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Title	The Effects of Barefoot and Shod Running on Limb and Joint Stiffness Characteristics in Recreational Runners.
Type	Article
URL	https://clok.uclan.ac.uk/11945/
DOI	
Date	2015
Citation	Sinclair, Jonathan Kenneth, Atkins, Stephen and Taylor, Paul John (2015) The Effects of Barefoot and Shod Running on Limb and Joint Stiffness Characteristics in Recreational Runners. Journal of Motor Behavior, 1 (7).
Creators	Sinclair, Jonathan Kenneth, Atkins, Stephen and Taylor, Paul John

Journal of Motor Behavior, Vol. 0, No. 0, 2015

RESEARCH ARTICLE

The Effects of Barefoot and Shod Running on Limb and Joint Stiffness Characteristics in Recreational Runners

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ABSTRACT. The authors aimed to determine the effects of barefoot (BF) and several commercially available barefoot-inspired (BFIS) footwear models on limb and joint stiffness characteristics compared with conventional footwear (CF). Fifteen male participants ran over a force platform at 4.0 m.s^{-1}, in BF, BFIS, and CF conditions. Measures of limb and joint stiffness were calculated for each footwear. The results indicate that limb and knee stiffness were greater in BF and minimalist BFIS than in CF. CF and more structured BFIS were associated with a greater ankle stiffness compared with BF and minimalist BFIS. These findings serve to provide further insight into the susceptibility of runners to different injury mechanisms as a function of footwear.

Keywords: barefoot, stiffness, running, biomechanics

Research interest into the biomechanics of barefoot (BF) running has expanded considerably in recent years. The increase in popularity of BF running is based on the pretext that the absence of footwear is more natural and may also be associated with a reduced incidence of chronic injuries when compared with traditional running footwear (Lieberman et al., 2010). In response to the recent interest in BF running, new footwear models have been developed that are designed to integrate the benefits of running BF into a shod condition (Sinclair, Hobbs, Currigan, & Taylor, 2013). Several BF-inspired shoe (BFIS) models are now commercially available and vary considerably in terms of their design characteristics from minimalistic to more structured designs that offer some degree of midsole interface (Sinclair, Greenhalgh, Edmundson, Brooks, & Hobbs, 2013; Sinclair, Hobbs et al., 2013).

The importance of lower extremity limb stiffness is now recognized in biomechanical literature, as we seek to gain more insight into the mechanics of human locomotion and obtain more clinically relevant information regarding the etiology of chronic lower limb injuries (Butler, Crowell, & Davis, 2003). Stiffness is a reflection of the force applied to a body and the resultant deformation of that body (Latash & Zatsiorsky, 1993). During landing movements such as running, the support limb is modeled using a spring mass system (Blickhan, 1989), whereby the stance limb is indicative of a linear spring and the body mass is representative of the point mass (McMahon & Cheng 1990). The stance limb spring is able to shorten and lengthen as lower extremity joints flex and extend (Farley & Morgenroth, 1999).

Limb stiffness during running has been associated with both performance and injury etiology (Dutto & Smith, 2002; Granata, Padua, & Wilson, 2001; Kerdock, Biewener, McMahon, Weyand, & Herr, 2002; Williams, McClay Davis, Scholz, Hamill, & Buchanan, 2003). Limb stiffness is required for energy to be stored and released during the stance phase as a function of the stretch-shorten reflex (Arampatzis, Bruggemann, & Metzler, 1999). Indeed, higher levels of stiffness at the lower extremity joints during the absorption phase of running have been shown to effectively precondition the muscle-tendon units to store and utilize energy more effectively, which enhances mechanical efficiency and power during the push-off phase (Kyrolainen, Belli, & Komi, 2001). With regards to clinical effects, lower than optimal levels of limb stiffness have been associated with an enhanced susceptibility to soft tissue injuries, whereas higher leg stiffness indices have been linked to an increased risk of bone-related injuries (McMahon, Comfort, & Pearson, 2012).

In addition to limb stiffness it has also been suggested that the stiffness characteristics of the individual lower extremity joints be considered (Hamill et al., 2009). Q2 Measures of joint stiffness are important as they can be related to the attenuation of load transmission through the musculoskeletal system (Hamill et al., 2014). Q3 Joint stiffness is a reflection of the joint moment-angle relationship and can be modeled as a torsional spring system (Williams et al., 2003). Clinically, increased joint stiffness has also been linked to the etiology of chronic injuries as higher stiffness leads to an enhanced load imposed on the joint comparison to a more compliant joint (Hamill et al., 2009).

The mechanics of running BF and BFIS have been examined extensively to better understand the biomechanical effects of running without shoes. To date, the effects of BF and BFIS on limb stiffness characteristics have received little attention in biomechanical research. Several investigations have confirmed that running BF is associated with significantly greater limb stiffness in relation to conventional running shoes (CF; De Wit, De Clercq, & Aerts, 2000; Divert, Baur, Mornieux, Mayer, & Belli, 2005; Shih, Lin, & Shiang, 2013). Only one study however, has examined the effects of BFIS. Lussiana, Hébert-Losier, and Mourot (2014) demonstrated that limb stiffness was significantly larger in BFIS in comparison with CF.

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However, while the effects of BF and BFIS on limb stiffness parameters have previously been investigated, researchers did not consider the stiffness parameters of the lower extremity joints. The aim of the present investigation was to determine the effects of BF and several commercially available BFIS models on limb and joint stiffness characteristics in comparison to CF. In this study we tested the hypothesis that (a) running BF and in minimalist BFIS would be associated with significantly greater limb stiffness compared to CF and (ii) knee joint stiffness would significantly larger when running BF and in minimalist BFIS in comparison to CF, whereas ankle stiffness would be greater in CF.

Method

Participants

Fifteen male runners, completing at least 35 km per week, volunteered to take part in this study. All were free from musculoskeletal pathology at the time of data collection and provided written informed consent. All participants were nonhabitual BF runners and deemed to exhibit a heel-toe running pattern as they demonstrated an impact peak in their vertical ground reaction force time curve when wearing conventional footwear (Cavanagh & Lafortune, 1980). The mean characteristics of the participants were the following: age 23.5 ± 2.5 years, height 1.75 ± 0.05 m, and body mass 72.2 ± 6.7 kg. The procedure utilized for this investigation was approved by the University of Central Lancashire, School of Sport Tourism and Outdoors, ethical committee in agreement with the principles outlined in the declaration of Helsinki. No external funding was provided by any of the footwear manufacturers examined in this investigation.

Experimental Footwear

The shoes utilized during this study consisted of a Saucony Pro Grid Guide II, Vibram Five Fingers, Vivo barefoot Ultra, Merrell Bare Access, Inov-8 Evoskin, and Nike Free 3.0. The shoes were the same for all runners; they differed in size only (sizes 7–10 in men's UK shoe sizes). In accordance with previous recommendations the Vibram Five Fingers, Merrell, and Inov-8 were considered to be minimalist BFIS and the Nike Free and Vivo were classified as structured BFIS (Sinclair, 2014; Sinclair, Hobbs et al., 2013).

Procedure

Participants ran at 4.0 m.s^{-1}, striking a force platform (Kistler, Kistler Instruments Ltd., Alton, England; length, width, height = 0.6 × 0.4 × 0.0 m) embedded in the floor (Altrosports 6mm, Altro Ltd,) with their right foot (Sinclair, Hobbs, Taylor, Currigan, & Greenhalgh, 2014). The force platform sampled at 1000 Hz. Running velocity was quantified using Newtest 300 infrared timing gates (Newtest, Oy Koulukatu, Finland), and a maximum deviation of ±5% from the predetermined velocity was allowed. The stance phase was delineated as the duration over which >20 N of vertical force was applied to the force platform (Sinclair, Edmundson, Brooks, & Hobbs, 2011). Runners completed five successful trials in each footwear condition. A successful trial was defined as one within the specified velocity range and where the foot made full contact with the force plate and no evidence of gait modifications due to the experimental conditions. The order in which participants ran in each footwear condition was randomized.

Kinematics and ground reaction force (GRF) data were synchronously collected. Kinematic data were captured at 250 Hz via an eight-camera motion analysis system (Qualisys Medical AB, Goteborg, Sweden). Lower extremity segments were modeled in 6-DOF using the calibrated anatomical systems technique (Cappozzo, Catani, Leardini, Benedeti, & Della, 1995). To define the segment coordinate axes of the right shank and thigh, retroreflective markers were placed unilaterally onto medial and lateral malleoli, medial and lateral epicondyles of the femur, and also the greater trochanter. Carbon fiber tracking clusters were positioned onto the shank and thigh segments. Static calibration trials were obtained allowing for the anatomical markers to be referenced in relation to the tracking markers and clusters. The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right hand rule and was oriented from medial to lateral.

Data Processing

Retroreflective markers were digitized using Qualisys Track Manager to identify markers and then exported as C3D files to Visual 3D (C-Motion, Germantown, MD). GRF and retroreflective marker trajectories were filtered at 50 and 12 Hz, respectively, using a low-pass Butterworth fourth-order zero-lag filter (Sinclair, 2014). Knee and ankle joint kinematics were calculated using an XYZ sequence of rotations (where X represents sagittal plane, Y represents coronal plane, and Z represents transverse plane rotations; Sinclair, Taylor, Edmundson, Brooks, & Hobbs, 2012). Newton-Euler inverse dynamics were also adopted, which allowed knee and ankle joint moments to be calculated. To quantify joint moments, segment mass, segment length, GRF, and angular kinematics were utilized. All kinematic waveforms were normalized to 100% of the stance phase before processed trials were averaged within subjects. Discrete kinematic measures from the knee and ankle extracted for statistical analysis were (a) angle at footstrike, (b) peak angle, (c) joint angular excursion (representing the angular displacement from footstrike to peak angle), and (d) peak joint moment.

Estimation of limb stiffness during running used a mathematical spring-mass model (Blickhan, 1989). Limb stiffness was calculated from the ratio of the peak vertical GRF to the maximum compression of the leg spring which was calculated as the change in thigh length from footstrike to minimum thigh length during the stance phase (Farley & Morgenroth, 1999). The torsional stiffness of the knee and ankle joints were calculated as a function of the ratio of the change in sagittal joint moment to joint angular excursion in the sagittal plane between the beginning of the ground contact phase and the instant when the joints were maximally flexed (Farley & Morgenroth, 1999). Limb/joint stiffness and joint moment parameters were normalized to body mass. Limb stiffness was expressed as N.kg.m^{-1}, joint moments as Nm.kg^{-1}, and joint stiffness as $\text{Nm.kg}^{-1}.\text{rad}^{-1}$.

Statistical Analysis

Differences in limb and joint stiffness parameters across all of the different footwear conditions were examined using one-way repeated measures ANOVAs, with significance accepted at the $p \leq .05$ level. Effect sizes were calculated using partial omega^2 (pω^2). Post hoc pairwise comparisons were conducted on all significant main effects. The data was screened for normality using a Shapiro-Wilk test, which confirmed that the normality assumption was met. All statistical actions were conducted using SPSS version 22.0 (SPSS Inc., Chicago, IL).

Results

Table 1 and Figures 1–2 present the footwear differences in limb and joint stiffness. The results also indicate that the experimental footwear significantly affected limb and knee joint stiffness parameters.

Joint Kinematics

At the knee a main effect ($p \leq .05$, p$\omega^2 = .33$) was shown for knee angle at footstrike. Post hoc analysis showed the BF condition exhibited greater flexion at footstrike than the CF, Nike Free, and Vivo footwear (Table 1, Figure 1a). There was also a main effect ($p \leq .05$, p$\omega^2 = .28$) noted for knee excursion. Post hoc analysis revealed that excursion was larger in the CF and Nike Free conditions compared with BF (Table 1, Figure 1a). Finally a main effect ($p \leq .05$, p$\omega^2 = .29$) for the peak knee extensor moment. Post hoc analysis indicated that the peak moment was greater in the CF and Nike Free footwear in comparison with BF (Table 1, Figure 1b).

At the ankle a main effect ($p \leq .05$, p$\omega^2 = .28$) was shown for the angle at footstrike. Post hoc analysis showed that the BF condition was associated with a more plantarflexed ankle position compared with the CF and Nike Free footwear (Table 1, Figure 1c). In addition a main effect ($p \leq .05$, p$\omega^2 = .29$) was shown for peak dorsiflexion. Post hoc analysis showed that the BF and Inov-8 conditions exhibited a larger peak dorsiflexion compared with the CF, Nike Free, Vivo, and Merrell footwear (Table 1, Figure 1c). There was also a main effect ($p \leq .05$, p$\omega^2 = .62$) for ankle excursion. Post hoc analysis revealed that ankle excursion was larger in the BF and Inov-8 conditions compared with the CF, Nike Free, and Vivo footwear (Table 1, Figure 1c). Finally a main effect ($p \leq .05$, p$\omega^2 = .61$) for the peak ankle plantarflexor moment. Post hoc analysis indicated that ankle plantarflexor moments were larger in the BF and Inov-8 conditions compared with the CF and Nike Free footwear (Table 1, Figure 1d).

Spring Mass Characteristics

A main effect ($p \leq .05$, p$\omega^2 = .22$) was shown for limb compression. Post hoc analysis revealed that limb compression was larger in the CF and Nike Free footwear compared with the BF and Inov-8 conditions (Table 1, Figure 2b). In addition a main effect ($p \leq .05$, p$\omega^2 = .23$) was observed for limb stiffness. Post hoc analysis revealed that limb stiffness was larger in the BF, Inov-8, and Merrell conditions compared with the CF and Nike Free footwear (Table 1, Figure 2a). There was also a main effect ($p \leq .05$, p$\omega^2 = .22$) for knee stiffness. Post hoc analysis revealed that knee stiffness in the BF condition was larger than the CF and Nike Free footwear (Table 1, Figure 2c). Finally, a main effect ($p \leq .05$, p$\omega^2 = .23$) was observed for ankle stiffness. Post hoc analysis revealed that ankle stiffness was larger in the CF, Nike Free, and Vivo footwear compared with the BF and Inov-8 conditions (Table 1, Figure 2d).

Discussion

In the present investigation we aimed to determine the effects of BF and BFIS on limb and joint stiffness parameters in comparison to CF. There is presently little published research concerning the effects of BF and BFIS on limb and joint stiffness characteristics during running. The current investigation provides additional information by comparatively examining the limb and joint stiffness characteristics of running in BF and BFIS compared to CF.

The first key finding from the current investigation is that limb stiffness was shown to be larger when running BF and in minimalist BFIS in comparison to CF and more structured BFIS. This observation is in agreement with our hypothesis and concurs with the observations of De Wit et al. (2000), Divert et al. (2005), Shih et al. (2013), and Lussiana et al. (2014), who also reported significant increases in limb stiffness when running BF and in BFIS. It

TABLE 1. Limb and Joint Stiffness Characteristics as a Function of Different Footwear

	Barefoot		Conventional		Vibram Five Fingers		Inov-8		Merrell		Nike Free		Vivo		
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
Knee footstrike (rad)	0.25	0.1	0.14	0.11	0.21	0.13	0.23	0.11	0.19	0.12	0.11	0.13	0.11	0.17	*
Knee peak flexion (rad)	0.64	0.14	0.64	0.14	0.66	0.15	0.65	0.14	0.62	0.13	0.61	0.13	0.57	0.15	
Knee excursion (rad)	0.39	0.07	0.5	0.06	0.45	0.05	0.42	0.06	0.44	0.09	0.5	0.09	0.46	0.12	*
Ankle footstrike (rad)	−0.01	0.2	0.12	0.16	0.03	0.12	0.03	0.16	0.03	0.17	0.12	0.11	0.05	0.18	*
Ankle peak dorsiflexion (rad)	0.38	0.12	0.32	0.11	0.33	0.12	0.4	0.12	0.28	0.11	0.3	0.13	0.29	0.12	*
Ankle excursion (rad)	0.39	0.12	0.2	0.1	0.3	0.09	0.37	0.11	0.26	0.14	0.18	0.06	0.24	0.11	*
Limb compression (m)	0.04	0.01	0.05	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.05	0.01	0.05	0.01	*
GRF (N.kg^{-1})	21.41	3.35	21.15	3.56	21.28	3.03	21.13	2.66	21.87	4.72	19.94	3.88	21.44	2.77	
Knee moment (Nm.kg^{-1})	2.63	0.81	2.91	0.78	2.76	0.77	2.75	0.90	2.82	0.67	2.88	0.64	2.72	0.87	*
Ankle moment (Nm.kg^{-1})	−2.54	0.40	−2.32	0.48	−2.50	0.41	−2.55	0.46	−2.43	0.62	−2.30	0.58	−2.55	0.68	
Limb stiffness (Nkg.m^{-1})	610.21	210.34	460.17	140.54	560.38	110.87	620.48	280.22	680.77	470.53	480.89	260.34	490.11	140.79	*
Knee stiffness (Nm.kg^{-1}.rad^{-1})	7.07	2.78	5.88	1.34	6.28	1.44	6.57	1.84	6.68	1.88	5.79	1.26	5.96	2.30	*
Ankle stiffness (Nm.kg^{-1}.rad^{-1})	7.21	1.52	11.72	5.84	9.35	2.42	7.31	2.11	11.13	4.26	13.52	2.43	11.32	2.80	*

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is proposed that this observation relates to the decrease in limb compression noted during BF and minimalist conditions which in conjunction with the similar GRF values observed between footwear leads to higher limb stiffness.

It is proposed that decreases in limb compression were caused by the reduced stance times typically associated with BF and BFIS compared with the CF. Morin, Samozino, Zameziati, and Belli (2007) and Hamill, Russell, Gruber, and Miller (2011) demonstrated that reduced stance times are associated with increases in limb stiffness, with alterations in contact time associated with up to 90% of the change in limb stiffness. Clinically, higher levels of limb stiffness have been linked to an increased risk from bone-related injuries, supporting the observations of Sinclair, Hobbs, et al. (2013) and Sinclair, Taylor, and Andrews (2013), who showed significant increases in tibial accelerations when running BF. As such running BF and in minimalist BFIS appears to place runners at increased risk from bone injuries yet increased stiffness may protect from injuries to the soft tissues (McMahon et al., 2012).

In addition, the findings from this study confirmed that knee stiffness was larger in the BF condition compared with the CF and structured BFIS. This observation serves to support our hypothesis and is likely to relate to the reduction in knee excursion noted when running BF, particularly in light of the concurrent reduction in knee extensor moment. Decreased knee excursions noted

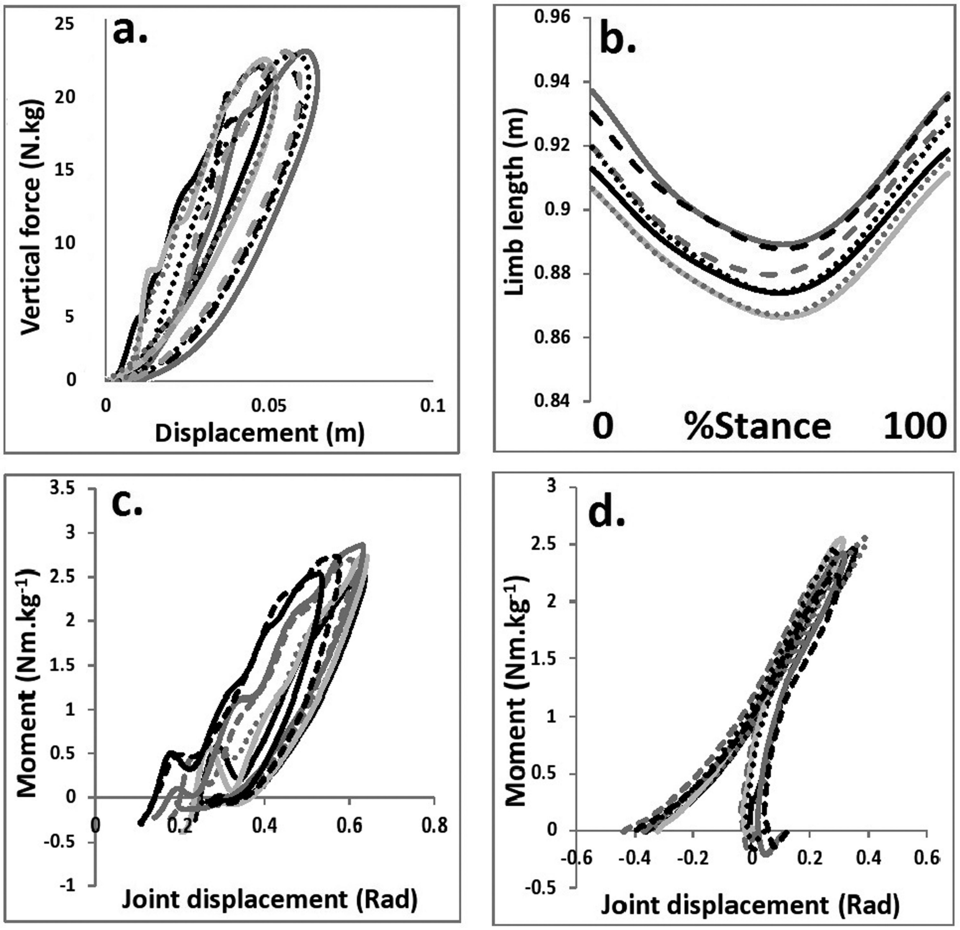

FIGURE 1. Knee and ankle kinetics and kinematics as a function of footwear: (a) = knee angle, (b) = knee extensor moment, (c) = ankle angle, and (d) = ankle plantarflexor moment. FL = flexion, EXT = extension, DF = dorsiflexion, PF = plantarflexion; barefoot = black, Nike Free = black dash, conventional = dark grey, Vibram five-fingers = light grey, Vivo = dot, Merrell = dark grey dash, Inov-8 = dark grey dot.

when running BF agree with the observations of Sinclair, Greenhalgh, et al. (2013) and Sinclair, Hobbs, et al. (2013) and may also subsequently relate to the decreased stance phase durations observed when running without shoes. Decreases in stance phase duration facilitates an increase in step frequency which served to reduce the role of the knee joint for energy absorption during the impact phase of running (Kulmala, Avela, Pasanen, & Parkkari, 2013), thus the flexion range of motion is reduced.

Similarly, in support of our hypothesis the findings show that ankle stiffness was higher in the CF and structured BFIS conditions. This observation relates to the increase in ankle excursion noted when running BF. Increased ankle excursions were a function of the increases in plantarflexion at footstrike noted when running BF and in minimalist BFIS (Sinclair, Greenhalgh, Edmundson, Brooks, & Hobbs, 2013; Sinclair, Hobbs et al., 2013). The increases in knee and ankle moments in the CF and BF conditions are in agreement with the findings of Sinclair (2014), who noted similar findings in relation to joint kinetics. Therefore the current investigation also provides further support to the notion that running BF and in minimalist BFIS may attenuate the risk of knee pathologies but also subsequently place runners at increased risk from ankle injuries (Kulmala et al., 2013; Sinclair, 2014).

A limitation of the present study that may reduce its generalizability is that only male runners were examined. Females exhibit distinct kinetics and kinematics when compared to male recreational runners (Ferber, Davis, & Williams, 2003; Sinclair, Greenhalgh, Edmundson, Brooks, & Hobbs, 2012b). In addition, women have also been shown to differ in their limb stiffness parameters in relation to males (Granata et al., 2001). This therefore suggests that further investigation using a female sample is warranted. In addition that only nonhabitual BF runners were examined may serve as a limitation to this work. Research investigating the kinetics of BF running in shod populations has

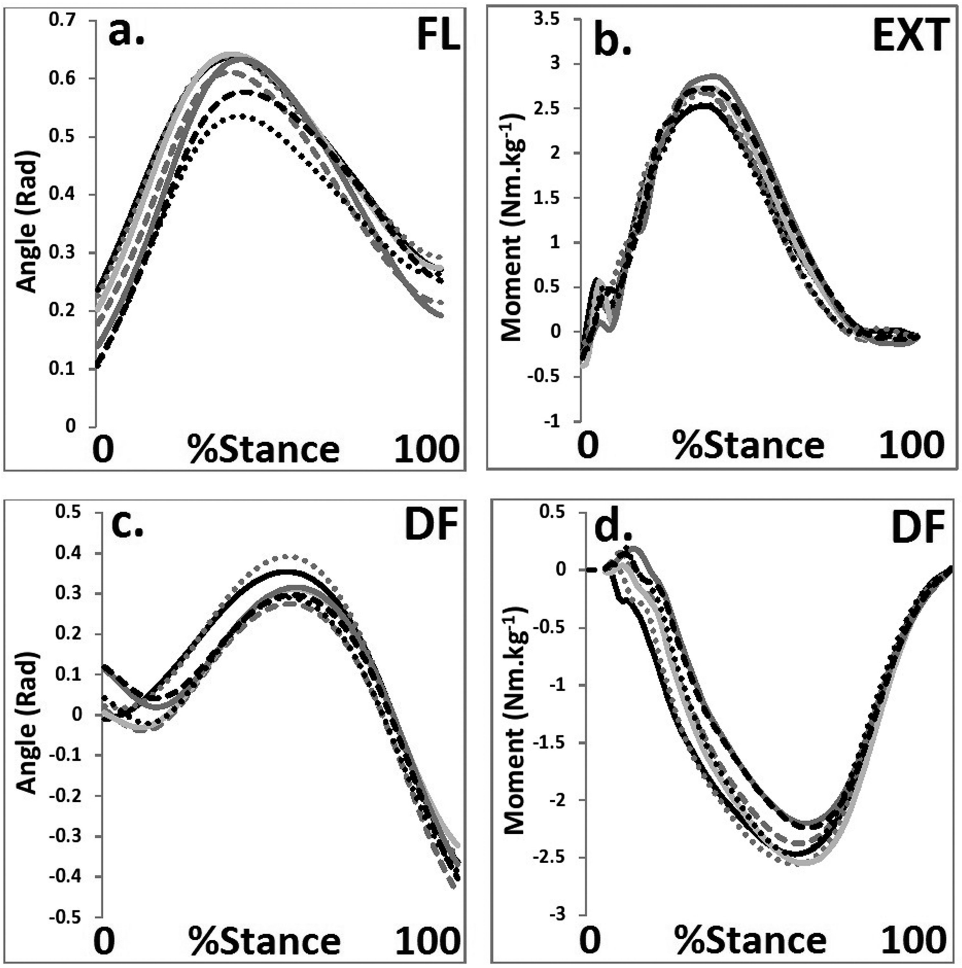

FIGURE 2. Limb and joint stiffness curves as function of footwear: (a) = limb stiffness, (b) = limb displacement, (c) = knee stiffness, (d) = ankle stiffness. barefoot = black, Nike Free = black dash, conventional = dark grey, Vibram five-fingers = light grey, Vivo = dot, Merrell = dark grey dash, Inov-8 = dark grey dot.

shown that vertical impact loading is greater when running BF (Sinclair, Greenhalgh, et al., 2013; Sinclair, Hobbs et al., 2013). Conversely when habitually BF participants are examined impact loading is greater when running shod (Lieberman et al., 2010; Squadrone & Gallozzi, 2009). This indicates once again that there is scope of further investigation of limb and joint stiffness parameters using participants who habitually run BF.

In conclusion, although differences in running mechanics have been examined extensively, the current knowledge regarding the effects of BFIS on limb and joint stiffness parameters is limited. The present investigation therefore adds to the present knowledge by providing a comprehensive evaluation of the limb stiffness characteristics of running in BF and BFIS. On the basis that peak ankle plantarflexor moment and knee–limb stiffness were shown to be greater in BF and minimalist BFIS and peak knee extensor moment was shown to be larger in CF, the findings from the current investigation may provide further insight into the susceptibility of runners to different injury mechanisms as a function of footwear. The current investigation indicates that running BF and in minimalist BFIS reduces the risk of chronic knee pathologies but also places runners at increased risk from ankle pathologies. Future analyses are nonetheless necessary to provide prospective clinical information of running BF and in BFIS on the etiology of running injuries.

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Received January 19, 2015
Revised March 26, 2015
Accepted April 17, 2015