduce plantar pressures in patients with diabetes and transmetatarsal amputation. *Diabetes Care*. 20(4):637-41, 1997.
9. Nigg, B.M., Cole, G.K. and Brüggemann, P. Impact forces during heel-toe running. *Journal of Applied Biomechanics*, 11(4): 407-432, 1995.
10. Nigg, B.M. The role of impact forces and foot pronation: a new paradigm. *Clin J Sports Med*, 11:2-9, 2001.
11. Nigg, B. M. and Wakeling, J. M. Impact forces and muscle tuning - a new paradigm. *Exercise and Sport Sciences Review*, 29(1), 37-41, 2001.
12. van Schie, C., Ulbrecht, J.S., Becker, M.B., Cavanagh, P.R. Design criteria for rigid rocker shoes. *Foot Ankle Int*. 21(10):833-44, 2000.
13. von Tscharner, V. Intensity analysis in time-frequency space of surface myoelectric signals by wavelets of specified resolution. *J. Electromyogr. Kinesiol*. 10, 433-445, 2000.
14. von Tscharner V., Goepfert B., Nigg B.M. Changes in EMG signals for the muscle tibialis anterior while running barefoot or with shoes resolved by non-linearly scaled wavelets. *J Biomech* 36(8):1169-76, 2003.
15. Waddington, G., Seward, H., Wrigley, T., Lacey, N., Adams, R. Comparing wobble board and jump-landing training effects on knee and ankle movement discrimination. *J Sci Med Sport*. 3(4):449-59, 2000.
16. Waddington, G.S., Adams, R.D. The effect of a 5-week wobble-board exercise intervention on ability to discriminate different degrees of ankle inversion, barefoot and wearing shoes: a study in healthy elderly. *J Am Geriatr Soc*. 52(4):573-6, 2004.

17. Wakeling, J.M., Pascual, S.A., Nigg, B.M., von Tscherner, V. Surface EMG shows distinct populations of muscle activity when measured during sustained sub-maximal exercise. *Eur J App Phys*, 86, 40-4, 2001.
18. Wakeling JM, Pascual SA, Nigg BM. Altering muscle activity in the lower extremities by running with different shoes. *Med Sci Sports Exerc*. 34(9):1529-32, 2002.
19. Wakeling, J.M., Liphardt, A, Nigg, B.M. Muscle activity reduces soft-tissue resonance at heel-strike during walking. *J Biomech*. 36: 1761-69, 2003.
20. Wedderkopp, N., Kalltoft, M., Lundgaard, B., Rosendahl, M., Froberg, K. Prevention of injuries in young female players in European team handball. A prospective intervention study. *Scand J Med Sci Sports*. 9(1):41-7, 1999.
21. Wester, J.U., Jespersen, S.M., Nielsen, K.D., Neumann, L. Wobble board training after partial sprains of the lateral ligaments of the ankle: a prospective randomized study. *J Orthop Sports Phys Ther*. 23(5):332-6, 1996.
22. Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture*. 16(1):1-14, 2002.

APPENDIX A

TABLES

TABLE 4: Center of pressure excursion values (mean and SD) for the control (CON) and MBT shoe during quiet standing for the initial and the retest testing session.

		ML (mm)	AP (mm)
Session 1	CON	6.96 (1.42)	12.82 (4.98)
	MBT	16.59* (5.34)	29.50* (15.03)
Retest	CON	6.09 (1.91)	18.55 (4.59)
	MBT	13.03* (4.21)	29.43* (6.61)

Note: '*' indicates MBT significantly different from control

TABLE 5: Lower extremity muscle EMG intensity values (mean and SD) for the control (CON) and MBT shoe during quiet standing for the initial and the retest testing session. Values are the normalized to the average total intensity of the control shoe condition.

		CON Low	MBT Low	CON High	MBT High	CON Total	MBT Total
Session 1	TA	0.28 (0.07)	0.63* (0.30)	0.34 (0.13)	0.67* (0.34)	1.00	1.79* (0.79)
	GAS	0.32 (0.08)	0.28 (0.13)	0.27 (0.06)	0.25 (0.16)	1.00	0.91 (0.43)
	VM	0.32 (0.16)	0.68 (0.38)	0.34 (0.24)	0.50 (0.33)	1.00	1.10 (0.34)
	BF	0.33 (0.08)	0.23 (0.14)	0.29 (0.11)	0.38 (0.25)	1.00	0.97 (0.60)
	GM	0.34 (0.16)	0.60* (0.33)	0.29 (0.27)	0.50 (0.26)	1.00	1.51* (0.64)
Retest	TA	0.28 (0.07)	0.51* (0.23)	0.33 (0.08)	0.55* (0.28)	1.00	1.70* (0.85)
	GAS	0.28 (0.07)	0.96† (0.60)	0.30 (0.10)	0.89† (0.52)	1.00	1.38† (0.41)
	VM	0.30 (0.14)	0.89† (0.57)	0.34 (0.18)	0.40 (0.19)	1.00	1.37† (0.46)
	BF	0.33 (0.06)	0.35 (0.23)	0.28 (0.11)	0.33 (0.19)	1.00	1.11 (0.69)
	GM	0.39 (0.15)	0.50† (0.22)	0.22 (0.17)	0.39† (0.16)	1.00	1.28† (0.78)

Note: '*' indicates MBT significantly different from corresponding control value

'†' indicates MBT significantly different from corresponding MBT session 1 value

TABLE 6: Ankle joint peak angle values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Ab/Adduction (deg)		In/Eversion (deg)		Dorsi/plantarflexion (deg)	
		1	2	1	2	1	2
		Session 1	CON	4.99 (2.11)	-4.56 (4.78)	2.42 (2.53)	3.81 (2.28)
	MBT	4.68 (4.77)	-4.76 (4.59)	3.29 (2.33)	2.69 (1.71)	-4.59* (4.21)	-11.40 (3.84)
Retest	CON	5.61 (3.92)	-4.32 (3.86)	1.62 (2.55)	2.86 (2.21)	5.55 (3.64)	-10.85 (2.52)
	MBT	4.58 (8.14)	-3.45 (5.93)	3.63 (5.22)	2.71 (5.00)	-4.23* (4.58)	-9.83 (4.48)

Note: '*' indicates MBT significantly different from control

TABLE 7: Knee joint peak angle values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Int/Ext Rotation (deg)		Ab/Adduction (deg)		Flex/extension (deg)	
		1	2	1	2	1	2
		Session 1	CON	-9.45 (4.50)	5.48 (4.36)	-6.37 (3.09)	-3.63 (3.31)
	MBT	-8.02 (5.31)	6.05 (4.62)	-6.09 (2.96)	-3.30 (3.68)	-15.91 (5.65)	0.86 (5.40)
Retest	CON	-11.54 (5.93)	5.99 (4.08)	-9.01 (3.95)	-6.45 (4.39)	-17.84 (5.10)	1.70 (6.71)
	MBT	-10.17 (4.51)	6.32 (4.17)	-7.73 (6.43)	-5.22† (6.23)	-17.66 (5.19)	1.91 (6.32)

Note: '†' indicates MBT significantly different from corresponding MBT session 1 value

TABLE 8: Hip joint peak angle values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Int/Ext Rotation (deg)		Ab/Adduction (deg)		Flex/extension (deg)	
		1	2	1	2	1	2
Session 1	CON	5.93 (4.03)	-10.99 (3.38)	-11.22 (4.00)	-10.15 (4.36)	-25.45 (4.42)	24.31 (3.34)
	MBT	5.18 (5.07)	-11.11 (3.41)	-11.00 (3.39)	-10.15 (3.49)	-24.45 (3.97)	23.76 (2.37)
Retest	CON	5.12 (3.81)	-13.74 (2.99)	-14.04 (4.23)	-13.01 (3.39)	-28.88 (3.38)	26.09 (3.92)
	MBT	6.15 (6.32)	-12.99 (3.77)	-14.32† (4.45)	-13.55† (3.42)	-27.06 (2.14)	26.62 (3.53)

Note: '†' indicates MBT significantly different from corresponding MBT session 1 value

TABLE 9: Ankle joint rotational impulse values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Ab/Adduction (Nms)		In/Eversion (Nms)		Dorsi/plantarflexion (Nms)	
		1	2	1	2	1	2
Session 1	CON	52.60 (16.35)	-262.20 (220.34)	-125.79 (71.62)	-189.61 (161.94)	766.50 (402.68)	3321.17 (835.45)
	MBT	48.11 (16.31)	-350.78* (147.70)	-258.53* (94.70)	-156.22 (165.21)	1381.94* (553.11)	3408.74 (693.19)
Retest	CON	30.68 (9.31)	-351.78 (215.79)	-96.44 (60.79)	-141.63 (154.54)	913.40 (478.03)	3490.97 (774.05)
	MBT	50.97 (25.71)	-314.07 (331.59)	-352.48*† (133.63)	-290.66*† (268.70)	1132.90*† (4196.65)	3295.13 (671.95)

Note: '*' indicates MBT significantly different from control
 '†' indicates MBT significantly different from MBT session 1 value

TABLE 10: Knee joint rotational impulse values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Int/Ext Rotation (Nms)		Ab/Adduction (Nms)		Flex/extension (Nms)	
		1	2	1	2	1	2
		Session 1	CON	41.49 (6.36)	-368.19 (150.68)	-806.50 (446.36)	-744.78 (456.00)
	MBT	32.84 (33.17)	-347.02 (132.61)	-713.44 (434.52)	-813.76 (489.22)	318.13 (330.80)	-795.25 (434.13)
Retest	CON	32.09 (6.82)	-371.05 (143.69)	-765.78 (434.74)	-676.05 (357.52)	578.41 (399.97)	-898.65 (372.47)
	MBT	37.57 (31.03)	-383.17 (169.98)	-968.72 (623.11)	-952.72 (544.49)	432.12 (345.97)	-762.15 (453.14)

TABLE 11: Hip joint rotational impulse values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Int/Ext Rotation (Nms)		Ab/Adduction (Nms)		Flex/extension (Nms)	
		1	2	1	2	1	2
		Session 1	CON	-247.45 (160.44)	378.55 (124.58)	-2423.37 (758.47)	-2320.96 (759.63)
	MBT	-173.03 (123.65)	341.50 (101.98)	-2471.28 (763.08)	-2353.10 (588.58)	1674.88 (496.82)	-1779.91 (552.75)
Retest	CON	-250.80 (127.24)	423.25 (137.92)	-2659.74 (569.12)	-2525.52 (686.32)	1756.04 (659.91)	-1725.67 (449.21)
	MBT	-249.95† (166.73)	397.19 (216.88)	-3060.23† (672.72)	-2934.89† (514.34)	1823.05 (594.64)	-1913.76 (592.90)

Note: '†' indicates MBT significantly different from MBT session 1 value

TABLE 12: Ground reaction force values (mean and SD) during locomotion for the control (CON) and MBT shoe during the first (1) and second (2) half of stance for the initial and the retest testing session.

		Mediolateral (BW)		Anteroposterior (BW)		Vertical (BW)	
		1	2	1	2	1	2
Session 1	CON	0.06 (0.02)	-0.05 (0.01)	0.25 (0.04)	-0.26 (0.03)	1.14 (0.09)	1.12 (0.08)
	MBT	0.04* (0.01)	-0.05 (0.01)	0.27 (0.04)	-0.23 (0.03)	1.14 (0.09)	1.10 (0.08)
Retest	CON	0.06 (0.02)	-0.06 (0.01)	0.28 (0.03)	-0.28 (0.03)	1.28 (0.08)	1.28 (0.07)
	MBT	0.04* (0.02)	-0.06 (0.01)	0.30 (0.04)	-0.27 (0.03)	1.31† (0.09)	1.28 (0.08)

Note: '*' indicates MBT significantly different from control

'†' indicates MBT significantly different from MBT session 1 value

TABLE 13: Lower extremity muscle EMG intensity values (mean and SD) for the control (CON) and MBT shoe during locomotion 100 ms prior to heel strike for the initial and the retest testing session. Values are the normalized to the peak total intensity of the control shoe condition.

		CON Low (%)	MBT Low (%)	CON High (%)	MBT High (%)	CON Total (%)	MBT Total (%)
Session 1	TA	0.11 (0.03)	0.06* (0.02)	0.11 (0.06)	0.09 (0.09)	0.42 (0.14)	0.28* (0.18)
	GAS	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.02)	0.01 (0.02)
	VM	0.12 (0.09)	0.13 (0.13)	0.02 (0.01)	0.03 (0.02)	0.24 (0.15)	0.26 (0.21)
	BF	0.21 (0.07)	0.11* (0.06)	0.06 (0.03)	0.03* (0.02)	0.54 (0.15)	0.27* (0.11)
	GM	0.05 (0.05)	0.05 (0.04)	0.01 (0.01)	0.01 (0.01)	0.09 (0.06)	0.12 (0.11)
Retest	TA	0.15 (0.04)	0.10* (0.03)	0.13 (0.08)	0.09* (0.06)	0.50 (0.14)	0.35* (0.13)
	GAS	0.01 (0.01)	0.03 (0.03)	0.01 (0.01)	0.01 (0.01)	0.03 (0.02)	0.03 (0.02)
	VM	0.08 (0.06)	0.08 (0.06)	0.01 (0.01)	0.01 (0.01)	0.17 (0.11)	0.17 (0.12)
	BF	0.14 (0.09)	0.12† (0.08)	0.07 (0.05)	0.07 (0.07)	0.35 (0.21)	0.35† (0.22)
	GM	0.07 (0.06)	0.08 (0.06)	0.01 (0.01)	0.01 (0.01)	0.18 (0.12)	0.22 (0.12)

Note: '*' indicates MBT significantly different from corresponding control value

'†' indicates MBT significantly different from MBT session 1 value

TABLE 14: Lower extremity muscle EMG intensity values (mean and SD) for the control (CON) and MBT shoe during locomotion 100 ms after to heel strike for the initial and the retest testing session. Values are the normalized to the peak total intensity of the control shoe condition.

		CON	MBT	CON	MBT	CON	MBT
		Low (%)	Low (%)	High (%)	High (%)	Total (%)	Total (%)
Session 1	TA	0.13 (0.07)	0.06* (0.03)	0.14 (0.07)	0.06* (0.04)	0.50 (0.11)	0.21* (0.09)
	GAS	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.02 (0.02)	0.02 (0.03)
	VM	0.26 (0.11)	0.30 (0.22)	0.07 (0.05)	0.07 (0.05)	0.57 (0.23)	0.63 (0.32)
	BF	0.15 (0.15)	0.13 (0.09)	0.02 (0.02)	0.02 (0.03)	0.33 (0.27)	0.36 (0.27)
	GM	0.23 (0.11)	0.24 (0.20)	0.02 (0.01)	0.03 (0.02)	0.51 (0.23)	0.50 (0.26)
Retest	TA	0.15 (0.05)	0.08* (0.03)	0.12 (0.05)	0.07* (0.04)	0.51 (0.10)	0.28* (0.08)
	GAS	0.03 (0.03)	0.03 (0.02)	0.01 (0.01)	0.02 (0.03)	0.05 (0.03)	0.05 (0.02)
	VM	0.23 (0.09)	0.22 (0.08)	0.03 (0.01)	0.03 (0.01)	0.54 (0.10)	0.54 (0.23)
	BF	0.15 (0.08)	0.14 (0.11)	0.03 (0.05)	0.05 (0.06)	0.37 (0.17)	0.41 (0.31)
	GM	0.23 (0.12)	0.29 (0.27)	0.03 (0.01)	0.03 (0.02)	0.54 (0.19)	0.42 (0.20)

Note: '*' indicates MBT significantly different from corresponding control value

TABLE 15: Quadriceps soft tissue vibration values (mean and SD) for the control (CON) and MBT shoe during locomotion for the initial and the retest testing session.

		Quad		
		Max Acc (m·s ⁻²)	Time to Max (ms)	Frequency (Hz)
Session 1	CON	26.97 (16.59)	61.88 (8.09)	36.90 (7.38)
	MBT	28.51 (12.71)	64.32 (7.53)	46.50 (8.50)
Retest	CON	24.19 (13.04)	65.21 (8.90)	48.00 (5.97)
	MBT	26.81 (14.24)	62.72 (6.61)	45.00 (9.87)

TABLE 16: Hamstring soft tissue vibration values (mean and SD) for the control (CON) and MBT shoe during locomotion for the initial and the retest testing session.

		Hamstring		
		Max Acc (m·s ⁻²)	Time to Max (ms)	Frequency (Hz)
Session 1	CON	23.22 (16.98)	29.42 (5.24)	68.60 (11.78)
	MBT	21.69 (18.49)	38.06* (3.50)	46.50* (5.05)
Retest	CON	16.22 (4.60)	30.81 (6.66)	46.50† (4.32)
	MBT	17.20 (3.60)	36.45* (5.32)	51.40 (3.07)

Note: '*' indicates MBT significantly different from control

'†' indicates MBT significantly different from control session 1 value

TABLE 17: Gastrocnemius soft tissue vibration values (mean and SD) for the control (CON) and MBT shoe during locomotion for the initial and the retest testing session.

		Gastrocnemius		
		Max Acc (m·s ⁻²)	Time to Max (ms)	Frequency (Hz)
Session 1	CON	23.51 (12.71)	37.52 (5.53)	80.00 (9.67)
	MBT	20.32 (8.86)	43.38 (10.38)	53.30* (9.71)
Retest	CON	17.89 (8.35)	40.40 (9.62)	39.50† (11.23)
	MBT	18.22 (5.45)	42.46 (7.63)	65.60 (10.17)

Note: '*' indicates MBT significantly different from control

'†' indicates MBT significantly different from control session 1 value

TABLE 18: Metabolic values (mean and SD) for the control (CON) and MBT shoe during locomotion for the initial and the retest testing session.

	VO ₂ (L/min/kg)	HR (b/min)	Calories (kcal/min)
CON	12.87 0.95	93.60 12.70	4.71 0.07
MBT	13.19* 0.83	93.20 13.24	4.84* 0.06

Note: '*' indicates MBT significantly different from control