Does wearing shoes with unstable sole construction stimulate metabolic activity in the lower limbs?

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1. Executive summary

In this study, we investigated the extent to which wearing shoes with an unstable sole construction (Masai Barefoot Technology (MBT)) on a daily basis can stimulate metabolic activity in the musculature of the lower limbs.

Toward this end, differences in oxygen consumption and heart rate (a) for MBT shoes; (b) for running shoes that weigh the same as MBT shoes; and (c) walking barefoot were investigated.

The study subjects (six females and ten males, age 29.8 ± 6.8) underwent at rest (standing) tests in a laboratory setting wearing walking shoes and MBT shoes with a view to detecting metabolic differences while at rest (standing) in these shoes. During at rest (standing) tests for two six minute periods, significantly higher oxygen consumption was observed with MBT shoes relative to running shoes ($p < 0.01$). The mean oxygen consumption increase amounted to 9.3 ± 5.2%.

In addition, oxygen consumption and heart rate were analyzed on a laboratory treadmill at various walking speeds ranging from 4-7 km/h and at horizontal inclinations ranging from +10 to -10%. The MBT shoe data were compared with (a) data from control shoes weighing the same as the MBT shoes; and (b) walking barefoot. Additional female (n = 5) and male (n = 11) subjects (age 32.8 ± 7.5) were recruited for these tests. In the n = 16 subjects tested, no significant increase in oxygen consumption or heart rate was detected between MBT shoes and control shoes of the same weight (p values for speed/angle of inclination ranging from 0.12 to 0.83 for oxygen consumption, and 0.35 to 0.89 for heart rate).
A comparative analysis of MBT shoes and walking barefoot (horizontal, 5 km/h) yielded different results, however. Subjects wearing MBT shoes registered 4.4 ± 8.2% higher oxygen consumption ($p < 0.01$) and a 3.6 ± 7.3% higher heart rate ($p < 0.01$) relative to walking barefoot.

In a field test conducted with five male subjects (age 29.7 ± 3.1) on a 400 meter running track, no oxygen consumption or heart rate difference between MBT shoes and running shoes was observed. However, oxygen consumption tended to range higher for MBT shoes relative to walking barefoot ($p < 0.1$), but not for heart rate ($p = 0.25$).

Inasmuch as the unstable MBT sole appears to induce heightened metabolism during standing in particular, wearing these shoes on a daily basis is likely to increase calorie consumption.

Although the change only occurs in the roughly 20 kJ/h range, the cumulative effect over a 12 month period could be highly relevant for certain individuals.

In addition, a functional benefit resulting from sensorimotor activation of the small foot muscles and the lower-limb musculature, particularly for type 1 muscle fiber, is likely to occur. This would promote additional joint musculature stabilization, as well as balance optimization.

2. Introduction

Footwear has numerous effects on its wearer during periods of walking and standing. Shoes affect gait, movement patterns, pressure distribution on the sole of the foot, balance and muscle activation.

Based on Masai Barefoot Technology (MBT), the MBT shoe is a sports training and rehabilitation device that can worn on a daily basis. MBT shoes are based on the concept that the human foot and the human locomotor system are optimally configured for standing, walking and running on a soft surface. The MBT sole aims to replicate a soft, natural walking surface similar to sand, so as to allow for a gait that is similar to that of the Masai people of East Africa (Romkes et al. 2006).

The unstable sole of the MBT shoe (see figure 1) stimulates the sensorimotor system and the musculature of the lower limbs (Nigg et al. 2005). Moreover, the sole's rounded form destabilizes the wearer's balance in the anterior-posterior plane. The wearer offsets this effect through additional muscle activation and proprioceptive reflexes, thus causing the body to straighten up; and this in turn has a positive effect on overall body posture. The heel of the MBT shoe integrates a so called Masai sensor that is extremely supple and induces the aforementioned instability. In front of this sensor lies the more rigid balancing area, over which the foot is forced to roll while walking.

Figure 1: MBT shoe ("Chapa black")
with its heel comprising the relatively supple Masai sensor and the relatively rigid balancing area

A number of investigators have studied the biomechanics of unstable sole construction.
Nigg et al. (2005) investigated muscle activity electromyographically and various kinetic and kinematic parameters during walking and standing in various types of shoes. Their results revealed heightened electromygraphic intensity for MBT shoes in all tested muscles – although a statistically significant increase was observed solely in the tibialis anterior muscle. Romkes et al. (2006) investigated differences in muscle activity patterns during walking in conventional shoes and MBT shoes. Their study found that MBT shoes mainly induce changes in movement and muscle activity patterns in the ankle, as well as the gastrocnemius and tibialis anterior muscles. Another study (Romkes, 2008) investigated the effect of MBT

shoes on force application timing, with a view to analyzing the wearer's balance control response. This study revealed a significant difference in bipedal balance control between walking barefoot and in MBT shoes. A study that compared the effects of MBT shoes and sensorimotor training on postural stability and rate of force development (Gollhofer et al., 2004) found that both sensorimotor training and MBT shoes improve postural stability and that sensorimotor training is beneficial for rate of force development, while MBT has no effect in this regard.

The sole study that has addressed the issue of metabolism in such settings (Müller, 2007) compared metabolism during moderate-speed running on a treadmill in MBT shoes versus walking shoes. The study found that MBT shoes increase energy consumption by 13%, ventilation by 8%, oxygen consumption by 2.6% and heart rate by 2% relative to walking shoes.

None of the aforementioned studies investigated metabolism under the kind of everyday loads that occur during walking and standing. The present study aims to fill this gap.

3. Study design

The study comprised following test series:

1.) Laboratory measurements while standing
2.) Laboratory measurements on a treadmill
3.) Field measurements on a 400 meter running track with a Tartan surface

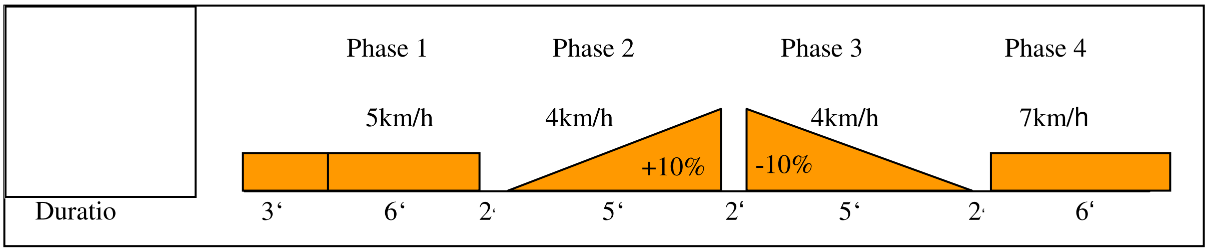
3.1 Laboratory measurements while standing

Oxygen intake was measured for six minutes in a precisely defined position while at rest (standing) using an Oxycon Alpha device (Jäger GmbH, Würzburg, Germany). This test was conducted with MBT and conventional shoes in a randomized order. For tests in both MBT and conventional shoes, the subjects were instructed to (a) stand on two marks that were 25 cm apart with their feet parallel to each other; and (b) look straight ahead and hold their arms at their side. During the MBT tests, the subjects were instructed to find and keep their balance in the balancing area of the shoe. Oxygen consumption and heart rate data were then compared reciprocally.

3.2 Laboratory measurements during walking

The walking laboratory measurements were conducted using a Woodway PPS Sport treadmill (Woodway GmbH, Weil am Rhein, Germany). The subjects were asked to go through the following sequence of phases (see graphic 1):

Warm-up:	5 km/h, horizontal position, 3 minutes
Phase 1:	5 km/h, horizontal position, 6 minutes
Phase 2:	4 km/h, 10 percent upward incline, 6 minutes
Phase 3:	4 km/h, 10 percent downward incline, 6 minutes
Phase 4:	7km/h, horizontal position, 6 minutes



Graphic 1: treadmill tests

All subjects performed the series twice: once wearing MBT shoes and a second time wearing running shoes that weighed the same as the MBT shoes. Phase 1 was repeated one additional time barefoot. The sequencing of the shoe and barefoot tests was randomized. Oxygen intake and heart rate were measured, and were then compared with each other.

3.3 Field measurements

The field measurements were performed on a 400 meter long running track with a Tartan surface (see figures 2-4). As in phase 1 of the laboratory tests, oxygen intake and heart rate were measured for six minutes at a speed of 5 km/h using a Cosmed K4b2 (Cosmed, Rome, Italy). All subjects realized the tests wearing MBT shoes, running shoes with the same weight as the MBT shoes, and barefoot. The sequencing of the shoe and barefoot tests was randomized. Walking speed was regulated by means of acoustic signals, as well as surface markings at 10 meter intervals. Effective speed was measured using a GPS system that was integrated into the Cosmed K4b2.

Figures 2-4: Field tests on a 400 meter running track with a Tartan surface

4. Working hypotheses

The study was conducted on the basis of the following working hypotheses:

1. H1: heightened muscle activity while standing in MBT shoes will induce a measurable increase in oxygen intake (H1a) and heart rate (H1b) relative to running shoes.

2. H2: Heightened muscle activity while walking in MBT shoes will induce a measurable oxygen intake and heart rate increase compared to walking in shoes of the same weight or walking barefoot. This hypothesis was tested during all phases of the treadmill and field tests.

5. Materials and methods

5.1 Subject characteristics

Six females and 10 males were recruited for the standing tests (age: 29.8 ± 6.8; height: 178 ± 6.7 cm; weight 72.3 ± 11.4 kg). All of these subjects were healthy individuals of average physical fitness.

Five females and 11 males were recruited for the treadmill tests (age: 32.8 ± 7.5; height: 173.1 ± 7.6 cm; weight 66.4 ± 12.4 kg). All of these subjects were healthy individuals of average physical fitness.

Five males were recruited for the field tests (age: 29.7 ± 3.1; height: 175 ± 4.2 cm; weight 69 ± 8.4 kg). All of these subjects were healthy individuals of average physical fitness.

The study was approved by the Bern canton ethics commission.

5.2 Materials

Laboratory tests
Ventilation and respiratory gas parameters were recorded using an Oxycon Alpha spirometer (Jäger GmbH, Würzburg, Germany); heart rate was recorded using a Polar belt. A Woodway PPS Sport treadmill was used (Woodway GmbH, Weil am Rhein, Germany). The laboratory investigations were conducted at the Swiss Health and Performance Lab (SHPL), which is part of the Department of Anatomy at the University of Bern (Switzerland).

Field investigation
Ventilation and respiratory gas parameters were documented using a portable Cosmed K4b2 spirometer (Cosmed, Rome, Italy); heart rate was recorded using a Polar belt. The test was conducted on the 400 meter running track at Leichtathletikstadion in Bern-Neufeld, Switzerland.

Figures 5-7: Weight equalization of MBT shoes and running shoes

Figures 5-7 show the weight equalization process for MBT shoes and walking shoes. The equalization was accurate to within plus or minus 5 grams, including the duct tape.

5.3 Measurement parameters

Continuous spirometric recording of oxygen intake and heart rate was realized for each inspiration during standing. The values for these two parameters were computed at 30 second intervals.

The same values were recorded during the treadmill and field tests and were likewise computed at 30 second intervals. In addition, following each treadmill load phase the subjects' subjective perception of load was documented using the Borg scale (6-20).

5.4 Statistical analyses

In the interest of obtaining reliable data on metabolic balance, statistical analyses were performed solely for the readings from the last two minutes of each standing test.

The mean oxygen intake and heart rate values for these periods were compared with each other. The percentage changes induced by the running shoes versus the MBT shoes were analyzed for each subject. The significance of the resulting values was then determined for n = 16 via paired, bilateral, homoskedastic T-tests.

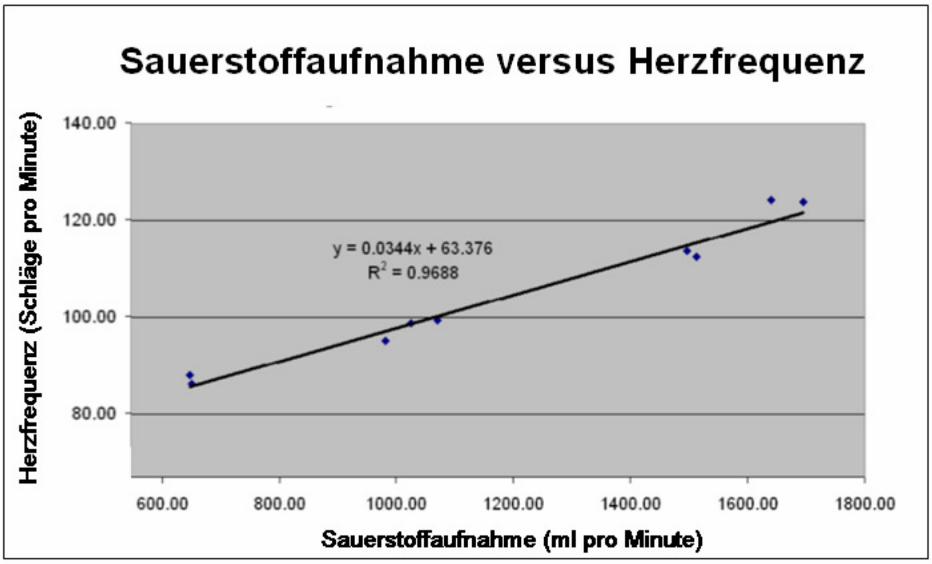
In the interest of obtaining reliable data on metabolic balance for each test phase, statistical analyses were performed solely for the readings from the last two minutes of each walking test phase (horizontal: 5 km/h; 10 percent upward incline: 4 km/h; 10 percent downward incline: 4 km/h; horizontal: 7 km/h).

Statistical analyses were performed solely for the mean oxygen intake and heart rate readings from the last two minutes of each walking test. The mean values thus derived from metabolic balance were then reciprocally compared for n = 16 via paired, bilateral, homoskedastic T-tests. The percentage changes induced by the weight-adjusted running shoes and MBT shoes were reciprocally compared and their statistical significance was determined. The same procedure was used for the MBT versus barefoot comparison and for the field test on the 400 meter track.

The significance level for all tests was $p < 0.05$.

5.5 Statistical quality control

The correlation between heart rate and oxygen intake was determined for the treadmill tests (see graphic 2). The fact that these two values correlate with the coefficient of determination (R = 0.98) indicates that the measurements realized during the tests were highly accurate.



Vertical: Heart rate (heartbeats per minute)
Top line: Oxygen intake relative to heart rate

6. Results

6.1 Working hypothesis H1

Hypothesis H1a, which holds that heightened muscle activity while standing in MBT shoes will induce a measurable increase in oxygen intake and heart rate relative to running shoes, was confirmed (see table 1).

Higher oxygen intake during at-rest standing for two six minute periods was observed for MBT shoes relative to running shoes. The mean oxygen uptake increase amounted to 9.3 ± 5.2% ($p < 0.01$).

Hypothesis 1b, which held that a measurably heightened heart rate will be observed during standing in MBT shoes was not confirmed.

Oxygen intake (in ml/min)
MBT versus running shoes

Subject	MBT	Running shoes	Change for MBT (in percent)
1	342	305	12.1
2	352	327	7.6
3	388	368	5.4
4	404	385	5.0
5	407	348	16.9
6	415	392	5.9
7	406	368	10.5
8	385	374	2.9
9	302	257	17.2
10	440	407	8.1
11	310	307	0.9
12	382	331	15.4
13	356	324	9.8
14	287	277	3.7
15	519	446	16.4
16	497	450	10.5
Mean	387	354	9.3
SD	64	55	5.2
T-TEST (MBT versus running shoes)			p = 0.000005

Cardiac rate (heartbeat/min)
MBT versus running shoes

Subject	MBT	Running shoes	Change for heart rate (in percent)
1	81	75	8.6
2	79	68	17.3
3	84	84	0.7
4	80	86	-6.7
5	83	85	-2.6
6	123	90	35.6
7	75	75	0.2
8	82	82	0.2
9	81	87	-6.9
10	99	100	-0.8
11	67	65	3.7
12	72	74	-2.2
13	80	77	3.8
14	100	101	-1.3
15	85	84	0.6
16	68	65	5.4
Mean	84	81	3.5
SD	14	11	10.4
T-TEST (MBT versus running shoes)			p = 0.25

Table 1: Laboratory readings while standing: highly significant increase in oxygen consumption while standing. No significant increase in heart rate.

6.2 Working hypothesis H2: lab treadmill results

Hypothesis H2 – which held that heightened muscle activity while walking in MBT shoes will induce a measurable oxygen intake and heart rate increase compared to walking in shoes of the same weight or walking barefoot – was not confirmed by the lab treadmill results (see table 2).
However, in the comparison of MBT and barefoot walking, the MBT oxygen intake readings for walking on a level surface were 4.4 ± 8.2% higher than the counterpart barefoot readings ($p < 0.05$); heart rate readings were an average of 3.6% higher than for walking on a level surface ($p < 0.05$).

Oxygen intake (in ml/min)

n=16	Mean values for MBT	Mean values for running shoes	MBV versus running shoes p value	Mean value for walking barefoot	MBT versus barefoot p value
Phase 1	1025	1070	0.38	981	0.008
Phase 2	1497	1512	0.47		
Phase 3	647	650	0.83		
Phase 4	1695	1640	0.12		

Heart rate

n=16	Mean values for MBT	Mean values for running shoes	MBV versus walking shoes p value	Mean value for running barefoot	MBT versus barefoot p value
Phase 1	99	99	0.62	95	0.005
Phase 2	114	113	0.67		
Phase 3	88	86	0.35		
Phase 4	124	124	0.89		

Oxygen intake increase for MBT versus walking barefoot	4.4 ± 8.2%
Heart rate increase for MBT versus walking barefoot	3.6 ± 7.3%

Table 2: Lab readings for the walking tests: no significant increase in MBT oxygen intake or heart frequency relative to walking shoes; significant increase in MBT oxygen intake and heart frequency relative to walking barefoot.

6.3 Field data for hypothesis H2

Hypothesis H2 – which held that heightened muscle activity while walking in MBT shoes will induce a measurable oxygen intake and heart rate increase compared to walking in shoes of the same weight or walking barefoot – was not confirmed by the field test readings. This also held true for heart rate (see table 3).
The results for the comparison of MBT and barefoot walking can be summarized as follows: (a) oxygen intake was 7.1 ± 6.5% higher ($p < 0.1$); (b) the mean heart rate was 3.6 ± 3.8% higher ($p = 0.15$).

Oxygen intake (in ml/min)

Mean values

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Mean values
MBT	997	774	929	825	878	881
Running shoes	947	815	887	839	874	872
Barefoot	859	782	850	802	822	823

T-TEST	
MBT versus running shoes	0.66
MBT versus barefoot walking	0.08

Increased oxygen intake MBT versus barefoot walking
7.1 ± 6.5%

Heart rate

Mean heart rate

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Mean values
MBT	67	106	66	103	87	86
Running shoes	68	95	68	107	82	84
Barefoot	66	98	66	103	82	83

T-TEST	p values
MBT versus running shoes	0.55
MBT versus barefoot walking	0.15

Increased oxygen intake MBT versus barefoot walking
3.6 ± 3.8%

Table 3: Field measurements on a 400 meter running track: no significant increase in MBT oxygen intake or heart frequency relative to walking shoes; significant increase in MBT oxygen intake and heart frequency relative to barefoot walking.

7. Discussion

The standing measurements that we conducted in the first part of the study with a view to determining the differences in oxygen intake between MBT shoes and running shoes prompted us to conclude that the MBT shoe's unstable sole intensifies sensorimotor processes such as proprioception, thus inducing increased oxygen intake. The heightened electromyographic activity that has been observed in biomechanical studies found its metabolic correlate in our own trial, thus supporting the findings of Nigg und Romkes (Nigg et al. 2005; Romkes et al. 2006)

No difference in respect to heart rate between MBT shoes and running shoes was observed during standing, a fact probably attributable at least in part to the fact that the at rest (standing) heart rate does not differ appreciably from the resting heart rate. Inasmuch as the heart rate is chiefly regulated by the vegetative and hormonal factors that govern the body's basic functions, musculoskeletal activities play a relatively minor role in heart rate regulation in such settings.
Moreover, presumably any minor alteration in heart rate induced by heightened muscle activity by wearing MBT shoes while standing is likely to be lost in the shuffle of normal heart rate fluctuations. Oxygen intake is regulated in a more stable fashion in the presence of low level muscle activity and correlates more strongly with muscle activity than is the case with heart rate.

No difference between MBT and weight compensated running shoes was observed during treadmill walking. The absence of any change in heart rate and oxygen consumption suggests that the MBT shoe's unstable sole has no supplemental effect on metabolism during walking. The treadmill readings correlated with those from the field trials, where no difference in metabolism was observed either. These findings are at odds with other published data (Müller et al., 2007), although this discrepancy may be attributable to the fact that (a) this study investigated metabolic data not during walking but rather during moderate-speed jogging; or (b) the weight of the MBT shoes and running shoes was not equalized. In our study, the mean weight difference between the MBT shoes and running shoes was 253 ± 37 g per shoe. The higher the running speed, the more likely it is that the inertia induced by additional weight will affect metabolic processes.

On the other hand, an oxygen intake difference between MBT shoes and walking barefoot was observed during treadmill walking. However, we were unable to determine whether this difference is attributable to the unstable MBT sole or the weight of the MBT shoes. It appears that walking barefoot allows for reduced oxygen consumption – a finding also borne out by our field test, whose five subjects exhibited lower oxygen intake while walking barefoot. This finding would probably have been significant had a larger number of subjects been tested. The low p values of 0.08 and 0.15 relative to the number of subjects might well have been significant for $n > 10$ subjects; this contention was borne out by the sensitivity analyses we conducted.

In evaluating our results, we also compared the absolute values of the treadmill analyses and the GPS based field test on the 400 meter Taran-covered running track. These comparisons revealed that absolute treadmill oxygen intake was higher than for the field test. We attribute this phenomenon to the fact that walking on a hard and even surface is a reflexive function that is learned in early childhood, whereas use of a treadmill involves walking on a far less familiar surface that is also in motion; and this in turn induces a higher level of muscular activity.

8. Conclusions

Our study suggests that shoes with an unstable sole may have beneficial effects. This holds true in particular for standing in such footwear, which increases the level of metabolic exertion that the body must make in response to the effects induced by the unstable sole.
Hence MBT shoes would appear to be beneficial above all (and particularly in the long term) for individuals who spend a great deal of their time standing. Further field trials with larger random samples and a strong focus on data related to everyday activities could provide further and more precise insight into these matters.

9. Acknowledgements

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And lastly, we would like to thank the study subjects whose commitment to and interest in the project enabled us to gather extensive data and realize the trial as a whole.

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11. Annex

	MBT		Running shoes		Barefoot	
Phase 1	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
V'E l/min	26.73	5.97	27.08	4.86	32.11	24.64
BF (1/min)	22.22	5.82	22.68	5.56	21.68	6.04
Oxygen intake [ml/min]	1024.78	211.42	1069.81	156.11	981.13	175.26
Oxygen intake/kg [ml/min/kg]	15.47	2.39	16.21	1.15	14.81	1.44
CO2 intake [ml/min]	877.54	183.82	902.79	135.28	832.54	164.95
RER	0.86	0.05	0.84	0.05	0.85	0.05
HR [1/min]	98.66	8.7	99.26	12.07	95.14	12.09
Borg	9.18	1.84	8.73	1.81	8.73	1.81
Phase 2	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**		
V'E l/min	36.43	7.34	35.69	7.33		
BF (1/min)	23.59	4.61	22.44	4.91		
Oxygen intake [ml/min]	1496.81	247.47	1512.05	234.53		
Oxygen intake/kg [ml/min/kg]	22.63	1.93	22.86	1.33		
CO2 intake [ml/min]	1294.51	225.91	1297.62	224.47		
RER	0.86	0.04	0.86	0.04		
HR [1/min]	113.61	14.76	112.54	13.88		
Borg	11.45	1.74	10.82	1.91		
Phase 3	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**		
V'E l/min	20.39	3.99	19.97	4.86		
BF (1/min)	22.78	4.92	21.11	7.29		
Oxygen intake [ml/min]	646.58	110.48	650.03	115.31		
Oxygen intake/kg [ml/min/kg]	9.81	1.31	9.83	1.08		
CO2 intake [ml/min]	567.64	102.36	587.45	111.56		
RER	0.88	0.07	0.9	0.07		
HR [1/min]	88.03	14.03	86.08	9.29		
Borg	7.82	1.49	7.5	1.07		
Phase 4	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**		
V'E l/min	42.44	8.43	40.57	8.26		
BF (1/min)	25.62	5.94	24.35	6.86		
Oxygen intake [ml/min]	1694.65	256.62	1639.6	238.12		
Oxygen intake/kg [ml/min/kg]	25.67	2.21	24.85	1.78		
CO2 intake [ml/min]	1475.56	245	1431.29	258.31		
RER	0.87	0.04	0.87	0.05		
HR [1/min]	123.87	17.65	124.32	19.75		
Borg	12.5	2.35	12.27	2.12		

Table 4: Lab readings for the walking tests: mean values and standard deviation for all treadmill phases.