Federolf, P., Roos, L., Nigg, B. (2012). The effect of footwear on postural control in bipedal quiet stance. *Footwear Science, 4*, 115-122.

Abstract

Assessments of the occurrence of falls in elderly populations reported an increased risk when barefoot as compared to shod conditions, suggesting that footwear has an effect on the postural control system. However, the results of studies analyzing static stability in laboratory tests by evaluating the center of pressure (COP) excursion are inconsistent. The purpose of this study was therefore to investigate the effects of footwear on the postural control system by quantitatively assessing the postural movements executed during quiet stance. The postural movements of twenty nine subjects were recorded using a standard marker based motion analysis system. Three footwear conditions were tested: barefoot, a casual athletic shoe and so called unstable shoes. One-dimensional principal movement components were determined by performing a principal component analysis on the posture vectors consisting of the 3D coordinates of all markers. The relative contribution of the first five PM to the entire postural movement, their range of motion, and their persistence (detrended fluctuation analysis) were determined. Repeated measures ANOVAs revealed significant differences between all three shoe conditions. Specifically, when standing in unstable as compared to the normal shoes it was found that higher order principal components contributed less to the entire movement, that the range of motion in all five principal movements was substantially increased, and that the persistence was higher in the first two principal movements. When comparing barefoot to normal shoes it was found that in barefoot standing higher order principal components contributed less to the entire movement and the persistence was increased in the first and decreased in the third principal component. These results demonstrate that a direct analysis of postural movements reveals additional information that about the effect of footwear that is not available from COP measurements.

Key Words

Stability; static balance; principal component analysis (PCA); coordination of movements; postural control strategy.

1. Introduction

In modern societies a fast majority of people use footwear in most of their standing or walking activities. It is therefore an important field of postural control research to determine if footwear might influence the risk of falling. There are several pathways of how footwear might influence the postural control system. Footwear might change a) the position and posture of the feet (Shultz et al. *in press*), the pressure distribution at the foot during the ground contact (Shorten 2009), and/or it may affect several sensory systems that contribute to the postural control (Magnusson et al. 1990, Robbins and Waked 1997, Maki et al. 1999, Patel et al. 2008, Wilson et al. 2008, Hatton et al. 2009).

Evaluation of the center of pressure (COP) excursion during quiet bipedal stance is one of the most frequently used approaches to quantify static stability. However, the results of studies analyzing the effects of footwear on the COP excursion are inconsistent. Some studies report differences in quiet stance COP excursions between barefoot and shod standing (Brenton-Rule et al. 2011) or between different types of footwear (Lord et al. 1999), while several other studies found no significant difference between barefoot and shod conditions (Lord and Bashford 1996, Landry et al. 2010) or between different types of footwear (Lindemann et al. 2003, Whitney and Wrisley 2004, Van Geffen et al. 2007, Wilson et al. 2008, Brenton-Rule et al. 2011). Only for "extreme" cases of footwear, quiet stance experiments have been able to conclusively document an effect on the postural control system, for instance, for high heeled shoes (Menant et al. 2008) or for so called "unstable" shoes, such as the MBT™ shoe (Masai Barefoot Technology Inc., Switzerland) which creates increased instability through a rocker sole and a soft heel pad (Nigg et al. 2006a, Landry et al. 2010).

A direct assessment of the occurrence of falls in an elderly population provided conclusive evidence that footwear had a substantial effect on the risk of falls (Koepsell et al. 2004). In this study athletic style footwear and canvas shoes were associated with the lowest risk of fall while for barefoot or stocking conditions a 1.3-fold increased risk of falls was observed. This result suggests that postural control is affected by footwear. Since the results of COP excursion measurements did not conclusively reveal such a relationship, one might speculate that COP measurements might not be sensitive to all factors affecting postural control and static stability.

The COP position is a 2-dimensional “output” variable of the postural control system that gives only indirect clues about how the body maintains postural stability. Postural stability is facilitated by postural movements such as a sway of the whole body around the ankle joint, “ankle strategy”, or a motion around the hip joint, “hip strategy” (Horak, Nashner, & Diener, 1990; Winter, Prince, Frank, Powell, & Zabjek, 1996; Gatev, Thomas, Kepple, & Hallett, 1999). In recent years it has also been pointed out that the human body is a multi-joint system and that the movements around other joints (knee, upper body joints) are also important for postural control (Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007). Such individual multi-joint movement patterns are difficult to quantify, however, it has been demonstrated for dynamic movements such as walking (Troje, 2002; Daffertshofer, Lamoth, Meijer, & Beek, 2004) or cycling (Moore, Kooijman, Schwab, & Hubbard, 2011) that a principal component analysis (PCA) can be used to identify and quantify one-dimensional movement components in complex multi-joint whole body movements. This study is, to the best of our knowledge, the first study to apply PCA on postural movements in standing. We speculated that an investigation of the actual principal movement components conducted during postural control of quiet bipedal stance might be more sensitive to changes in footwear than the assessment of COP.

The purpose of this study was therefore to present an alternative approach to the conventional analysis of the COP excursion that focuses on a quantitative analysis of the postural movements that can be observed during quiet stance. Specifically, it was investigated if the effects of different footwear conditions on the postural control system by a quantitative analysis of the postural movements executed in quiet stance. Three footwear conditions were tested: standing barefoot, an athletic-type casual shoe, and an example of the so called “unstable shoes”. It was hypothesized that a) differences in the postural control movements would be observed between the unstable shoes and the other two footwear conditions, and b) that differences might also be identified between standing barefoot and standing in a normal casual shoe.

2. Methods

2.1. Participants

Twenty-nine subjects (13 women, 16 men; age 24,0 ± 3.1; height 1.76 ± 0.08 m; weight 71.9 ± 13.3 kg) volunteered for this study. All subjects gave informed written consent. The study was approved by the appropriate institutional ethics committee. Nineteen subjects used unstable shoes for the first time in this study (Table 1). Ten subjects had owned a pair of unstable shoes for at least two months and wore them sporadically. Hence, “experience on unstable shoes” was considered a covariat in this study. None of the subjects had a recent lower extremity injury or any other known physical or mental condition that might affect the ability to execute a balance exercise.

2.2. Test shoes

The athletic-type casual shoe tested in this study was an “Ekiden 100” manufactured by Kalenji®, Decathlon SA. France. The unstable shoe was a “Mwalk” manufactured by Masai Barefoot Technology Inc. (MBT™), Switzerland. The MBT shoes feature a slightly elevated stance height, a rounded sole, and a soft pad in the sole under the heel of the foot. Previous studies evaluating center of pressure (COP) excursions (Nigg et al. 2006a, Landry et al. 2010) suggested that these shoes increase instability in anterior-posterior (COP excursion app. 100% increased) and in medial-lateral direction (COP excursion between 50% and 100% increased).

2.3. Data collection

In each shoe condition the subjects performed one quiet standing trial of 100 seconds with the explicit task to “stand as quiet as possible". The subjects were instructed to place their hands on the hips and to look straight ahead. The subjects’ inside edges of the feet were aligned with tape markings on the floor such that the distance between the feet was 15 cm.

Postural control movements were recorded using 28 reflective markers placed on all major segments of the subjects’ body (Figure 1). Specifically, the marker were placed on the left and right lateral malleolus, lateral epicondyle of the knee, anterior and posterior superior iliac spine, acromio-clavicular joint, lateral epicondyle of the elbow joint, both sides of the wrist joint, on the sternum, claviculum, 7th cervical vertebrae, and four markers were attached to a head band. Four additional markers were placed on the calcaneous and the second metatarsal head of both feet. In the two shod conditions the latter markers were placed on the shoe surface as close as possible to the original position. The other markers were not changed between conditions. The trajectories of all markers were recorded with eight high-speed video cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) using a sampling rate of 240 Hz. After the measurements, the three-dimensional marker traces were reconstructed with the software Eva Real-Time (EvaRT) manufactured by Motion Analysis Corporation, Santa Rosa, CA, USA.

2.4. Data analysis

A period of 80 seconds was selected in each trial, from second 15 to second 95, to avoid movements due to stepping into or out of the balance task. In each video frame, an 84-dimensional posture vector was defined, which consisted of the 3D positions of the 28 markers. Any postural movement executed by a subject during the analyzed 80 seconds led to a change in posture and resulted therefore in a different posture vector. A principal component analysis (PCA) was performed on the 19200 posture vectors collected in each trial (80 seconds * 240Hz) in analogy to the procedures described by Troje (2002) or Daffertshofer et al. (2004) for gait analysis. The PCA identified correlated changes in the marker coordinates. The configuration of the marker coordinates quantifies the posture of the subject. Correlated changes in the coordinates of the markers therefore represent changes in posture or “postural movements”. For example, if hypothetically the subject moved according to the “ankle strategy”, all markers above the ankle joint move in the same direction. This correlated change in marker positions will therefore form one principal component vector. If the subject moved according to the “hip strategy” then markers above the hip will move in one direction while markers on and below the hip will move in the opposite direction. This correlated change in marker positions therefore forms a different solution of the PCA, i.e. another principal component vector. During a quiet stance trial the actual postural movements of a subject will be a combination of several postural movements executed in an individual subject-specific fashion. Applying the PCA to the marker coordinates hence offers a way of splitting the complex whole body movement into one-dimensional movement components that collectively form the postural movements. These one-dimensional movement components can then be quantitatively assessed. For simplicity we called these one-dimensional movement components “principal movements (PM)”. Similarly to the assessment of the COP the principal movements characterize how the body maintains postural stability, however, they have the advantage that they directly quantify changes in posture while in COP measurements it cannot be determined what type of movement may have accelerated caused a change in the COP position.

More specifically, the PCA yielded, a) a set of principle component vectors, which each indicate for their PM the direction of changes in marker positions, b) eigen values, EV, quantifying the variability in posture vectors that occurs in direction of the PM they represent, and c) coefficients obtained by projecting the posture vectors onto the principal component vectors. These coefficients form time series that describe for each time point the deviation from the mean posture in direction of the associated PM (Troje 2002, Daffertshofer et al. 2004). In other words, they quanify the individual postural movements that a subject executed during the quiet stance trial.

In this study, the following variables were determined to quantitatively compare the PMs between shoe conditions:

a) Normalized EVs were calculated by dividing each EV through the sum of all EVs. Hence, each normalized EV quantifies the contribution of its PM to the entire postural movements observed during the trial.
b) The maximal amplitudes of the PMs were quantified by calculating the full range of motion, r, of the coefficient time series.
c) The temporal variability was quantified by calculating the *persistence*, α, of the coefficient time series through a de-trended fluctuation analysis (Peng et al. 1995).

2.5. Statistics

Repeated-measures ANOVAs were performed to compare the results of different stance conditions. *Gender* and *experience on unstable shoes* were treated as covariats in this analysis. All statistical tests were carried out using the PASW 18.0 package (SPSS Inc., Chicago, IL, USA). The α-level was initially set at 0.05 and in pair wise comparisons adjusted using the Bonferroni correction.

3. Results

The relative contributions of the first five PMs to the entire postural variability are shown in Figure 2. Differences between the athletic/casual shoe and barefoot and between the athletic/casual shoe and the unstable shoes were significant in all of the first five principal movements. Differences between standing barefoot or in unstable shoes were not significant. The covariate *experience with unstable shoes* did not have a significant main or interaction effect. However, the covariate *gender* showed a significant main effect in PM3 and the interaction between gender and shoe condition was significant in PM1 and PM3.

The amplitude and temporal characteristics of the first five principal movements are shown in Figure 3. The movement amplitude of the first five principal movements, quantified by the range of motion, was significantly larger when standing in unstable shoe as compared to barefoot or athletic/casual shoes (Figure 3A). The difference between the barefoot and athletic/casual shoe amplitudes was not significant. The covariate *experience with unstable shoes* did not have a significant main or interaction effect. However, the interaction between the covariate *gender* and the shoe condition was significant in PM3.

The temporal movement characteristics, as quantified by the DFA persistence, showed significant differences between shoe conditions in the first three principal movements, (Figure 3B). In PM4 and PM5 a trend was observed in the pairwise comparison of barefoot and unstable shoe (p=0.068; p=0.078, respectively). Neither *experience with unstable shoes* nor *gender* had a significant main or an interaction effect in the persistence results.

4. Discussion

The characteristics of the postural movements quantified by a PCA showed clear differences not only between the unstable shoe and the other two footwear conditions, but also between the athletic-type casual shoe and the barefoot condition. Hence, both hypotheses were supported by the results of this study. The results also suggest that the PCA decomposition of the postural movements into one-dimensional principal movement components offers a promising alternative approach to study postural control in humans as compared to the conventional analysis of COP excursions.

A general feature in all graphs presented in this study is that the characteristics of the first principal movement (PM1) differ from the characteristics of the higher order principal components. This suggests that PM1 and higher order movement components may functionally serve a different purpose and should therefore be discussed individually. PM1 has the largest amplitude (Figure 3A) and is the most persistent movement component (Figure 3B). This suggests that PM1 represents the dominant postural sway that has to be controlled in order to maintain stability. Higher order movement components showed substantially reduced amplitudes and were increasingly less persistent (Figure 3B). Both of these observations could be an indication that it is easier for the postural control system to change the direction of these movements. One may hypothesize that the function of these higher order movement components is a modulation or possibly a correction of the dominant sway.

The observed differences between the three shoe conditions are consistent with this interpretation: When standing in an athletic shoe, which has been shown to carry the least risk of falling (Koepsell et al. 2004), the higher order movement components contributed more to the entire postural changes as compare to the less stable barefoot or unstable shoe conditions (Figure 2). One may speculate that the collar of the shoes might provide additional sensory information that triggers higher order postural control movements earlier than when standing barefoot. The collar of unstable shoes would then provide similar information to the postural control system, but the reduced base of support in these shoes creates a less stable situation that leads to substantially increased range of motion in all postural movement components.

The suggested interpretation is also consistent with an important paradigm in motor control research. This paradigm suggest that a decrease in the system complexity may be an indication of a decrease in the system’s ability to cope with perturbations, hence leading to a less stable situation and to a higher risk of fall (Lipsitz and Goldberger 1992, Goldberger et al. 2001, Vaillancourt and Newell 2002, Cavanaugh, J.T., Guskiewicz K.M., Stergiou N., 2005, Hong

2008). Newell (1998) proposed to interpret the “complexity of the postural control system” in the context of Bernstein’s degree of freedom problem (Bernstein, N., 1967) in the sense that a more complex system would be characterized by having more degrees of freedom and thus more states available, whereas a less complex system is characterized by fewer degrees of freedom and thus fewer accessible states. In this study the normalized EV quantified how much the different PMs contributed to the entire postural movements observed during a trial. In analogy to Newell’s interpretation we suggest that a situation where higher movement components contributed less to the entire postural movements could be interpreted as a less complex situation because the solution space of postures had fewer dimensions and therefore fewer states were accessible for the postural control system. A situation where higher order movement components contributed more would then be more complex since the solution space was spread out in more dimensions and thus more states were accessible for the postural control system. The postural movements when standing in the more stable athletic shoe contained more higher order movement components (Figure 2) and would in this interpretation be more complex and thus more stable. The “more one-dimensional” postural movements in barefoot would then indicate lower complexity and thus lower stability. For the more dynamic movement of walking a conceptually similar approach has already been developed by Verrel and colleagues (2009).

The results of this study also allow several interesting observations regarding the effects of unstable shoes. For example, a previous publication (Nigg et al. 2009) reported that subjects suffering from moderate lower back pain showed substantially decreased levels of perceived pain after regularly using MBT shoes for six weeks, however, it remained unclear what mechanism might have led to reduction of perceived pain. The results of this study showed that the amplitudes of all analysed PMs increased significantly and substantially (Figure 3B). This suggests that not only whole body sway is increased when standing in unstable shoes but also that hip and upper body movements are increased. Hence, it is possible that this increased activity might reduce muscle tension in the lower back and may thus contribute to decrease the level of perceived pain in some patients.

Some previous studies where subjects followed a strict protocol for the use of MBT shoes reported adaptation effects (Ramstrand et al. 2008, Nigg et al. 2006b, Landry et al. 2010, Stöggl et al. 2010). In our study some subjects had casually used MBT shoes before participating in the postural test. Apparently this casual use of the unstable shoes was not sufficient to cause an adaptation. Our results are thus in line with studies reporting no significant training effect (Ramstrand et al. 2010, Turbanski et al. 2011).

The covariate gender showed one significant main effect and several interaction effects with the shoe condition. The former would suggest that women and men might control upright posture differently. Current research on gender differences in postural control yielded inconsistent results: one study found no gender effects (Hageman et al. 1995), while other studies reported some differences between the sexes (Wolfson et al. 1994, Farenc et al. 2003). The interaction effect between gender and shoe condition suggests that women and men might respond differently to an unstable shoe. In gait, such gender differences have already been described (Nigg et al. 2010).

Finally, it needs to be pointed out, that this study describes effects of footwear and gender on the postural control movements that were found in young, healthy subjects. More research is needed to investigate if older subjects, who are more prone to falls, show similar differences.

4.1. Limitations of this study

In this study the principal movements were calculated for each individual trial. This avoided artefacts due to differences in marker placements or due to the difference in the mean posture of the different stances. A consequence of this approach is that the actual movement represented by each principal component is different from trial to trial and from subject to subject. This limitation might be overcome by applying PCA to the whole dataset that combines the all trials of all subjects. However, such an approach would need an appropriate normalization procedure, which would mean that not all kinematic and postural information collected in each trial would enter the analysis. Future research will show if such an analysis is still sensitive to changes in footwear.

5. Conclusions

This study used a novel approach for the analysis of how the postural control system maintains static stability in quiet stance. This approach identified and quantified the main movement components (principal movements) of the postural movements executed in each trial by performing a principal component analysis on the coordinates of a full-body marker setup. Significant differences were found between all three shoe conditions, i.e. barefoot, an athletic/casual shoe, and an unstable shoe. The observations in this study could be interpreted in line with the framework of a widely accepted paradigm of postural control research, which suggests that a higher movement complexity might indicate that a system is better suited to cope with perturbations and might therefore be more mechanically stable. According to this paradigm, standing barefoot or in unstable shoes was less stable than standing in a casual/athletic shoe. When standing in unstable shoes substantially increased ranges of motion were observed in the first five principal movements. This suggests that the reduced base of support leads to increased range of motion in all postural control strategies used by a subject to maintain stability, including hip and upper body movements. The differences in range of motion found between barefoot standing and the athletic/casual shoe were not significant.

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Tables

Table 1: Statistical data of the subjects included in this study.

	Experience		No experience	
	Women (n = 4)	Men (n = 6)	Women (n = 9)	Men (n = 10)
age [years]	26.00 * (2.00)	24.33 (2.07)	22.11 * (2.42)	24.80 (3.85)
weight [kg]	58.13 $^{+}$ (5.98)	84.73 $^{+}$ (17.74)	66.67 (8.62)	74.43 (8.39)
height [m]	1.65 */$^{+}$ (0.05)	1.80 $^{+}$ (0.06)	1.73 */$^{+}$ (0.06)	1.81 $^{+}$ (0.07)

Significant differences (Student's t-test) between experienced and non-experienced subjects are indicated with an asterisk (*), the plus symbol ($^{+}$) indicates significant gender differences.

Figure captions

Figure 1 Marker setup used in this study.

Figure 2 Eigen values EV of the first five principal movements (PM), which quantify the relative contribution of each PM to the entire postural variability. Each bar indicates the mean over all subjects, the error bars indicate the standard error of the mean (SE).

Figure 3 Characteristics of the first five principal movements: A) Range of motion quantifying the maximum amplitude. B) Persistence α calculated in a detrended fluctuation analysis (DFA). Each bar indicates the mean over all subjects, the error bars indicate the standard error of the mean (SE).

Figure 1 Marker setup used in this study.

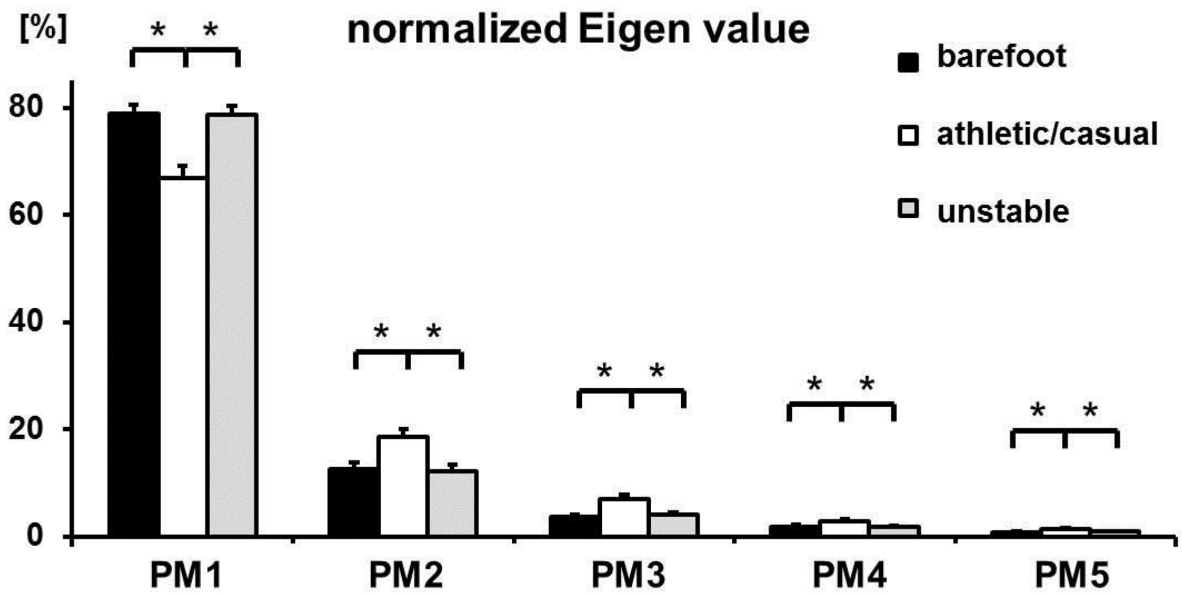

Figure 2 Eigen values EV of the first five principal movements (PM), which quantify the relative contribution of each PM to the entire postural variability. Each bar indicates the mean over all subjects, the error bars indicate the standard error of the mean (SE).

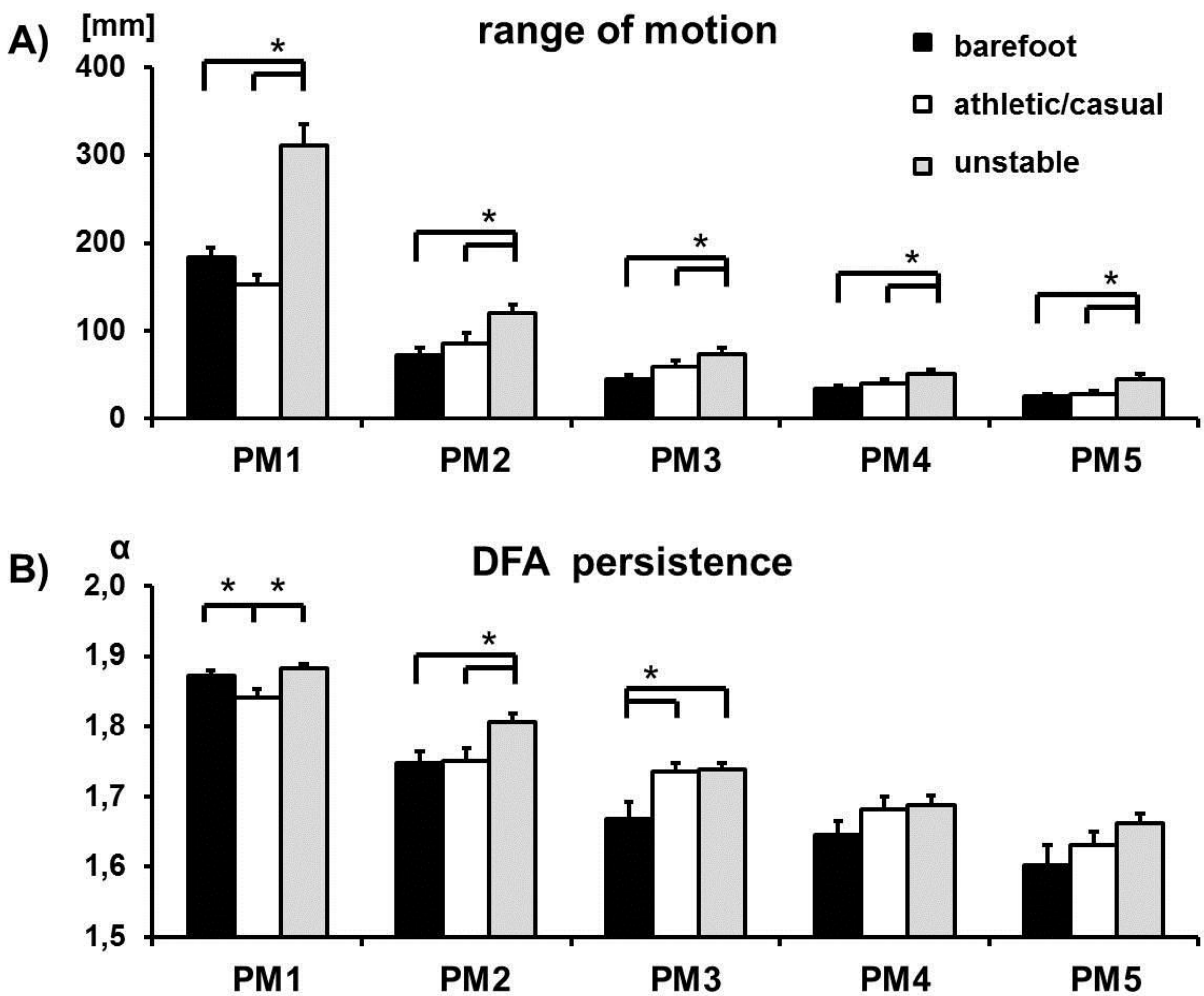

Figure 3 Characteristics of the first five principal movements (PM): A) Range of motion quantifying the amplitude. B) Persistence α calculated by detrended fluctuation analysis (DFA). Each bar indicates the mean over all subjects, the error bars indicate the standard error of the mean (SE).