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ORIGINAL ARTICLE

Effects of barefoot and footwear conditions on learning of a dynamic balance task: a randomized controlled study

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Abstract

Purpose Although barefoot balancing has shown to be more challenging compared to shod balancing, it is still unclear whether this may also influence the balance learning effects. The purpose of this study was to explore the impact of barefoot and shod exercising on learning of a dynamic balance task.

Methods Sixty healthy and physically active adults (mean age 25.3 ± 3.4 years) were randomly allocated into one of three groups (barefoot, shod and controls). The barefoot and shod intervention groups exercised once weekly over 7 weeks on a stability platform with an unstable surface. Each training session included 15 trials over 30 s. Before and after the intervention period, all participants completed two balance tests (stability platform and Balance Error Scoring System = BESS) under barefoot and shod conditions. Group effects in stability gains (pre to post-test differences) were analysed using ANOVA. Development of balance learning curves during the intervention period was analysed using a mixed effects model.

Results Balance times improved in both intervention groups ($p < 0.001$, 95% CI barefoot 5.82–9.22 s, shod 7.51–10.92 s) compared to controls. The barefoot intervention group showed a significantly less sloped balance learning curve compared to the shod intervention group ($p = 0.033$). No changes over time or differences between groups were found for the BESS test.

Conclusions Improvements in the dynamic balance task did not differ between individuals exercising barefoot or with footwear although the progression was slower in the barefoot group. The lack of changes in the BESS supports the task-specificity of balance learning effects.

Keywords Balance · Postural control · Barefoot · Shod · Motor learning

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Abbreviations

ANOVA	Analysis of variance
BESS	Balance error scoring system
CNS	Central nervous system
$\beta_{F,C}$	Intercept for the shod group
$\beta_{\Delta B,C}$	Differential intercept for the barefoot group compared to the shod group
$\beta_{F,L}$	Slope coefficient for the linear learning effect in the shod group
$\beta_{\Delta B,L}$	Differential slope coefficient for the linear learning effect in the barefoot group compared to the shod group
$\beta_{F,Q}$	Slope coefficient for the quadratic learning effect in the shod group
$\beta_{\Delta B,Q}$	Differential slope coefficient for the quadratic learning effect in the barefoot group compared to the shod group

Introduction

Individuals, especially in the Western population are used to footwear during most activities of daily living. From an anthropological perspective, barefoot walking is thought to be more natural and the use of footwear has long been discussed as an influencing factor on foot health and the development of movement patterns (Kurup et al. 2012). This is supported by studies showing that regular physical activities without footwear can be beneficial for the foot morphology, motor control and running foot strike patterns (Lieberman et al. 2010; Rao and Joseph 1992; Hollander et al. 2018; Zech et al. 2018). In detail, habitually barefoot living populations have a higher prevalence of wider feet (Rao and Joseph 1992), higher foot arches and fewer flat feet or hallux valgus conditions (Hollander et al. 2017a) when compared to shod living individuals. Regardless of the habituation to footwear, wearing shoes has an immediate effect on human biomechanics during standing and any kind of movement. Most types of footwear do not only change the standing and walking conditions due to cushioning but also provide an external fixation like a corset restricting the freedom of foot movement. This certainly changes the involvement of proximal body segments such as the ankle, knee and hip (Hall et al. 2013; Hollander et al. 2015). Furthermore, acute barefoot running in habitual shod individuals promotes forefoot striking, changes ankle and knee angles and reduces vertical forces during the touch down phase compared to shod running (Bishop et al. 2006; Lieberman et al. 2010; Hall et al. 2013; Hollander et al. 2014). These changes have long been discussed in association with a decreased risk for running related injuries, but no conclusive evidence was found (Nigg et al. 2015; Altman and Davis 2016; Hollander et al. 2017b).

Recently, differences in motor performance were shown between habitual shod and barefoot children and adolescents (Zech et al. 2018). The barefoot living individuals scored higher in the balance and jumping tasks. This finding indicates that learning of basic motor skills such as balance control is influenced by the use of footwear. However, this is still speculative since no prospective study has ever been performed on balance learning using barefoot vs. shod conditions. Balance skills are task-specific (Giboin et al. 2015) and highly adaptively, rapidly improving with increasing number of trials and training sessions (Taubert et al. 2010; Zech et al. 2010, 2014; Lesinki et al. 2015). Numerous sensory, biomechanical and coordination components have been described to interact with the performance during balancing (Horak et al. 1997). These include lower leg cutaneous, articular and muscular information (Horak et al. 1990) which can be differently influenced by presence or absence of footwear (Maurer et al. 2001; Corbin et al. 2007; Mildren and Bent 2016). Indeed, evidence exists that stabilization after jump landing (Zech et al. 2015) or standing balance control are impaired during barefoot conditions (Broscheid and Zech 2016; Federolf et al. 2012). This emphasizes that barefoot conditions might be more challenging for maintaining standing balance than shoe conditions and therefore, provide a different stimulus for balance learning.

The objective of this study was, therefore, to investigate whether learning of a dynamic balance task can be influenced by barefoot vs. shod conditions. Based on previous research, we hypothesized that due to the unfamiliar conditions, barefoot exercising will result in a slower learning progress than shod exercising. We used an established balance task able to elicit progressive improvements in motor performance during the time course of learning on the basis of central and peripheral adaptations (Taubert et al. 2010). We further examined if improvements in the dynamic balance task can be transferred to other dimensions of standing balance control.

Methods

Participants

Sixty healthy and physically active adults were included [mean age (SD) 25.3 (3.4) years; height 176.3 (7.6) cm; mass 70.6 (10.9) kg]. They were recruited among the sports student population of the local university. Inclusion criteria were an age between 18 and 35 years and regular physical activity using footwear. Exclusion criteria were regular participation in barefoot sports (e.g., gymnastics, judo, taekwondo), previous experience with the stabilometer platform and any lower extremity injury (acute or overuse) that prevented from participating in sports activities for at least 1 day in the previous 6 months. All participants were given detailed information on the study and written informed consent was obtained. The study was approved by the local ethics committee and was conducted in accordance with the Declaration of Helsinki.

Experimental design

A randomized controlled design was used for the prospective intervention study. Immediately after pre test, participants were randomly allocated into one of three groups (barefoot, shod and controls) using sealed envelopes.

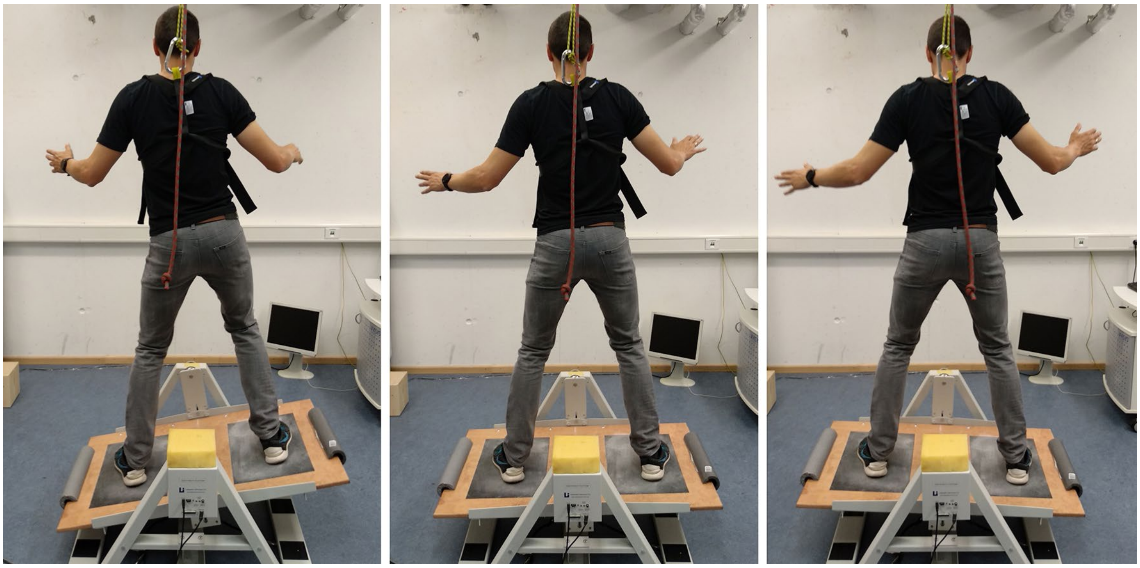


Fig. 1 Stability platform (stabilometer) used for balance exercising and testing

Procedures

The pre- and post-test procedure included a balance test on a stability platform (Stability Platform, Model 16030 L, Lafayette Instrument Company, Lafayette, IN, USA, Fig. 1) under barefoot and shod (ASICS, Kobe, Japan, Asics Cumulus 17) conditions.

The shoes had a 10 mm heel drop, no/neutral arch support and 336 g for US size 9. The order of barefoot and shod test conditions was counterbalanced across participants and each participant was randomly allocated to one order. The platform has been previously used in other studies on balance learning effects (Taubert et al. 2010; Rogge et al. 2017). All participants were given three 30 s-trials in each condition (barefoot and shod) after a 1-min trial for test familiarization. Participants were asked to keep the unstable surface (maximum deviation of 15°) of the platform as long as possible in a horizontal position (± 3° deviation) to each side of its horizontal alignment. No other instructions or verbal feedback was given to the participants before and during testing. One week after the final training session all participants completed post-tests using two balance trials on the stabilometer in the shod and barefoot condition.

In consideration of the task-specificity of balance exercises the transferability of potential improvements in the stabilometer test to other test situations of standing postural control was evaluated. Accordingly, the balance error scoring system (BESS test) was performed at pre- and post-tests (Bell et al. 2011; Docherty et al. 2006). The BESS test includes six 20 s standing conditions of increasing challenge using the double-leg, tandem and single-leg stance on firm and foam surfaces with closed eyed. In each condition the number of the standardized errors (lifting hands off, opening eyes, stepping, stumbling, falling, moving the hip, lifting the forefoot or heel, remaining out of the testing position for more than 5 s) was counted (Docherty et al. 2006).

Intervention

The intervention period for the barefoot and shod group started 1 week after pre tests and included seven training sessions on the stability platform. The intervention protocol was based on exercising conditions (stabilometer settings, number of repetitions and exercise volume) that has been previously successfully used to analyse motor learning effects (Taubert et al. 2010). Each training session comprised of 15 trials over 30 s with 1 min rest between trials. The time period between sessions was 6 days. All participants in the shod group used the same shoe model (fitted shoe size) for exercising (ASICS, Kobe, Japan, Asics Cumulus 17). No verbal feedback was given by the investigator throughout the training. The time the participants were able to keep the platform in a horizontal position (± 3° deviation) was measured in each trial. After each stabilometer exercise session, participants of both interventions groups performed a moderate and not exhausting treadmill running for 10 min with their allocated footwear condition to become familiar with the standardized shoe (shod group) and barefoot situation (barefoot group) during habitual bipedal locomotion.

Outcomes

Primary outcome was the total time a participant was able to balance within the ± 3° range of the horizontal position of the stabilometer platform during the 30 s trial. A longer time indicated a better balance performance. For pre- vs. post-test analysis the mean score of the three trials was calculated for barefoot and shod conditions in the three groups. To analyse the balance learning curve in both intervention groups, the mean time over the 15 trials was calculated for each of the seven exercise sessions.

Secondary outcome was the cumulative number of errors of the BESS test at pre and post-test.

Statistics

The group × time interaction effect in the paired (post- and pre-test) sample was analysed by testing for a group effect in the differenced (post-minus pre- test) data using ANOVA. Balance learning curves were analysed using a mixed effects model with a random intercept component and orthogonal polynomial contrasts. For computing the denominator degrees of freedom the Kenward–Roger approximation was applied. *P* values were adjusted for multiple testing (Benjamini and Hochberg 1995). Temporal improvements were modelled using orthogonal linear and quadratic polynomial contrasts, where the linear components model the slope of the regression curves (mean learning curves) and the quadratic components their curvatures. The degree of the polynomials was determined using a forward model selection process. To account for the individual effects in the repeated measurements design, we used a mixed effects regression model with Gaussian mean zero random intercept per participant and interaction effects between intervention groups and each component of the regression curves. The following model parameters were used: $\beta_{F,C}$ = intercept for the shod group; $\beta_{\Delta B,C}$ = differential intercept for the barefoot group compared to the shod group; $\beta_{F,L}$ = slope coefficient for the linear learning effect in the shod group; $\beta_{\Delta B,L}$ = differential slope coefficient for the linear learning effect in the barefoot group compared to the shod group; $\beta_{F,Q}$ = slope coefficient for the quadratic learning effect in the shod group; $\beta_{\Delta B,Q}$ = differential slope coefficient for the quadratic learning effect in the barefoot group compared to the shod group. P-values were adjusted to control the false discovery rate of this multiple testing problem (Benjamini and Hochberg 1995). Statistical analysis was performed using R (version 3.2.3).

Results

At baseline, there were no statistically significant differences between groups in age ($p = 0.868$), mass ($p = 0.638$), height ($p = 0.605$), BMI ($p = 0.405$), sex ($p = 0.984$), foot length ($p = 0.367$), shoe size ($p = 0.381$), and balance tests (shod on stabilometer: $p = 0.994$; barefoot on stabilometer: $p = 0.734$; BESS: $p = 0.268$). Out of the 60 participants seven did not complete the study (two in the shod group, one in the barefoot group and four in the control group) indicating a drop out rate of 11.7%. Mean adherence to balance exercising was 97.9% ± 5.1% (barefoot group: 97.1% ± 5.9%, shod group: 98.6% ± 4.3%).

Pre to post-test effects

Table 1 shows the summarized statistics of stabilometer measurements at pre- and post-tests, for each group and each test condition. Regarding pre to post-test effects, one-way ANOVA for differenced (post-minus pre-test) data showed significant between group effects ($p < 0.001$) for both testing conditions (Table 2). Post hoc *t* tests (Bonferroni adjusted) showed significant differences between the barefoot group and control group ($p < 0.001$), and the shod group and control group ($p < 0.001$) for both balance test conditions. No differences were found between both intervention groups (shod balancing: $p = 0.35$; barefoot balancing: $p = 1.000$) although there was a tendency towards higher improvements in the shod test condition for the shod intervention group (Fig. 2).

Balance learning curves

The estimation results for balance learning differences between both intervention groups are shown in Table 3. Mean curves significantly differ in their slope coefficients of the linear learning effects ($p = 0.033$). As seen in Fig. 3, the barefoot group initially showed better balance skills on the stabilometer than the shod group while the shod group catches up over the first three training sessions. There were no significant differences between the intervention groups in each exercise session.

Transfer effects to other balance skills

No group effects were found for pre (barefoot group: 16.6 ± 5.9; shod group: 13.9 ± 4.2; controls: 15.6 ± 5.1) vs. post-tests (barefoot group: 14.5 ± 5.4; shod group: 12.4 ± 3.3; controls: 14.1 ± 5.1) differences in the BESS score (Fig. 4).

Table 1 Pre- and post-test mean ± SD of the stabilometer performance (s) in the three groups for shod and barefoot test conditions

	Barefoot testing (s)		Shod testing (s)	
	Pre-test	Post-test	Pre-test	Post-test
Barefoot group	11.44 ± 4.30	19.57 ± 5.44	10.51 ± 3.67	18.03 ± 5.59
Shod group	10.99 ± 3.36	19.54 ± 3.44	10.50 ± 3.26	19.72 ± 3.70
Controls	10.49 ± 2.67	13.26 ± 3.26	10.39 ± 3.18	12.51 ± 2.87

Table 2 One-way ANOVA effects between groups

	Pre- to post-test difference (s)		95% CI	Effects		
	Mean	SD		*p* value	*F*	Generalized eta-squared
Shod testing						
Barefoot group	7.52	3.53	5.815–9.217	< 0.001	22.163	0.470
Shod group	9.21	3.43	7.509–10.916			
Controls	2.12	2.50	0.789–3.453			
Barefoot testing						
Barefoot group	8.14	3.46	6.472–9.803	< 0.001	14.638	0.369
Shod group	8.54	3.91	6.600–10.488			
Controls	2.77	2.80	1.281–4.268			

Fig. 2 Comparisons between groups for the pre- to post-test differences (time in s) and 95% family-wise confidence intervals regarding balance time on the stabilometer under shod and barefoot testing

Table 3 Estimation results for the fixed effects model components of motor learning curve comparison between both intervention groups

Parameter	Estimate	Std. Error	Adj. *p* value
$\beta_{F,C}$	17.801	0.928	< 0.001
$\beta_{\Delta B,C}$	− 0.044	1.359	0.974
$\beta_{F,L}$	4.784	0.408	< 0.001
$\beta_{\Delta B,L}$	− 1.381	0.597	0.033
$\beta_{F,Q}$	− 1.214	0.408	0.007
$\beta_{\Delta B,Q}$	0.635	0.597	0.347

F = shod group; B = barefoot group; C = intercept; L = slope coefficient for the linear learning effect; Q = slope coefficient for the quadratic learning effect; *Δ* = differential effects compared to the shod group

One-way ANOVA showed no significant effects between groups for the pre- to post-test differences ($p = 0.902$).

Discussion

The major finding is that footwear differently influences the learning of a dynamic balance task over time, but has no impact on the amount of improvements after completion of the intervention period. The improvements in standing postural control are in accordance with other studies evaluating the effects of balance exercising in healthy, physically active and young adults (Taubert et al. 2010; Zech et al. 2010; Lesinki et al. 2015; Hrysomallis 2011). We observed significant improvements in both intervention groups compared to non-trained controls. This is in agreement with Taubert et al. (2010), who used the same dynamic balance task on the stabilometer for six training sessions in healthy young adults. However, the improvements in our study were exclusively found in the same balance task that was used for exercising. No changes were observed in the BESS test. The task-specificity of balance tasks have previously been reported (Kümmel et al. 2016; Giboin et al. 2015; Zech et al. 2014).

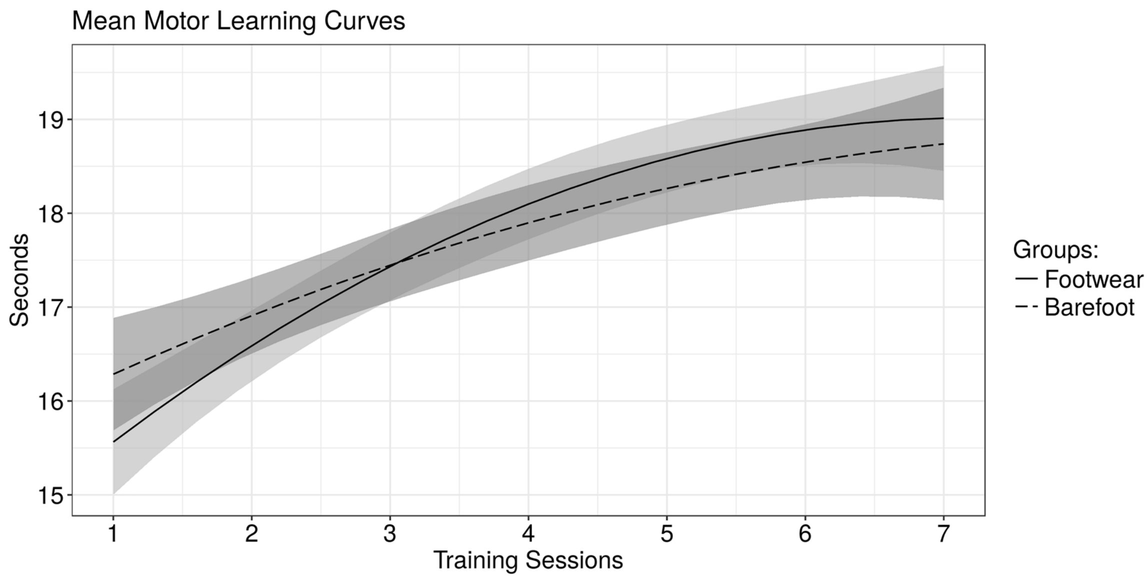
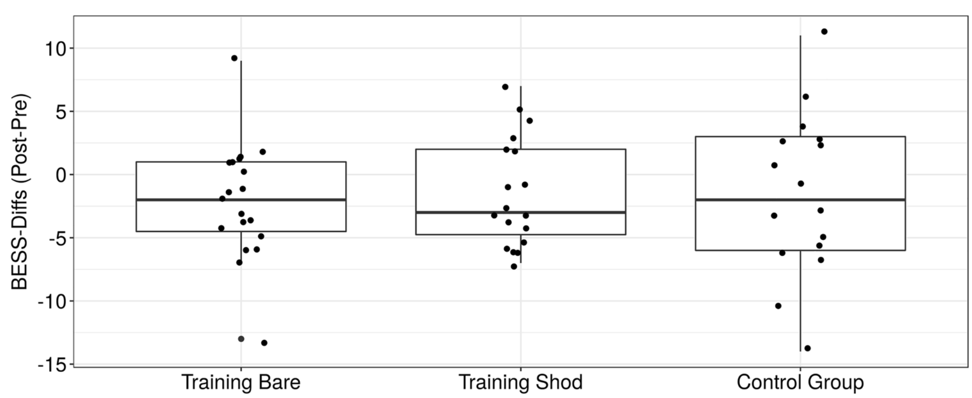


Fig. 3 Mean learning curves (with 95% confidence intervals) for balance time on the stabilometer in both intervention groups over the seven training sessions

Fig. 4 Boxplots for pre- vs. post-test differences in the BESS score in all groups



Considering that standing postural control seems particularly influenced by joint somatosensory information from the lower legs (Fitzpatrick and McCloskey 1994) we expected that balance learning would be influenced by barefoot or shod conditions. Indeed, we found significantly different learning curves between the barefoot vs. shod groups. The shod group improved balance control faster, whereas the barefoot group showed flatter learning curves. A possible explanation may be that barefoot activities are more unfamiliar or / and provide a greater sense of instability due to lower stiffness around the ankle or foot or alterations in muscle activation (Bishop et al. 2006; Shultz et al. 2012; Federolf et al. 2012). However, due to the lack of additional assessments the attribution of the observed footwear vs. barefoot impact to one or multiple underlying physiological mechanisms remains speculative. In this context, future studies investigating the influence of barefoot exercising on improvements in balance performance should consider the use of electromyography, magnetic resonance imaging or other neurophysiology approaches (e.g., peripheral nerve stimulation, transcranial magnetic stimulation) to get a better insight into the adaptation processes.

Although this indicates that footwear is more beneficial than barefoot situations for learning of a dynamic balance task several limitations should be taken into account for interpretation. First, all participants in our study were habitual shod living individuals. The habituation to footwear or barefoot activities influences foot anthropometrics and running gait control (Hollander et al. 2017a, 2018). Habitually barefoot living individuals may, therefore, respond differently to balance interventions with or without footwear. Second, the effects were shown only for the stabilometer balance task. Due to the task-specificity of balance abilities (Giboin et al. 2015; Kümmel et al. 2016), other balance task could be differently influenced by the presence or absence of footwear. It is also possible that different exercise protocols with longer intervention periods and a higher number or frequency of sessions could change the amount of improvements in the balance task. Third, the participants were recruited in a healthy sports student population limiting the generalizability of findings to other populations. The greatest development in balance abilities can be observed during childhood and adolescent years (Woll et al. 2011). Furthermore, older individuals particularly benefit from balance interventions due to positive effects on fall risk management, motor function, cognitive function and quality of life. Barefoot activities in these populations may be more demanding for motor coordination (Broscheid and Zech 2016) and could differently influence improvements compared to the healthy adult population. Nevertheless, our findings favour the use of footwear for quick improvements in balance control in healthy, habitually shod living individuals compared to barefoot situations. However, both conditions lead to similar improvements after at least seven exercise sessions using a single balance task.

Conclusions

In conclusion, balance improvements after a 7-week exercise period did not differ between individuals exercising barefoot or shod. However, the progression of improvements was slower in the barefoot group. The specific mechanism contributing to this effect and dimensions of adaptations during learning should be further investigated using different populations with or without physical impairments as well as various balance tasks for exercising.

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Author contributions AZ, KaHo and KM conceived and designed research. SM and KaHo conducted experiments. DL performed the statistical analysis. SM, KaHo and KiHo analyzed data. AZ wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest related to the publication of this article.

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