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OXYGEN CONSUMPTION WHILE STANDING WITH UNSTABLE SHOE DESIGN

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ABSTRACT
Purpose. This study explored the effects of unstable shoe design on oxygen consumption. **Methods.** Oxygen consumption (VO_2) and heart rate (HR) were measured in 16 individuals while barefoot, wearing unstable shoes (Masai Barefoot Technology) and wearing conventional sport shoes while standing and walking on a treadmill and for 5 individuals while walking around a 400 m track. **Results.** When wearing the MBT shoes, a significant ($p < 0.01$) increase of 9.3 ± 5.2% in VO_2 was measured while standing quietly for 6 min. No differences in VO_2 and HR were observed between the MBT shoes or weight-adjusted conventional shoes (to match the weight of the MBT shoes) while walking on a treadmill. However, significant increases ($p < 0.01$) in VO_2 (4.4 ± 8.2%) and HR (3.6 ± 7.3%) were observed for the MBT shoes compared with being barefoot. No significant differences in VO_2 and HR were recorded while walking around a 400 m track either with MBT shoes, weight-adjusted conventional shoes or barefoot. Nonetheless, a comparison of the MBT shoes with barefoot revealed a tendency for VO_2 to be higher when wearing the MBT shoes (7.1 ± 6.5%, $p < 0.1$) although HR was not significantly affected. **Conclusions.** The unstable shoe design predominantly effects oxygen consumption while standing, most likely due to increased muscle activity of the lower extremities.

Key words: oxygen consumption, heart rate, unstable shoe construction, MBT (Masai Barefoot Technology)

Introduction

Shoes affect both standing and walking [1]. They influence gait, muscle activity, balance and the pressure distribution in the sole of the foot [2–5]. The Masai Barefoot Technology (MBT) shoe has been described as a training and therapeutic shoe that can be worn during the normal course of the day [6]. The unstable nature of these shoes (Figure 1) is credited with stimulating musculature and sensorimotor activity in the lower extremities. Built into the heel is a rounded sole, the so-called Masai Sensor. It introduces a destabilising effect in the anterio-posterior direction, i.e. the frontal plane, causing a rocking motion as it is very soft and thus responsible for the instability. Additional muscular reflexes and activity compensate for this instability. According to the manufacturer, whole body posture is affected as a consequence of this design.

Several research institutes (University of Calgary, Universität Freiburg im Breisgau, Universität Salzburg) have already performed a wide gamut of studies examining the effects of such unstable shoe construction on physiological and biomechanical responses. Nigg et al. [7] examined the effects of varied shoe constructions on kinetic and kinematic variables and muscle activity using EMG while standing and walking. They found that muscle activity was elevated in all muscles in the distal portion of the lower extremities, however, this result was significant only for the musculus tibialis anterior. Romkes [6] examined differences in muscle activity patterns while walking with conventional and MBT shoes. This study found changes in muscle activity patterns in the talocalcaneal joint, in particular for the musculus gastrocnemius and musculus tibialis anterior. Analysing the ability to control balance while wearing these shoes, Romkes [5] examined the time course of the foot sole's pressure points. While standing, significant differences were observed in the ability to control balance in the anterio-posterior as well as the medio-lateral directions while wearing the MBT shoes compared with being barefoot.

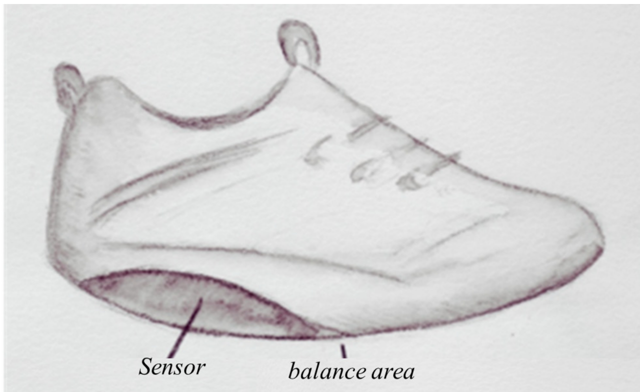

Figure 1. Construction of MBT shoe with the characteristic rounded sole, the soft sensor and harder area for balancing

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We are unaware of any study that has looked at differences in oxygen consumption between conventional and MBT shoes during routine everyday movements such as standing and walking. Therefore, our study was undertaken in an effort to gain better insight into energy expenditure while wearing such an unstable shoe design and formulated the following hypotheses:

Increased muscle activity caused by wearing MBT shoes should lead to an increase in metabolism and heart rate when compared with conventional shoes while standing.

Increased muscle activity caused by wearing MBT shoes should lead to an increase in metabolism and heart rate when compared with conventional shoes while walking.

Material and methods

The study hypotheses were tested in three experiments: 1) laboratory conditions while standing, 2) laboratory conditions while walking on a treadmill and 3) field conditions while walking around a 400 m running track (Figure 2) when wearing different types of shoe designs (MBT shoe, conventional shoe, weight-adjusted conventional shoe) as well as without footwear (barefoot).

All participants were healthy with an average level of fitness. Ethical permission was sought and granted by the Bernese Ethics Commission. For measurements while standing, six female and ten male participants were recruited with mean age, height, mass values of 29.8 ± 6.8 years, 178 ± 7 cm and 72.3 ± 11.4 kg, respectively. Measurements while walking involved five female and eleven male participants with mean age, height and mass values of 32.8 ± 7.5 years, 173 ± 7 cm and 66.4 ± 12.4 kg, respectively. Field measurements while walking involved only five male participants with mean age, height and mass values of 29.7 ± 3.1 years, 175 ± 4 cm and 69.4 ± 8.4 kg, respectively.

Laboratory measurements taken while standing included oxygen consumption (Oxycon Alpha metabolic cart, Jäger, Germany) and heart rate (RS300X, Polar, Switzerland) Participants stood quietly for 6 min in a relaxed position. Participants were instructed to stand on two marks on the floor placed 25 cm apart with feet parallel to each other. They were told to look straight ahead and keep their arms to their sides. Measurements were made while wearing the MBT shoe and conventional shoes. The order in which the shoes were worn was randomised. When wearing the MBT shoes participants were instructed to balance their weight on the rounded portion of the sole.

Laboratory measurements while walking were performed on a PPS Sport treadmill (Woodway, Germany) at different speeds and inclines. Oxygen concentration and heart rate were measured continuously, with the same equipment as described above, and included the warm-up. The order of phases 1–4 was randomised:

Warm-up: 5 km · h^{-1} at no incline for 3 min
Phase 1: 5 km · h^{-1} at no incline for 6 min
Phase 2: 4 km · h^{-1} at 10% positive incline for 6 min
Phase 3: 4 km · h^{-1} at 10% negative incline for 6 min
Phase 4: 7 km · h^{-1} at no incline for 6 min

The walking phases were performed wearing the MBT and conventional shoes. In this test, the weight of the conventional shoes was adjusted to equal that of the MBT shoes (± 5 g) using metal discs fixed with tape (Figure 3). The weights were fixed close to the ankle to optimise inertia and torque and allow for maximal freedom of movement. Phase 1 was also performed barefoot by all participants.

Field measurements were performed on a 400 m running track (Figure 2). Analogous to Phase 1 in the walking test, oxygen consumption (K4b2 gas analysis system, Cosmed, Italy) and heart rate (RS300X, Polar, Switzerland) were measured during a 6 min walk at 5 km · h^{-1}.

Figure 2. Field measurements of oxygen consumption and heart rate while walking in MBT, weight-adjusted and non-weight-adjusted conventional shoes as well as barefoot on the 400 m running track

Figure 3. Weight-adjustment of conventional shoes

This was performed by all participants using the MBT shoe, the weight-adjusted conventional shoe (Figure 3) and while barefoot, all in randomised order. To ensure correct walking speed, the running track was marked every 10 m and the participants were provided with an acoustic signal every 10 m to pace themselves. Their speed was subsequently verified using a GPS device. Measurement of oxygen consumption and heart rate was continuous [8].

Analysis of data was conducted using 30 s averages of oxygen consumption and heart rate. The last 2 min of each measurement phase was used for statistical analysis to ensure steady-state had been reached [9, 10]. To avoid calibration mistakes, all measurements were taken without interruption including when participants changed shoes.

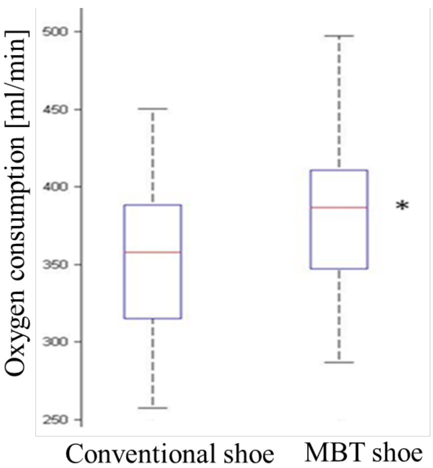
All statistical analyses were performed using Mathematica software (Wolfram Research, USA). The percent difference in oxygen consumption and heart rate were compared between shoe types and barefoot, when applicable, using paired two-way *t* tests assuming homoscedasticity. For comparisons of the MBT shoe, conventional shoe and barefoot, an analysis of variance (ANOVA) was performed and with post-hoc Scheffé tests. As mentioned, the last 2 min of each measurement phase was used for comparison. Gaussian distribution of the data was checked using the Jarque–Bera test [11]. Statistical significance was accepted at $p < 0.05$, while values between 0.05 and 0.1 were considered to indicate a tendency.

Results

The first hypothesis, assessed in laboratory conditions while standing, was confirmed (Table 1). An increase in the oxygen consumption rate (Figure 4) in the order of 9.3 ± 5.2% ($p < 0.01$) was recorded while standing in the MBT shoes compared with conventional shoes. Heart rate (Figure 5) was not significantly different ($p = 0.25$).

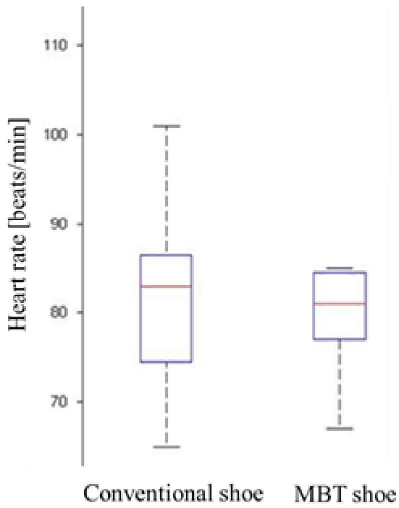
The second hypothesis, examined in laboratory conditions while walking, was not confirmed. No significant differences were observed in ANOVA while walking with the MBT, conventional shoes or barefoot (Table 1).

Similarly, the second hypothesis when tested in field conditions was also not confirmed. No significant differences were noted while walking with the MBT or weight-adjusted conventional shoes (Table 2). However, oxygen consumption tended to be 7.1 ± 6.5% ($p < 0.1$) higher when wearing the non-weight-adjusted conventional shoes and 5.9 ± 5.6% ($p < 0.1$) when barefoot. Heart



Significant difference indicated by asterisk ($p < 0.01$), line in box indicates median

Figure 4. Oxygen consumption while standing in conventional (354 ± 55 mL $O_2 \cdot min^{-1}$) and MBT (387 ± 64 mL $O_2 \cdot min^{-1}$) shoes ($n = 16$)



No significant difference ($p = 0.25$), line in box indicates median

Figure 5. Heart rate while standing in conventional (81 ± 11 beats $\cdot min^{-1}$) and MBT (84 ± 14 beats $\cdot min^{-1}$) shoes ($n = 16$)

Table 1. Mean values (± *SD*) of oxygen consumption (VO_2) and heart rate (HR) in laboratory conditions while walking in MBT shoes, conventional sports shoes and barefoot 5 km · h^{-1} at zero incline (Phase 1), 4 km · h^{-1} at 10% positive incline (Phase 2), 4 km · h^{-1} at 10 % negative incline (Phase 3) and 7 km · h^{-1} at zero incline (Phase 4)

VO_2 (mL O_2 · min^{-1})	MBT (*n* = 16)	Conventional (*n* = 16)	Barefoot (*n* = 16)	ANOVA	
				F	*p*
Phase 1	1025 ± 221.6	1070 ± 156.1	981 ± 176.1	0.942	0.397
Phase 2	1497 ± 251.4	1512 ± 235.7		0.031	0.861
Phase 3	647 ± 113	650 ± 115.6		0.007	0.933
Phase 4	1695 ± 256.7	1640 ± 238.1		0.395	0.534

HR (beats · min^{-1})	MBT (*n* = 16)	Conventional (*n* = 16)	Barefoot (*n* = 16)	ANOVA	
				F	*p*
Phase 1	99 ± 10.3	99 ± 12.7	98.1 ± 176.1	0.544	0.584
Phase 2	114 ± 15.2	113 ± 14.1		0.041	0.84
Phase 3	88 ± 14.9	86 ± 10.6		0.182	0.673
Phase 4	124 ± 18	124 ± 19.9		0.005	0.947

Scheffé Phase 1 VO_2		*p*
MBT	Conventional	0.785
MBT	Barefoot	0.797
Conventional	Barefoot	0.397

Scheffé Phase 1 HR		*p*
MBT	Conventional	0.99
MBT	Barefoot	0.713
Conventional	Barefoot	0.631

Table 2. Mean values (± *SD*) of oxygen consumption (VO_2) and heart rate (HR) in field conditions while walking in MBT shoes, conventional sports shoes and barefoot on a 400 m running track at 5 km · h^{-1}

VO_2 (mL O_2 · min^{-1}) *n* = 5	Test Shoe	Conventional	Barefoot
	881 ± 87.1	872 ± 50.5	823 ± 32.2

ANOVA *F*	VO_2 *p*
1.303	0.307

Scheffé	VO_2	*p*
MBT	Conventional	0.978
MBT	Barefoot	0.36
Conventional	Barefoot	0.464

Difference in VO_2 (mL O_2 · min^{-1})	
Test Shoe vs. barefoot	Conventional vs. barefoot
7.1 ± 6.5%	5.9 ± 5.6%

HR (beats min^{-1}) *n* = 5	Test Shoe	Conventional	Barefoot
	86 ± 19	84 ± 17.1	83 ± 17.3

ANOVA *F*	HR (beats · min^{-1}) *p*
0.032	0.969

Scheffé	HR	*p*
MBT	Conventional	0.987
MBT	Barefoot	0.97
Conventional	Barefoot	0.996

rate increased when wearing the MBT shoes by 3.6 ± 3.8% compared with the weight-adjusted conventional shoes and by 1.0 ± 1.6% when barefoot. However, these differences were not statistically significant ($p = 0.55$ and $p = 0.15$, respectively).

Discussion

Hettinger and Müller [1] quantified the effects of shoe mass on oxygen consumption, finding that the additional mass of shoes did result in increased oxygen consumption. In the present study, the increase in oxygen consumption while wearing shoes, compared with being barefoot, was of a similar magnitude to that measured by Hettinger and Müller. Thus, any increase in VO_2 seen while wearing the MBT shoes is more likely attributable to the sheer weight of the shoe rather than the unstable sole design.

A comparison of the absolute oxygen consumption values between the laboratory (1025 ± 221.6) and field (881 ± 87.1) measurements while walking horizontally at 5 km · h^{-1} revealed a higher value at 144 mL O_2 · min^{-1}, or approximately 14%, for walking on the treadmill. Statistically, this result was not significant. Nonetheless, one possible explanation for this result may be that the participants were not familiar with walking on a moving treadmill, thus resulting in increased muscular activity.

An increase in oxygen consumption was readily observable when standing in the MBT shoes with the unstable sole construction. It can be surmised that this increase in load is a result of interplay between joint geometry, increased muscular stabilisation and external forces [3, 5, 6, 8]. The cumulative effects may become more pronounced when standing for long durations, although the changes would probably only be in the range of 20 J · h^{-1} [12]. Nonetheless, any increase in muscular activity is welcomed for a number of reasons, including enhanced venous return from the legs via the muscular pump and the enhanced segmental stabilisation of the spinal column through the activation of reflex arcs.

The significant increase in oxygen consumption while standing in the MBT shoes can also be credited to increased sensorimotor activity such as muscular reflexes and the maintenance of muscle tone, tentatively as a consequence of the shoe's design. The absolute difference between the two shoe types is small however, particularly given the high variability (see *SD* values in Table 1). Nevertheless, our measurements recorded a definite increase in oxygen consumption while standing in the MBT shoe (Figure 4). Our data correlate well with the biomechanical studies of Nigg and Wakeling [7] and Romkes [6], which found increased EMG activity when wearing similar shoes while standing. As such, our data can be viewed to metabolically correlate the existing biomechanical evidence. A calculation of inter-test reliability resulted in a value of 0.92 for the measurements while standing, which, according to Bös [13], indicates exceptional reliability and supports the validity of the results.

With respect to heart rate, a difference of 3 beats · min^{-1} was found between the MBT (84 ± 14 beats · min^{-1}) and conventional shoes (81 ± 11 beats · min^{-1}) when standing, although this result was not statistically significant (Figure 5). The lack of significant changes in heart rate may be due to the fact that, at lower heart rates, the portion of the stroke volume supplying blood to the skeletal musculature is only very small [12] and any increase at this intensity would go largely unnoticed. The relationship between oxygen consumption and heart rate alters with changing intensity [5], where previous studies have shown that the relationship between oxygen consumption and heart rate at low intensity (e.g. lying, sitting, standing) is very weak [14–16]. This relationship is much stronger and is linearly proportional at mid to high intensities. At low intensities, changes can occur in heart rate without any corresponding change in oxygen consumption. At rest, Spurr et al [17] found that an increase in heart rate from 60 to 80 beats · min^{-1} did not show corresponding differences in oxygen consumption.

Another reason for the discrepancies between heart rate and oxygen consumption may be the stimulation of the heart via the sympathetic nervous system due to psychological stimulation [18]. Steady-state oxygen consumption is relatively stable compared with heart rate, which can vary significantly due to changes in stroke volume, peripheral resistance, blood distribution and mental state. Unlike blood, oxygen cannot be stored in the vascular system. The absolute difference in VO_2 (33 mL O_2 · min^{-1}) measured in our study was checked using a linear regression and was equivalent to 1.13 beats · min^{-1}. Thus, in contrast to the oxygen consumption rate, we expect that heart rate at low intensities, i.e. when standing, is too variable and the changes due to wearing the MBT shoes too small to have significantly affected heart rate.

No significant differences were observed between the MBT shoes and weight-adjusted conventional shoes in any of the walking phases on the treadmill. These data were in accord with the field measurements which also found no significant differences between the MBT and weight-adjusted conventional shoes. Thus, we conclude that walking in shoes with an unstable sole construction or shoes with a conventional flat sole has no effect on oxygen consumption. Walking on the treadmill with either the MBT or conventional shoes did, however, cause an increase in oxygen consumption and heart rate compared with walking barefoot. This tendency, although not statistically significant, was also observed in the field measurement data, where a power analysis suggests that a higher number of participants could strengthen such a conclusion.

Conclusions

Our study allows for the suggestion that the unstable shoe sole construction of the MBT shoe could produce positive therapeutic effects in people who spend a high proportion of time standing. We expect that such a shoe sole design could provide the best preventive effect when used as early as possible. With an increased prevalence of lifestyle diseases such as obesity and diabetes as well as vascular diseases such as peripheral artery occlusive disease or chronic venous insufficiency, the end manifestations of such disease states (e.g. polyneuropathy) have also increased. A consequence of this is that the ever-more serious clinical manifestations of peripheral neuropathy, most particularly in the distal part of the lower extremities, are occurring more often and at a younger age, leading to increases in the number of surgical interventions. Regular wearing of shoes with unstable sole construction may have positive therapeutic effects by targeted activation of the lower leg muscles, in particular, the smaller foot muscles. Future studies should evaluate the usefulness of unstable shoe construction in preventing the above clinical manifestations.

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