

**Influence of wearing an unstable shoe on thigh and leg muscle activity
and venous response in upright standing**

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Abstract

Purpose: To quantify the effect of unstable shoe wearing on muscle activity and haemodynamic response during standing.

Methods: Thirty volunteers were divided into 2 groups: the experimental group wore an unstable shoe for 8 weeks, while the control group used a conventional shoe for the same period. Muscle activity of the medial gastrocnemius, tibialis anterior, rectus femoris and biceps femoris and venous circulation were assessed in quiet standing with the unstable shoe and barefoot.

Results: In the first measurement there was an increase in medial gastrocnemius activity in all volunteers while wearing the unstable shoe. On the other hand, after wearing the unstable shoe for eight weeks these differences were not verified. Venous return increased in subjects wearing the unstable shoe before and after training.

Conclusions: The unstable shoe produced changes in electromyographic characteristics which were advantageous for venous circulation even after training accommodation by the neuromuscular system.

Keywords: *Electromyography; Haemodynamics; Muscle pumps*

1. INTRODUCTION

The primary function of venous circulation is to return blood to the heart. Effective venous return requires the interaction of a central pump, a pressure gradient, a peripheral venous pump, and competent venous valves to overcome the forces of gravity (Araki, Back et al., 1994; Ludbrook, 1966; Meissner, Moneta et al., 2007). Depending on activity and posture, 60 to 80% of the resting blood volume resides in the venous system (Katz, Comerota et al., 1994) and in the upright but motionless individual the hydrostatic pressure is higher (Meissner, Moneta, et al., 2007). As the thin-walled veins readily distend with relatively small increases in transmural pressure (Rothe, 1983), compensatory mechanisms must be present to prevent the blood from pooling in the extremities and aid in the return of blood to the heart. Indeed the peripheral pump may “drive” the circulation during exercise (Rowland, 2001).

The muscle pumps of the lower limb include those of the foot, calf and thigh. Among these, the calf muscle pump is the most important, as it is the most efficient, has the largest capacitance and generates higher pressures (Katz, Comerota, et al., 1994). The normal limb has a calf volume ranging from 1500 to 3000 cm³, a venous volume of 100 to 150 cm³, and ejects over 40 to 60% of the venous volume with a single contraction (Araki, Back, et al., 1994; Stewart, Medow et al., 2004). Evidence suggests that dynamic exercise produces increased blood flow when compared to continuous isometric exercise (Laughlin & Armstrong, 1985). During dynamic exercise, the muscle pump plays an important role in initial increase and maintenance of blood flow (Laughlin & Schrage, 1999) as blood flow increases between contractions, even for low intensity ones (Radegran, 1997). With walking, the limb venous pressure is reduced by approximately 78 mmHg within 7 to 12 steps

(Pollack & Wood, 1949). Similar pressure changes are observed during standing with ankle flexion or heel raising, with weight transferred to the forefoot (Nicolaides, Hussein et al., 1993; Pollack & Wood, 1949).

Chronic venous insufficiency explains those manifestations of venous disease resulting from ambulatory venous hypertension, which is associated with failure of the lower extremity muscle pumps due to outflow obstruction, musculo-fascial weakness, loss of joint motion or valvular failure (Araki, Back, et al., 1994; Nicolaides, Hussein, et al., 1993; Stewart, Medow, et al., 2004). Efficient peripheral pumps may compensate for some degree of reflux and obstruction and prevent chronic venous insufficiency symptoms (Padberg, Johnston et al., 2004; Plate, Brudin et al., 1986). It has been demonstrated that calf muscle strengthening exercises restore the pumping ability of the calf muscle and improve the haemodynamic performance in limbs with active ulceration subsequent to severe venous valvular and calf muscle pump impairment (Padberg, Johnston, et al., 2004).

It has been suggested that balance training devices, such as wobble-boards or unstable surfaces, can significantly improve ankle and knee muscle strength and proprioception (Waddington & Adams, 2004; Waddington, Seward et al., 2000; Wester, Jespersen et al., 1996). Previous experiments dealt with changes in gait characteristics, posturography and electromyographic activity (EMG) of several lower extremity muscles (gastrocnemius, tibialis anterior, vastus lateralis and medialis, rectus femoris, and semitendinosus) in healthy subjects (Nigg, Hintzen et al., 2006; Romkes, Rudmann et al., 2006; Stewart, Gibson et al., 2007), in children with development disabilities (Ramstrand, Andreson et al., 2008), in women aged over 55 years (Ramstrand, Thuesen et al., 2010), and in patients suffering from osteoarthritis (Nigg, Emery et al., 2006) in response to unstable shoe wearing.

Therefore, the purpose of this study was to quantify the effect of wearing an unstable shoe on muscle activity and haemodynamic response in lower extremities during standing before and after training intervention. Specifically, the purposes were:

(a) to evaluate the immediate effect of unstable shoe wearing on EMG activity of medial gastrocnemius (MG), tibialis anterior (TA), biceps femoris (BF) and rectus femoris (RF) muscles during standing, to provide evidence for changes in muscle activation;

(b) to analyse the influence of 8 weeks of unstable shoe wearing on EMG activity, to provide evidence for changes in muscle activation;

(c) to quantify the immediate effect of unstable shoe wearing on lower limb venous circulation;

(d) to quantify the influence of 8 weeks of unstable shoe wearing on lower limb venous circulation.

In all situations the values obtained before and after 8 weeks of intervention with the unstable shoe were compared to standard measures obtained during barefoot standing.

The following hypotheses were tested:

EMG activity

H1 - During quiet standing, the EMG intensity of all muscles analysed is higher for the unstable shoe condition compared to barefoot standing before and after the unstable shoe intervention.

H2 - During quiet standing, the EMG intensity levels are lower after 8 weeks of unstable shoe wearing.

Lower limb venous circulation

H3 - During quiet standing, lower limb venous circulation is higher for the unstable shoe condition compared to barefoot standing before and after the unstable shoe intervention.

H4 - During quiet standing, lower limb venous circulation is lower after 8 weeks of unstable shoe wearing.

2. METHODS

2.1 Subjects

Thirty healthy female individuals between the age of 20 and 50 years, distributed in 2 groups matching in age, weight and height were included. The study excluded subjects presenting one or more of the following aspects: (1) recent osteoarticular or musculetendinous injury of the lower limb; (2) background and signs of neurological dysfunction which could affect lower limb motor performance, sensory afferences and balance; (3) history of surgery in lower extremities; (4) pain in lower extremities and trunk for the past 12 months; (5) taking medication; (6) balance disorders and visual deficits; and (7) individuals who had used unstable footwear prior to the study. The same exclusion criteria were adopted for both groups.

The study included individuals whose professional occupation was mainly executed while standing statically. The experimental group included 14 individuals (age = 34.6 ± 7.7 years, height = 1.6 ± 0.1 m, weight = 65.3 ± 9.6 kg; mean \pm SD) and the control group included 16 individuals (age = 34.9 ± 8.0 years, height = 1.6 ± 0.1 m, weight = 61.1 ± 6.3 kg; mean \pm SD). In both groups, the dominant lower limb was the right. The study was conducted according to the institution ethical norms and conformed to the Declaration of Helsinki, with informed consent obtained from all participants.

2.2 Instrumentation

The EMG activity of the MG, TA, RF and BF was monitored using the *MP 150 Workstation* model from *Biopac Systems, Inc. (USA)*, bipolar steel surface electrodes, spaced 20 mm apart, and a ground electrode (*Biopac Systems, Inc.*). EMG signals during quiet standing show excellent repeatability (Lehman, 2002). Skin impedance was measured with an Electrode Impedance Checker (Noraxon USA, Inc.).

The cross-sectional area and the venous velocity of the common femoral (CFV) and popliteal (PV) veins were determined using an *Acuson CV 70* duplex ultrasound unit (*Siemens Medical Solutions, USA*), with a 5-10 MHz linear array probe.

2.3 Procedures

2.3.1 Skin preparation and electrode placement

We have prepared the subjects' lower limbs to reduce electrical resistance to less than 5000 Ω (Basmajian & De Luca, 1985) by (1) shaving the skin surface of the muscle belly area; (2) removing dead cells with alcohol; and (3) removing non-conductor elements between electrode and muscle with abrasive pad (Hermens, Freriks et al., 2000).

Electrodes were placed at the centre of the muscle belly of the MG, TA, RF and BF. The reference electrode was placed at the centre of the patella. To avoid movement and to ensure homogeneous and constant pressure, the electrodes were fixed to the skin with adhesive tape (Hermens, Freriks, et al., 2000). We waited 5 minutes after electrode placement to begin measurements as evidence suggest that there is a reduction of 20 to 30% in impedance values during the first 5 minutes after electrode placement (Vredenburg & Rau, 1973).

2.3.2 Data collection

In the experimental group, the EMG and haemodynamic data were collected in 2 conditions: (1) prior to using the unstable shoe and (2) after wearing it for a period of 8 weeks. Subjects in the control group were also assessed at 2 moments separated by 8 weeks, but using a conventional shoe between them. In both groups and in all assessments the variables evaluated were monitored under 2 conditions: (1) upright barefoot standing and (2) upright standing wearing the unstable shoe (Figure 1). Trials were randomised to reduce the order effect, which can be caused by previous muscle activation or learning. Measurements were performed on the dominant limb, which was the right limb. Before data acquisition, all subjects underwent an instruction session by a qualified instructor who explained how to use the unstable test shoe, followed by approximately 10 minutes of walking, until the instructor felt they walked properly and were comfortable using the shoe (Nigg, Hintzen, et al., 2006).

All individuals were asked to remain comfortably standing, with the support base aligned at shoulder width, keeping their arms by their sides. To ensure optimum test-retest reliability, they were also given a target 2 meters away at eye level on which to focus during the 30 seconds of data acquisition. Data acquisition initiated 3 seconds after the beginning of the testing procedure and was done in a total of 3 trials.

EMG signals were acquired at a sample rate of 1000 Hz, then digitised and stored on a computer for subsequent analysis by the *Acqknowledge* software (Biopac Systems, Inc. USA). Signals were pre-amplified at the electrode site and then fed into a differential amplifier with adjustable gain setting (12-500 Hz; Common Mode Rejection Ratio (CMRR): 95 dB at 60 Hz and input impedance of 100 M Ω). The gain range used was 1000. A 30 second window of EMG signal was used for analysis,

and signals were band-pass filtered between 20 and 450 Hz. This window of raw EMG activity was processed using the Root Mean Square (RMS) procedure. The mean of the RMS was normalised in relation to a maximal isometric contraction, performed after a warm-up consisting of 3 submaximal isometric contractions (Lehman & McGill, 1999). TA and MG maximal isometric contractions (MIC) were measured with the ankle in neutral position. MIC for the BF and RF were measured with the knee at 90°. For all muscles manual resistance was applied.

The cross-sectional area and venous velocity were monitored in the CFV and PV. PV measurements were examined directly behind the knee joint and CFV measurements were taken approximately 2 cm above the saphenofemoral junction.

Three separate measurements of venous velocity were obtained and the mean values computed. As the peripheral blood flow is affected by respiratory manoeuvres (Tortora & Anagnostakos, 1990; Willeput, Rondeaux et al., 1984), subjects were asked to maintain a stable respiratory pattern during data acquisition. The maintenance of constant temperature conditions was also provided (Henry & Gauer, 1950). The volume flow rate (Q) in the blood vessel was calculated by multiplying the cross-sectional area of the blood vessel (A) by the mean velocity (v) of the blood within it (Brown, Halliwell et al., 1989):

$$Q = v \times A$$

Following an initial evaluation, subjects in the experimental group were given a pair of the unstable test shoe. They were instructed to wear them as much as possible, for at least 8 hours a day, 5 days a week, for 8 weeks, as it has been demonstrated that wearing unstable shoes during a period of 8 weeks induces improvements on postural control (Ramstrand, Andreson, et al., 2008; Ramstrand, Thuesen, et al., 2010). Also, there is evidence that 6 weeks of unstable wearing

induces training effects (Kalin & Segesser, 2004; Nigg, Hintzen, et al., 2006; Romkes, Rudmann, et al., 2006; Vernon, Wheat et al., 2004). Subjects were given a guide on how to use the shoes and participants in the control group were asked to continue their normal activities and not begin any new exercise regime. The second evaluation was performed 8 weeks after the first, using the same protocol. The experimental group wore the unstable shoe only during working time (at least 8h per day). As all subjects were hairdressers, they were most of the time in upright standing.

2.4 Statistics

Statistical analysis was processed with *Statistic Package Social Science (SPSS)* from *IBM Company (USA)*. The sample was characterised by descriptive statistics.

Differences in lower extremity venous return and EMG activity between the first and second evaluation were analysed using the Paired Samples t-test and the Wilcoxon test, respectively, as EMG values did not follow a normal distribution. To analyse differences between groups, the Independent Samples t-test was used to compare venous return measurements and the equivalent non-parametric test. The Mann-Whitney U test was used to compare EMG measurements. Differences between measurements with the unstable test shoe and barefoot were analysed using the Wilcoxon test for the EMG measurements, as these values did not follow a normal distribution, and the equivalent parametric test, the Paired Samples t-test, for the venous flow. A 0.01 significance level was used for inferential analysis.

3. RESULTS

3.1 Influence of unstable footwear on muscle activity

Comparing the mean of EMG activity of each muscle between the experimental and control groups, it can be stated that there were no significant differences in TA, MG, BF and RF muscles in the first and the second evaluation (Figure 2). There were no significant differences in muscle activity level in the experimental group, before and after 8 weeks of wearing the unstable shoe, and in the control group, before and after 8 weeks of conventional shoe wearing (Figure 2).

In the first measurement, both groups presented significantly higher MG activity while wearing the unstable shoe when compared to barefoot (experimental group: $p=0.006$; control group: $p=0.009$), with no significant differences for the other muscles studied (Figures 2). In the second measurement, the experimental group showed no statistically significant differences in MG, TA, BF and RF activity between the 2 evaluated conditions (Figure 2). In the control group, both before and after the 8-week period, MG activity was higher when using the unstable shoe ($p=0.007$), while all other muscles studied showed no significant differences (Figure 2).

3.2 Influence of unstable footwear on venous return

Comparing the mean of flow rate at CFV and PV between the experimental and control groups, it can be stated that there were no significant differences between the control group and the experimental group for both the first and second evaluations (Figure 3).

A comparison between measurements taken with and without the unstable shoe shows a higher level of venous return with the unstable shoe in both groups during the first and second evaluation in PV (experimental group: $p=0.006$ and $p=0.002$, respectively; control group: $p=0.004$ and $p=0.001$, respectively) and CFV (experimental group: $p=0.002$ (for both situations); control group: $p=0.001$ (for both situations)) (Figure 3). As to the influence of 8 weeks of unstable shoe wearing, there

were no differences between the first and second evaluation, both with and without the unstable shoe (Figure 3). The same was verified in subjects that wore conventional footwear (Figure 3).

4. **DISCUSSION**

In upright standing small postural adjustments occur, mainly at the ankle (one of several possible balancing strategies), and these adjustments are accompanied by small fluctuations in the activity and muscle length of plantar flexors (Loram, Maganaris et al., 2005), resulting in centre of mass (CoM) displacements (Gatev, Thomas et al., 1999). The results of this study show that using an unstable shoe (versus barefoot) leads to increased MG activity. In the study of Romkes, Rudmann et al. (2006) it has been demonstrated that using an unstable shoe changes movement patterns during gait, especially at the ankle, and increases muscle activity as well. It has also been shown that accommodations to a rockered sole during running occur only at the ankle (Boyer & Andriacchi, 2009). It seems that wearing an unstable shoe leads to changes in the ankle control pattern in a variety of activities. According to Ivanenko, Levik et al. (1997), when standing on a rocking support (seesaw), the CoM deviation is accompanied by changes in ankle movement pattern and plantar pressure distribution, which are compensated by gastrocnemius muscle activation as in this condition, instead of moving the CoM, subjects shift the point of contact of the rocking platform with the ground under the CoM. Nigg, Hintzen et al. (2006) reported an increase only for the TA during standing with the unstable shoe, when compared to the conventional shoe. Based on its construction, the unstable shoe used in this study forced the user to land more towards the midfoot. There is evidence that standing in unstable footwear leads to increased plantar flexion at the

ankle joint, which corroborates the increased MG activity observed in this study (New & Pearce, 2007).

The experimental group results show that after 8 weeks of unstable shoe wearing, the MG activity with the unstable test shoe was not significantly different from the values obtained in the barefoot measurement, as verified before training. The design of unstable footwear used in the present study (MBT) is based on observations of the Masai tribe, who are not accustomed to wearing shoes. This design recreates natural uneven walking surfaces to reduce problems caused by today's rigid soled shoes and hard ground. The adaptation of the human biological system for movement control (Ferrel, Leiffen et al., 2000) includes changes in the response of neural receptors (Theunissen, Kroeze et al., 2000) and changes in the function of central and autonomous nervous systems (LeBlanc, Dulac et al., 1975; Pia, 1985). Exercises repeated daily or weekly can improve postural control (Hu & Woollacott, 1994) and generate structural and functional adaptations in the neuromuscular system (Hakkinen, Kallinen et al., 1996). Our results as to the MG corroborate the idea that wearing an unstable shoe leads to neuromuscular system functional adaptations. Results obtained in the control group reinforce that differences between conditions in the first and second evaluations in the experimental group resulted from wearing the unstable shoe for 8 weeks. According to Ramstrand, Thuesen et al. (2010), reactive balance can be improved by prolonged and regular use of shoes incorporating an unstable sole construction. Standing with unstable shoes effectively activates extrinsic foot muscles and can have implications for strengthening and conditioning these muscles, as postural sway while standing with unstable shoes also decreases over a 6-week accommodation period (Landry, Nigg et al., 2010). Although the triceps surae is involved in plantar flexor activity, the

gastrocnemius muscle seems to play a central role in the phasic control of balance (Borg, Finell et al., 2007). Results obtained by Gatev, Thomas, et al., (1999) showed that there is a significant statistical correlation between gastrocnemius activity and the position of spontaneous body sway, which was measured as the CoM position. This supports the notion that active torque is provided by gastrocnemius muscle contractions in response to body sway.

As to venous return, the results of this study show an increase in both PV and CFV measurements made while wearing the unstable shoe. This increase was observed in both groups and for both veins. Dynamic exercise causes higher and less heterogeneous blood flow than intermittent isometric exercise at the same exercise intensity (Laaksonen, Kalliokoski et al., 2002). During exercise the contraction rhythm of peripheral skeletal muscles results in the compression of intramuscular veins, granting the venous blood a considerable amount of kinetic energy that facilitates its return to the heart (Stewart, Medow, et al., 2004). The results of this study show that wearing an unstable shoe led to increased MG activity, which can lead us to think that venous return variations were more associated to MG EMG activation. Instantaneous changes in surface EMG amplitude may provide a good estimate of intramuscular pressure changes during the rising part of isometric, but also of concentric, voluntary contractions (Maton, Thiney et al., 2006). During contraction, the gastrocnemius and soleus muscles drive blood into large capacity PV and CFV. Although thigh veins are surrounded by muscle, the contribution of thigh muscle contraction to venous return is minimal when compared to the calf muscle pump (Ludbrook, 1966).

During quiet standing, measurement of low intrinsic ankle stiffness (Loram & Lakie, 2002a), analysis of ballistic character of sways (Loram & Lakie, 2002b) and

investigations of balance in an analogous task using a weak spring (Lakie, Caplan et al., 2003) provide increasing evidence that intermittent ballistic-like adjustments in muscle length (Loram & Lakie, 2002b) may be responsible for the apparently random sway pattern that is seen in quiet standing. As reported by Nigg, Hintzen et al. (2006), visual control of EMG signals (without signal processing and statistical analysis) showed more variation in measurements with the unstable shoe. Taking this into account, together with the fact that dynamic muscle contractions are advantageous to venous circulation, it would be interesting to investigate how the use of an unstable shoe affects muscle activity and muscle length time variation.

It is important to note that, although MG activity with the unstable shoe did not differ from barefoot measurements after 8 weeks of training in the experimental group, venous return did not decrease when compared to measurements made before the training period (Figure 3). Moreover, measurements made with the unstable test shoe after training revealed significantly higher venous return than barefoot measurements. According to Ivanenko, Levik et al. (1997), during overground standing the triceps surae muscles generally work in an eccentric mode of contraction, and on the seesaw in a concentric one. Unstable shoe sole configuration is similar to the seesaw used in (Ivanenko, Levik et al., 1997), and therefore it can be assumed that it also favours concentric activity. These findings may explain why, despite MG neuromuscular adaptation, the venous flow remained higher while wearing the unstable test shoe, as most of the venous return occurs during the concentric phase of contraction (Hogan, Grasse et al., 2003). RMS analysis shows that EMG activity may be related to increased venous flow. Nevertheless, future studies focusing a temporal analysis, could help understanding

the influence of wearing unstable shoes in time variation of muscle parameters and its impact on venous flow to confirm our results.

It has been demonstrated that balance training improves postural control performance both in healthy subjects (Heitkamp, Horstmann et al., 2001) and in injured individuals (Mattacola & Lloyd, 1997). Taking into account that patients with venous disease show weak calf muscle strength (Yang, Vandongen et al., 1999), it would be important, in future studies, to analyse the influence of using an unstable shoe on calf muscle activity and venous flow in patients with venous disease.

5. CONCLUSIONS

The findings of this study show that wearing an unstable shoe leads to a short-term increase in MG activity. However, after 8 weeks of unstable shoe wearing the activity of this muscle with unstable shoe was more close to the one obtained in the barefoot condition. As to venous return, results show that wearing an unstable shoe leads to increased venous return in PV and CFV and that this increase was maintained after 8 weeks of using the unstable shoe.

In summary, using an unstable shoe produced changes in EMG characteristics during upright standing which are advantageous for venous circulation even after training adaptation by the neuromuscular system.

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FIGURE CAPTIONS

Figure 1: Unstable shoe model used in this study: The MBT shoe has a rounded sole in the antero-posterior direction, thus providing an unstable base.

Figure 2: Representation of values for mean (bars) and standard deviation (error bars) of MG, TA, RF and BF muscles activity (% MIC) during standing with and without the unstable shoe before and after 8 weeks of unstable shoe wearing (USW) by the experimental group (a) and the same period of conventional shoe wearing (CSW) by the control group (b). The Wilcoxon test was used to compare EMG activity obtained with and without the unstable shoe, the values obtained before and after the 8-week period, and the values obtained by the experimental group and the control group.

Figure 3: Representation of mean and standard deviation values of venous velocity at the common femoral (CFV) and popliteal (PV) veins during standing with and without the unstable shoe before and after 8 weeks of unstable shoe wearing (USW) by the experimental group and 8 weeks of conventional shoe wearing (CSW) by the control group. The paired samples T-test was used to compare venous circulation obtained with and without the unstable shoe, before and after the 8-week period and between the experimental group and the control group.

FIGURES

Figure 1



Figure 2

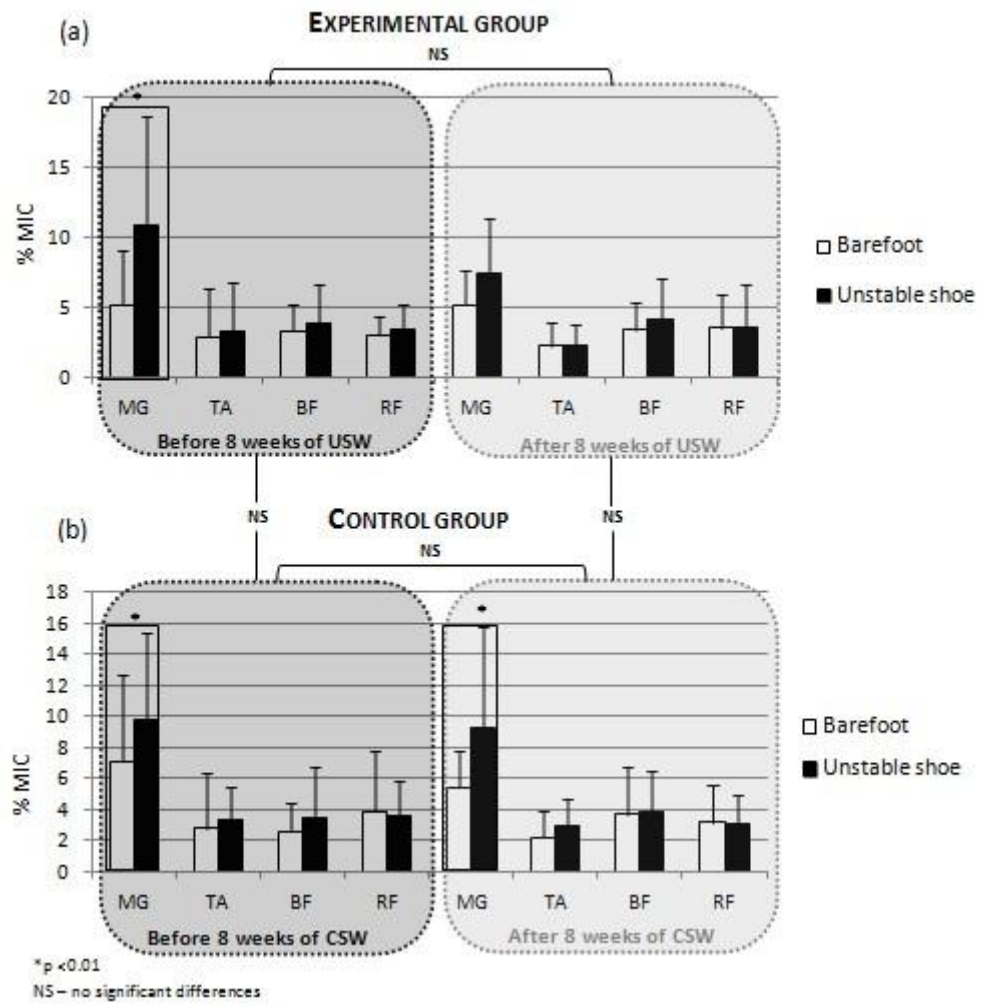


Figure 3

