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Isolated Effects of Footwear Structure and Cushioning on Running Mechanics in Habitual Mid/Forefoot Runners

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ABSTRACT

The true differences between barefoot and shod running are difficult to directly compare because of the concomitant change to a mid/forefoot footfall pattern that typically occurs during barefoot running. The purpose of this study was to compare isolated effects of footwear structure and cushioning on running mechanics in habitual mid/forefoot runners running shod (SHOD), barefoot (BF), and barefoot on a foam surface (BF+FOAM). Ten habitually shod mid/forefoot runners were recruited (male=8, female=2). Repeated measures ANOVA (α=0.05) revealed differences between conditions for only vertical peak active force, contact time, negative and total ankle joint work, and peak dorsiflexion angle. Post hoc tests revealed that BF+FOAM resulted in smaller vertical active peak magnitude and instantaneous vertical loading rate than SHOD. SHOD resulted in lower total ankle joint work than BF and BF+FOAM. BF+FOAM resulted in lower negative ankle joint work than either BF or SHOD. Contact time was shorter with BF than BF+FOAM or SHOD. Peak dorsiflexion angle was smaller in SHOD than BF. No other differences in sagittal joint kinematics, kinetics, or ground reaction forces were observed. These overall similarities in running mechanics between SHOD and BF+FOAM question the effects of footwear structure on habituated mid/forefoot running described previously.

Introduction

Barefoot running has been proposed to potentially lower the risk of running related injury because it results in a shorter stride length, reduced collision force, greater somatosensory information, and greater foot muscle strength compared with shod running (refer to (Hall et al., 2013; Jenkins & Cauthon, 2011; Tam et al., 2014) for comprehensive reviews). However, it is unclear how barefoot running directly compares with shod running because of the concomitant change to a mid/forefoot footfall pattern (Divert, Mornieux, et al., 2005; Gruber, Silvernail, et al., 2013).

A change from a rearfoot to a mid/forefoot pattern is suggested to be a kinematically mediated effect of running barefoot on a hard surface without cushioning to protect the heel (Frederick, 1986; Gruber, Silvernail, et al., 2013) and may be the primary mechanism for the mechanical differences between shod and barefoot running (De Wit et al., 2000; Lieberman et al., 2010). Further, removing the cushioning from the foot-ground interface will result in altered joint stiffness (e.g. (Ferris et al., 1998; Hardin et al., 2004; Nigg et al., 1987; Sinclair et al., 2016)), which is also affected by footfall pattern (Hamill, Gruber, et al., 2014; Lussiana et al., 2017). Changing the total stiffness of the system (individual-footwear-surface) will thus introduce changes in running mechanics that cannot be separated from the effects of simply removing the shoe structure because the cushioning is also removed.

Features of traditional running shoes, such as heel flare, heel-toe drop, and heel lift, may not be important when initial contact is anterior on the foot, or may have different effects on mid/forefoot running mechanics than were intended for rearfoot running. Given the high interaction of footfall pattern on the mechanical differences between barefoot versus shod running, it is unclear if the potential benefits, or detriments, of barefoot running are a result of being unshod alone, the subsequent change in footfall pattern, or the cushioning properties of the foot-ground interface.

A previous study comparing barefoot versus shod running while controlling for footfall pattern used habitually shod rearfoot runners (Shih et al., 2013). Having participants perform rearfoot and mid/forefoot patterns under both barefoot and shod conditions using a within-participants design is an excellent method to isolate the effects of footwear while removing the influence of footfall pattern. Although runners in both habitual footfall pattern groups seem to replicate the alternate pattern successfully in studies comparing footfall patterns while shod (Boyer et al., 2014; Williams et al., 2000), introducing two sources of task novelty –alternate footfall pattern and running barefoot– may cause altered running mechanics than those who are habituated. This altered movement may result in running mechanics that are either too variable to uncover meaningful relationships between outcomes or do not represent the running mechanics of a habitual barefoot runner. For example, habitual minimalist and barefoot runners tend to land with a mid/forefoot pattern (Goss & Gross, 2012; Hollander et al., 2017; Lieberman et al., 2010), but this footfall pattern is not universally adopted by habitually shod rearfoot runners during acute exposure to barefoot or minimalist shoe running (Gruber, Silvernail, et al., 2013; Hollander et al., 2015; Paquette et al., 2013; Williams et al., 2012). Therefore, error in running mechanics or increased variability may lead to inappropriate conclusions regarding the characterization of a barefoot gait pattern and the potential benefits of barefoot running. Examining the differences in running mechanics between shod and barefoot running in habitual mid/forefoot runners would identify the direct influence of the shoe without introducing error from task novelty.

The complex interaction of footfall pattern with shod versus barefoot running make it difficult to understand if the shoe properties, shoe cushioning, or the change in footfall pattern cause the well-documented changes in gait mechanics with barefoot running (e.g., (Hall et al., 2013; Jenkins & Cauthon, 2011; Tam et al., 2014)). Only by controlling for both cushioning and task-specific movement control (i.e., habitual footfall pattern), can the effects of running barefoot/unshod be understood. The effects of being unshod can be isolated from the effect of cushioning by comparing the change in gait mechanics within habitual mid/forefoot runners while running shod verses barefoot on a foam surface constructed out of a common footwear material, ethyl-vinyl acetate (EVA). The effects of cushioning the foot-ground interface can be isolated from the effects of being unshod by comparing barefoot running on a bare, laboratory floor with barefoot running on EVA foam. Therefore, the aim of the present study was to examine the differences in strike index, impact forces, and joint kinetics as well as relevant frontal and sagittal joint angles between running shod, barefoot on concrete, and barefoot on EVA foam in habitual mid/forefoot runners using a within-subjects design. We consider this study descriptive and preliminary and so we present the null hypothesis: there will be no significant differences in gait mechanics between conditions in habitually shod, mid/forefoot runners.

Materials and Methods

Participants

Runners were recruited as part of a larger study involving rearfoot and non-rearfoot runners via flyers posted on the university campus and surrounding community. All participants were healthy and free of musculoskeletal pain or injury within at least the previous 12 months. Ten habitually shod mid/forefoot runners (8 midfoot strikers, 2 forefoot strikers) were enrolled for the present study following footfall pattern screening (8 male, 2 female; Mean ± SD; Age (years): 25 ± 7; Stature (cm) 177 ± 0.1; Mass (kg) 71.32 ± 6.54, current running volume (km·week^{-1}) 46.5 ± 25.9). Habitual footfall pattern was assessed while participants ran overground at their preferred pace while wearing the allocated footwear for the shod running condition (RC 550, New Balance, Brighton, MA, USA). Participant footfall pattern was confirmed using the strike index (Cavanagh & Lafortune, 1980), sagittal plane ankle angle measurements, and a blunted or absent vertical impact peak (Gruber, Boyer, et al., 2013). Participants gave written informed consent before participating. Ethical approval was granted by the University of Massachusetts institutional review board.

Equipment

Participants were brought to an indoor biomechanics lab and were asked to run over ground at 3.5 $m \cdot s^{-1}$ (± 5%) under three conditions: barefoot ("BF"); barefoot with foam mats ("BF+FOAM", EVA 2.0cm depth, 55 Shore C durometer foam); and traditional, neutral running shoes ("SHOD", RC 550, New Balance, Brighton, MA, USA, 215.7 g). Testing took place over a 25 m runway embedded with a force platform (OR6-5, AMTI, Watertown, MA, USA) measuring 120 x 60 cm. Ground reaction force (GRF) and centre of pressure data were collected at 1200 Hz. During the BF+FOAM condition, the foam mats were laid over the length of the runway continuously. The mat in the centre of the collection volume included a cut-out that matched the dimensions of the force platform. The height of the contact surface above the force platform was addressed in the data processing (see below). Running speed was monitored by photoelectric sensors (Lafayette Instruments, Lafayette, IN, USA) positioned 3m before and after the centre of the force platform. Kinematic data were captured at 240 Hz using an eight-camera optical motion capture system (Oqus 300, Qualisys AB, Göthenburg, SWE). Retro-reflective spherical markers were placed on the pelvis and right lower extremity using an established marker set (Hamill, Selbie, et al., 2014) and secured with tape and textile foam wraps. Markers placed on the foot were secured with tape on the shoe over the heel, 1st and 5th metatarsal heads, and distal end of the great toe for the shod condition. Markers were secured on the skin with tape over the same anatomical landmarks for both barefoot conditions (BF, BF+FOAM).

Testing Procedure

A standing calibration was collected before the shod and first barefoot condition in order to calculate segment lengths and joint centre positions (Hamill, Selbie, et al., 2014). Participants were instructed to "run normally" and practiced running under each condition until they felt comfortable and found a starting point that allowed them to contact the force platform with the whole foot (≥8 m). Ten acceptable trials were completed for each participant in each of the three conditions (BF, BF+FOAM, SHOD). Trials were considered acceptable if the participant ran within the speed threshold ($3.5\ m\cdot s^{-1} \pm 5\%$), did not change running speed within the collection volume, landed on the force plate with the whole foot of the right limb, and did not target or alter stride to land on the force platform completely. The order of the conditions was semi-randomised determined using a random number generator; barefoot conditions were presented together (but in a random order) to avoid differences in marker placement between BF and BF+FOAM. Therefore, SHOD was presented randomly but constrained to be either first or last.

Data Processing

Marker position data were tracked using Qualisys Track Manager software (Qualisys AB, Göthenburg, SWE) and exported to Visual3D software for signal processing (C-Motion, Rockville, MD, USA). Marker positions and force platform data were filtered using a 4th order low-pass Butterworth filter using cut-off frequencies of 15 Hz and 50 Hz, respectively. Raw GRF data were filtered at 15 Hz before the joint moments were calculated (Kristianslund et al., 2012). The minimum force threshold was 20 N. Prior to any filtering or data processing, the "FORCE_STRUCTURES" command in Visual3D was used for the BF+FOAM condition to account for the contact surface of the foam being offset from the surface of the force platform (refer to C-Motion, Inc. online documentation).

Contact time was the time between initial contact with the force platform and toe-off. Strike index (SI) was calculated to assess footfall pattern as a continuous variable (Cavanagh & Lafortune, 1980). Vertical active peak (VActP) was the magnitude of the global maximum of the vertical ground reaction force. Maximum instantaneous vertical loading rate (VLR) was calculated by first identifying the time of peak vertical impact force using the method of Blackmore et al. (Blackmore et al., 2016) for all trials. Next, the first derivative of the filtered (50 Hz cut-off) vertical force platform data was calculated using the central difference method to find the largest instantaneous slope magnitude between 20%-80% of the time to peak vertical impact force. The method by Blackmore et al. (Blackmore et al., 2016) was used to ensure a data-driven method for identifying the time to peak vertical impact force. The instantaneous VLR calculation method was selected because it follows the method used in previous research examining the association of VLR to running injuries (Zadpoor & Nikooyan, 2011) and many papers comparing footfall patterns and barefoot running (e.g. (Au et al., 2018; Boyer et al., 2014; Rice & Patel, 2017; Samaan et al., 2014; Shih et al., 2013)). Anterior-posterior loading rate (APLR) was calculated as the largest instantaneous slope magnitude between 20%-80% of the time to the first visible local maximum in the breaking phase.

Three-dimensional joint angles and joint kinetics were calculated using established procedures (Hamill, Selbie, et al., 2014; Selbie et al., 2014). Specifically, joint angles were calculated using an X-Y-Z (mediolateral-anteroposterior-vertical axes) using Cardan rotation sequence with the proximal segment as reference. Ankle joint angles were calculated using a virtual foot segment coordinate system that was aligned with the lab coordinate system. Internal joint moments were calculated using a Newton-Euler inverse dynamics procedure. Positive angles indicated hip and knee flexion, ankle dorsiflexion, knee and hip adduction, and ankle inversion. Positive joint moments followed the same convention except for knee flexion, which was negative.

Ankle, knee, and hip joint work in the sagittal plane was determined by first calculating joint power as the product of the joint moments and joint angular velocity then integrating the area under the joint power-time curve. Total joint work was the cumulative area under positive and negative portions of the power-time curve. Positive and negative work was the sum of the positive and negative areas under the power-time curve, respectively.

Peak values for specific sagittal and frontal plane joint angles and moments were used in the examination of differences between conditions. Angles at initial ground contact were also examined to aid in the assessment of dynamics at the foot-ground interface. For this descriptive study, variables were selected in consideration of previous studies comparing barefoot, minimalist, and shod running and comparing rearfoot and mid/forefoot patterns (e.g., (Anderson et al., 2020; Hall et al., 2013; Jenkins & Cauthon, 2011; Tam et al., 2014; Xu et al., 2021)). Select frontal plane joint angle variables were also included given their potential relevance to running injury development (e.g., (Ceyssens et al., 2019; Dudley et al., 2017; Kuhman et al., 2016)). Peak ankle inversion moment was included because it is a suggested key variable for recommending habitual mid/forefoot runners avoid traditional footwear (Davis et al., 2017; Rice et al., 2016). Refer to Tables 1 and 2 for a complete list of variables.

Statistical Analysis

Differences between conditions (BF, BF+FOAM, SHOD) were examined with a repeated measures ANOVA. Statistical significance was accepted at $\alpha \leq 0.05$. Specific mean differences ($\text{Mean}_{\text{diff}}$) between conditions were examined using pairwise comparisons under an adjusted Bonferroni correction given the three comparisons (SPSS V20.0, SPSS Inc., Chicago, Illinois, USA). Additionally, 95% confidence intervals (CI_{diff}) are reported and considered in the interpretation of the likelihood of the difference. Data were verified for normality using a Shapiro-Wilk test. A Huynh-Feldt correction was used where data failed Mauchly’s test of

Sphericity. Effect sizes are reported as partial eta squared (ηp^2) for main effects. Given the small sample size and multiple comparisons, we will only consider a main effect as meaningful if the main effect is both significant and ηp^2 is a large effect (>0.14) (Cohen, 1988).

Results

Contact Time, Strike Index, & Ground Reaction Force Variables

Descriptive statistics for all ground reaction force variables are listed in Table 1. Vertical and anteroposterior force curves are presented in Figure 1. There was a significant main effect of condition for VActP ($F_{(2,18)} = 6.169$; $P = 0.009$; $\eta p^2 = 0.41$). Pairwise comparisons identified that VActP was significantly greater in SHOD versus BF+FOAM ($Mean_{diff}$ 118.8N; 95% CI_{diff} [5.8 to 231.8N]; $P = 0.039$), but VActP was similar between BF and BF+FOAM conditions ($Mean_{diff}$ 33.26; 95% CI_{diff} [-28.9 to 95.42N]; $P = 0.453$) and between SHOD and BF conditions ($Mean_{diff}$ 85.56N; 95% CI_{diff} [-36.13 to 207.25]; $P = 0.208$).

A significant main effect of condition was also observed for VLR ($F_{(2,18)} = 7.134$; $P = 0.005$; $\eta p^2 = 0.44$). Pairwise comparisons identified that VLR was significantly greater in the BF versus SHOD condition ($Mean_{diff}$ 42970 N/s; 95% CI_{diff} [2023 to 83981 N/s]; $P = 0.040$), but no difference in VLR was observed between BF and BF+FOAM ($Mean_{diff}$ 20879 N/s; 95% CI_{diff} [-10307 to 52065 N/s]; $P = 0.243$) or between SHOD and BF+FOAM ($Mean_{diff}$ 22091 N/s; 95% CI_{diff} [-4215 to 48398 N/s]; $P = 0.108$).

There were no significant differences in APLR between conditions ($F_{(2,18)} = 0.556$; $P = 0.583$; $\eta p^2 = 0.058$).

Descriptive statistics for strike index and contact time are presented in Table 1. No main effect of condition was observed for strike index ($F_{(2,18)} = 0.368$; $P = 0.697$; $\eta p^2 = 0.04$). A significant main effect of condition was observed for contact time ($F_{(2,18)} = 13.579$; $P \leq 0.001$; $\eta p^2 = 0.60$). Pairwise comparisons identified a longer contact time during SHOD versus BF

($\text{Mean}_{\text{diff}}$ 0.009 s; 95% CI_{diff} [0.003 to 0.016 s]; P = 0.009) and a longer contact time during BF+FOAM versus BF ($\text{Mean}_{\text{diff}}$ 0.009 s; 95% CI_{diff} [0.004 to 0.013 s]; P = 0.001). No difference in contact time between BF+FOAM vs SHOD was observed ($\text{Mean}_{\text{diff}}$ 0.001 s; 95% CI_{diff} [-0.005 to 0.007 s]; P = 1.00).

Joint moments

Descriptive statistics for all joint moments can be observed in Table 1. Joint moment curves over stance are presented in Figure 2. No main effects of condition were observed for peak hip flexion moment ($F_{(2,18)} = 0.218$; P = 0.806; $\eta p^2 = 0.02$), peak knee extensor moment ($F_{(2,18)} = 0.497$; P = 0.617; $\eta p^2 = 0.05$), or peak ankle inversion moment ($F_{(2,18)} = 1.368$; P = 0.280; $\eta p^2 = 0.13$).

A main effect of condition was observed for peak plantarflexion moment ($F_{(2,18)} = 4.289$; P = 0.030; $\eta p^2 = 0.32$). However, pairwise comparisons identified no significant specific differences between SHOD versus BF ($\text{Mean}_{\text{diff}}$ 13.67 N*m; 95% CI_{diff} [-7.93 to 35.27 N*m]; P = 0.289), and SHOD versus BF+ FOAM ($\text{Mean}_{\text{diff}}$ 18.77 N*m; 95% CI_{diff} [-3.35 to 40.89 N*m]; P = 0.103).

Joint work

Descriptive statistics for all joint work variables are listed in Table 1. Joint power curves are presented in Figure 3. No significant main effect of condition was observed at the hip joint for positive work ($F_{(2,18)} = 0.555$; P = 0.584; $\eta p^2 = 0.06$), negative work ($F_{(2,18)} = 2.886$; P = 0.082; $\eta p^2 = 0.24$), or total work ($F_{(2,18)} = 2.521$; P = 0.108; $\eta p^2 = 0.22$). For the knee joint, no significant main effect of condition was observed for positive work ($F_{(2,18)} = 0.245$; P = 0.785; $\eta p^2 = 0.03$), negative work ($F_{(2,18)} = 0.259$; P = 0.774; $\eta p^2 = 0.03$), or total work ($F_{(2,18)} = 0.546$; P = 0.589; $\eta p^2 = 0.06$).

There was no significant main effect of condition for ankle positive work ($F_{(2,18)}$ = 0.647; P = 0.458; ηp^2 = 0.07). Significant main effects of condition were observed for both negative work ($F_{(2,18)}$ = 11.956; P = 0.003; ηp^2 = 0.57) and total work ($F_{(2,18)}$ = 26.217; P ≤ 0.001; ηp^2 = 0.74). With respect to negative ankle joint work, pairwise comparisons identified significantly more negative work during BF versus BF+FOAM ($\text{Mean}_{\text{diff}}$ 6.23 J; 95% CI_{diff} [-0.35 to 12.12 J]; P = 0.038), as well as more negative ankle work during SHOD versus BF+FOAM ($\text{Mean}_{\text{diff}}$ 20.56 J; 95% CI_{diff} [6.76 to 34.38 J]; P = 0.005). However, there was no difference in negative ankle work between BF and SHOD ($\text{Mean}_{\text{diff}}$ 14.33 J; 95% CI_{diff} [-1.63 to 30.3 J]; P = 0.082). Total ankle joint work was significantly less during SHOD than both BF ($\text{Mean}_{\text{diff}}$ 12.49 J; 95% CI_{diff} [3.82 to 21.15 J]; P = 0.007) and BF+FOAM ($\text{Mean}_{\text{diff}}$ 16.97 J; 95% CI_{diff} [10.15 to 23.79 J]; P ≤ 0.001). There was no difference in total ankle work comparing BF versus BF+FOAM ($\text{Mean}_{\text{diff}}$ 4.48 J; 95% CI_{diff} [-1.06 to 10.03 J]; P = 0.125).

Joint Angles

Descriptive statistics and differences in sagittal and frontal plane joint angles for the hip, knee, and ankle are summarized in Table 2 and presented in Figure 4. No significant main effects were observed for any hip or knee angle variable and three ankle angle variables (P > 0.121).

At the ankle, a significant main effect of condition was observed for the peak dorsiflexion angle ($F_{(2,18)}$ = 9.480; P = 0.006; ηp^2 = 0.51). Pairwise comparisons identified SHOD resulted in a greater peak dorsiflexion angle than BF ($\text{Mean}_{\text{diff}}$ 3.15 deg; 95% CI_{diff} [1.13 to 5.03 deg]; P = 0.003). However, no significant difference in peak dorsiflexion angle wase observed between SHOD versus BF+FOAM ($\text{Mean}_{\text{diff}}$ 2.86 deg; 95% CI_{diff} [-0.23 to 5.94 deg]; P = 0.072) or between BF+FOAM versus BF ($\text{Mean}_{\text{diff}}$ 0.27 deg; 95% CI_{diff} [-1.52 to 2.06 deg]; P = 1.00).

There was a significant main effect of conditions for frontal plane ankle angle at touch down ($F_{(2,18)} = 4.650$; $P = 0.024$; $\eta p^2 = 0.34$). However, pairwise comparisons did not identify significant differences between SHOD versus BF ($\text{Mean}_{\text{diff}}$ 3.12 deg; 95% CI_{diff} [-0.35 to 6.59 deg]; P = 0.081), SHOD versus BF+FOAM ($\text{Mean}_{\text{diff}}$ 2.93 deg; 95% CI_{diff} [-0.82 to 6.67 deg]; P = 0.143), or between BF+FOAM versus BF ($\text{Mean}_{\text{diff}}$ 0.20 deg; 95% CI_{diff} [-2.61to 3.01 deg]; P = 1.00).

Discussion and Implications

The purpose of this study was to characterize the specific effects of being barefoot on running mechanics by eliminating any potential effects of habitual footfall pattern and isolating effects of cushioning by including a condition of running barefoot on an EVA foam surface. Comparing the SHOD and BF+FOAM conditions isolated the effects of being unshod while cushioning between the foot-ground interface was maintained whereas comparing BF and BF+FOAM conditions isolated the effects of cushioning alone. Our null hypothesis was not supported. When cushioning of the foot-ground interface was maintained (SHOD vs. BF+FOAM), being unshod resulted in reduced peak vertical active force and negative ankle joint work but increased total ankle joint work. Remaining unshod but removing cushioning from the foot-ground interface (BF vs. BF+FOAM) resulted in a shorter contact time and increased negative ankle joint work. Compared with shod running, running barefoot with no external cushioning (SHOD vs. BF) resulted in a shorter contact time, greater vertical loading rate, and greater total ankle joint work. No differences in peak joint angles, peak joint moments, or joint work were observed at the hip and knee and no variable was significantly different between all three conditions. The differences in joint mechanics were isolated at the ankle which supports previous conclusions that shod forefoot running was controlled at the ankle whereas shod rearfoot running was controlled at the knee (Davis et al., 2017; Hamill, Gruber, et al., 2014). Few studies have directly examined the differences in barefoot and shod running in habitual mid/forefoot runners, making direct comparison of our findings to current literature limited. Given that this was a descriptive study, the mechanisms for the observed differences between conditions need further investigation.

Barefoot running is often advocated to prevent running injuries, in part, by reducing the VLR (Divert, Baur, et al., 2005; Divert, Mornieux, et al., 2005; Samaan et al.; Utz-Meagher et al., 2011), but this effect had limited evidence in a recent systematic review and was dependent on footfall pattern (Hall et al., 2013). Our results suggest that the effects of barefoot running on VLR may be dependent on habituation to a mid/forefoot pattern and surface conditions given that strike index did not change between SHOD, BF, and BF+FOAM. Some previous studies comparing barefoot and shod running found no differences in VLR when footfall pattern was maintained by either including habitual mid/forefoot runners (Paquette et al., 2013) or by asking habitual rearfoot runners to run with a mid/forefoot pattern (Shih et al., 2013). Those findings contrast with Rice et al. (Rice & Patel, 2017) who concluded that both, minimalist footwear and a forefoot pattern, were required together to reduce VLR compared with either rearfoot or forefoot running in traditional footwear. However, minimalist and barefoot running are not equivalent (Bonacci et al., 2013; Sinclair et al., 2013; Squadrone et al., 2015). Our findings suggest that habitual mid/forefoot runners reduce VLR when shod compared with barefoot running on a hard surface, but this difference disappears when running barefoot whilst cushioning is maintained.

Caution is needed when comparing our VLR results with previous studies. Researchers have used different methods when identifying peak impact force for VLR calculations during mid/forefoot running including: identifying peak impact force at the same, specific point within stance for all trials (Boyer et al., 2014; Rice & Patel, 2017; Samaan et al.; Willy et al., 2008), using the time to peak impact force from other trials in which a peak impact force was visible

(Lieberman et al., 2010), or did not report the complete details of the calculation (Paquette et al., 2013). Like others (e.g. (Au et al., 2018; Warne et al., 2016; Yang et al., 2020)), we used the method of Blackmore et al. (Blackmore et al., 2016) to determine the time of peak vertical impact force from which our VLR was calculated from the original, filtered force platform signal. This method isolates the impact force from the summated vertical GRF waveform, which has been recommended to remove effects of upper body motion on VLR (Gruber et al., 2017) and is argued to be a robust, data driven method to isolate the impact force when a distinctive peak is not visible. Recent studies found that VLR was not a significant factor associated with running injury in collegiate runners regardless of calculation method (Schmida et al., 2021) and three instantaneous VLR calculation methods were statistically similar in rearfoot runners (Ueda et al., 2016). However, the sensitivity of various calculation methods for comparing impact force variables between footfall patterns should be considered in future footfall pattern and barefoot running research.

Barefoot running has the greatest effect on ankle joint mechanics, findings which are largely consistent across studies (Hall et al., 2013; Jenkins & Cauthon, 2011; Tam et al., 2014) and generally attributed to changing to a mid/forefoot pattern when barefoot (De Wit et al., 2000; Kurz & Stergiou, 2004; Lieberman et al., 2010; Squadrone et al., 2015). In the present study, pairwise differences were only observed for peak dorsiflexion angle, total ankle joint work, and negative ankle joint work. Previous researchers found similar changes with ankle work but, unlike the present study, they found knee and hip work differences between shod and barefoot possibly related to differences in ankle angle at contact (Bonacci et al., 2013; Williams et al., 2012). Greater peak dorsiflexion angle in SHOD versus BF conditions could be related to the shoe elevation and structure (Kerr et al., 2009). Similarly, the smaller lateral heel flare is suggested to minimize frontal plane ankle joint moments, which is a key factor recommending that mid/forefoot runners run in minimalist footwear or barefoot (Davis et al., 2017; Rice et al., 2016). However, non-significant differences in joint angles and joint moments between SHOD and BF+FOAM condition questions the effects of stack height, heel-toe drop, heel flare, and other footwear features on habituated mid/forefoot running mechanics described elsewhere (Davis et al., 2017; Lieberman et al., 2010; Rice et al., 2016).

Similarly, footwear structure and cushioning had no effect on frontal plane joint angles. Hall et al. (Hall et al., 2013) in a systematic review identified limited evidence that ankle eversion was lower during barefoot running when compared with shod, as did De Witt et al. (De Wit et al., 2000). The role of ankle eversion in injury is poorly understood as this mechanism may increase some injuries (Chuter & Janse de Jonge, 2012; Ness et al., 2008), aid in impact absorption and hence reduce the risk of bony injuries (Chuter & Janse de Jonge, 2012; Hall et al., 2013; Hreljac et al., 2000), or have no influence (Kuhman et al., 2016; Nielsen et al., 2014). This variable is important because of the proliferation of gait measurement in the prescription of pronation control running shoes. Given that no differences in frontal plane ankle joint angles were observed in the present study, it appears that the difference in cushioning and footwear structure (and subsequent neuromuscular adjustments) may not influence the eversion angle in habituated mid/forefoot runners.

The reduced contact time when BF compared with both BF+FOAM and SHOD in this study was consistent with many observations of shorter ground contact times when comparing barefoot and shod running regardless of whether the footfall pattern was controlled (Divert, Baur, et al., 2005; Divert, Mornieux, et al., 2005; Lussiana et al., 2015; McCallion et al., 2014; Paquette et al., 2013; Shih et al., 2013; Squadrone & Gallozzi, 2009). Inconsistent with our findings, two previous studies found contact time to be similar between shod and barefoot running in in habitual mid/forefoot runners (Paquette et al., 2013) and habitual rearfoot runners performing a mid/forefoot pattern (Shih et al., 2013). Our findings suggest that removal of both cushioning and footwear structure are required to elicit changes in contact time given that contact time was similar between SHOD and BF+FOAM conditions.

A strength of the present study is that we included participants who were already accustomed to a mid/forefoot footfall pattern. Previous studies have examined the effect of acute changes to footwear both with and without instructing footfall pattern, but this method does not account for the complex neuromuscular adaptations that may occur with footfall pattern habituation. For example, making a deliberate, acute switch from a rearfoot to a mid/forefoot pattern or from shod to barefoot may not allow for gradual, more sensitive changes to leg stiffness and joint geometry that may be present after long-term habituation. It is also important to note that since the present study controls for footfall pattern, we eliminate the complex interaction of footfall pattern on barefoot versus shod running, and therefore comparisons of the shod and barefoot conditions in the present study must only be considered in those who mid/forefoot strike (who represent a minority of the population (Bertelsen et al., 2013; Hanley et al., 2019; Hasegawa et al., 2007; Hébert-Losier et al., 2021; Larson et al., 2011)).

Another strength of the present study is that a foam EVA running surface was included to minimize any kinematic or kinetic mediated effects of cushioning to isolate the mechanical differences resulting from shoe structure. More studies are needed in this area.

Limitations

A potential limitation of the present study is that participants only had a short time to practice and become accustomed to each condition. However, experienced runners have been observed to adjust leg stiffness in the first step onto different surface conditions (Ferris et al., 1999); thus, the potential influence of the short practice time likely did not have a strong effect on these within-subjects comparisons.

An additional limitation was that the participants were not experienced barefoot runners and only one participant anecdotally reported previous experience with barefoot running. Experienced barefoot runners may have an alternate neuromuscular strategy, although the differences in neuromuscular strategies between experienced and inexperienced barefoot habitual mid/forefoot runners has yet to be catalogued to our knowledge. Indeed, some of our results contrast with previous studies comparing barefoot and shod running in experienced barefoot runners (Squadrone & Gallozzi, 2009; Willwacher et al., 2015). However, those previous studies observed changes in ankle angles that could reflect a change in footfall pattern or a significant change in strike index that were not observed in the present study. Although all participants were habitual mid/forefoot runners when shod, and the mid/forefoot pattern is frequently observed with barefoot and minimalist footwear running (De Wit et al., 2000; Hollander et al., 2017; Kurz & Stergiou, 2004; Lieberman et al., 2010; Squadrone et al., 2015), experience with barefoot or minimalist running does not necessarily equate to also being a mid/forefoot runner when shod (e.g. (Au et al., 2018; Lieberman et al., 2010)).

Care should be taken in the inference of this data, given that only mid/forefoot runners were included, and the vast majority of runners are rearfoot across recreational and elite endurance runners (Bertelsen et al., 2013; Hanley et al., 2019; Hasegawa et al., 2007; Hébert-Losier et al., 2021; Larson et al., 2011). Although participants were asked if they have always run with a mid/forefoot pattern versus switching from rearfoot, this information was anecdotal as it was not collected in a formal survey. Those who reported switching from a rearfoot to mid/forefoot had done so at least 12-months prior to data collection.

Due to the more descriptive rather than mechanistic nature of the present study, leg and joint stiffness were not calculated thus the complex interaction of surface/footwear and footfall pattern on stiffness is an area for future research.

The lack of significant post hoc differences for frontal plane ankle angle at touch down and peak plantarflexion moment were likely a result of either type 1 error of the main effect or otherwise the conversative Bonferroni correction applied to the analysis. It is important to note that the p-value from an omnibus versus a post-hoc test reflect different questions. Regardless of the reason, given the sample size of N=10 in the present experimental study, we suggest this effect should be explored further in replicated studies for further clarification.

Finally, the present study included a sample size of N=10 because it was exploratory, and no comparable publications were available at the time of study planning for which to base the sample size calculation. The present study provides data that can be used to calculate appropriate sample sizes for future studies.

Conclusion

The present study is one of the first attempts at elucidating the specific effects of shoe structure and shoe cushioning on barefoot running. Our findings suggest that removal of both cushioning and footwear structure were required to elicit changes in running mechanics when habitually mid/forefoot runners ran barefoot. Conflicting findings with previous research may be related to changes in ankle angle at contact or strike index between barefoot and shod conditions. The few significant differences in ankle mechanics between SHOD and BF+FOAM running conditions and the lack of significant findings for the hip, knee, and other ankle variables in habituated mid/forefoot runners questions the effects of footwear structure on running mechanics suggested previously.

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Figures

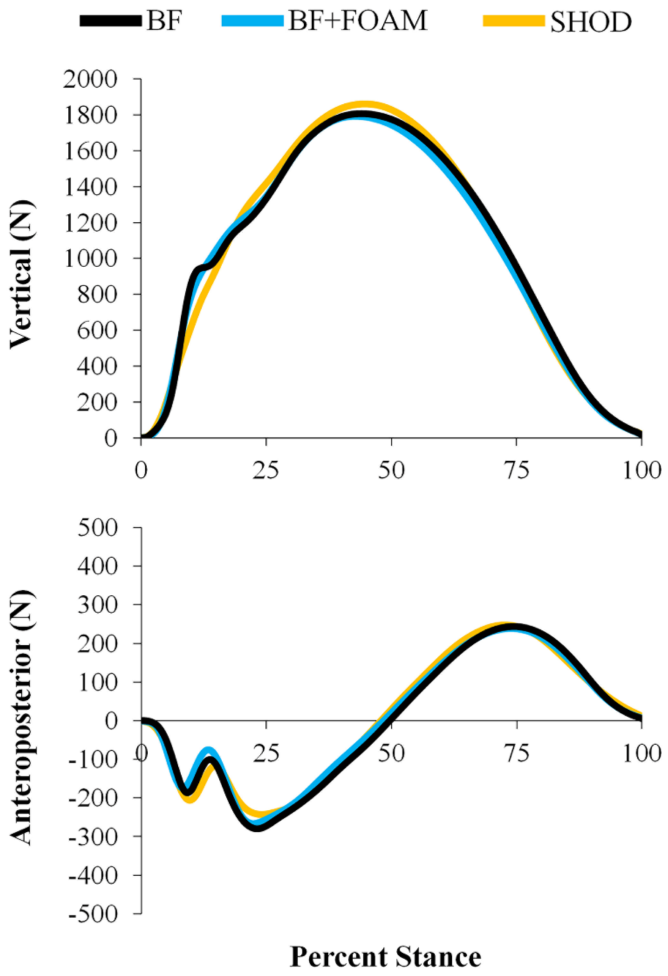
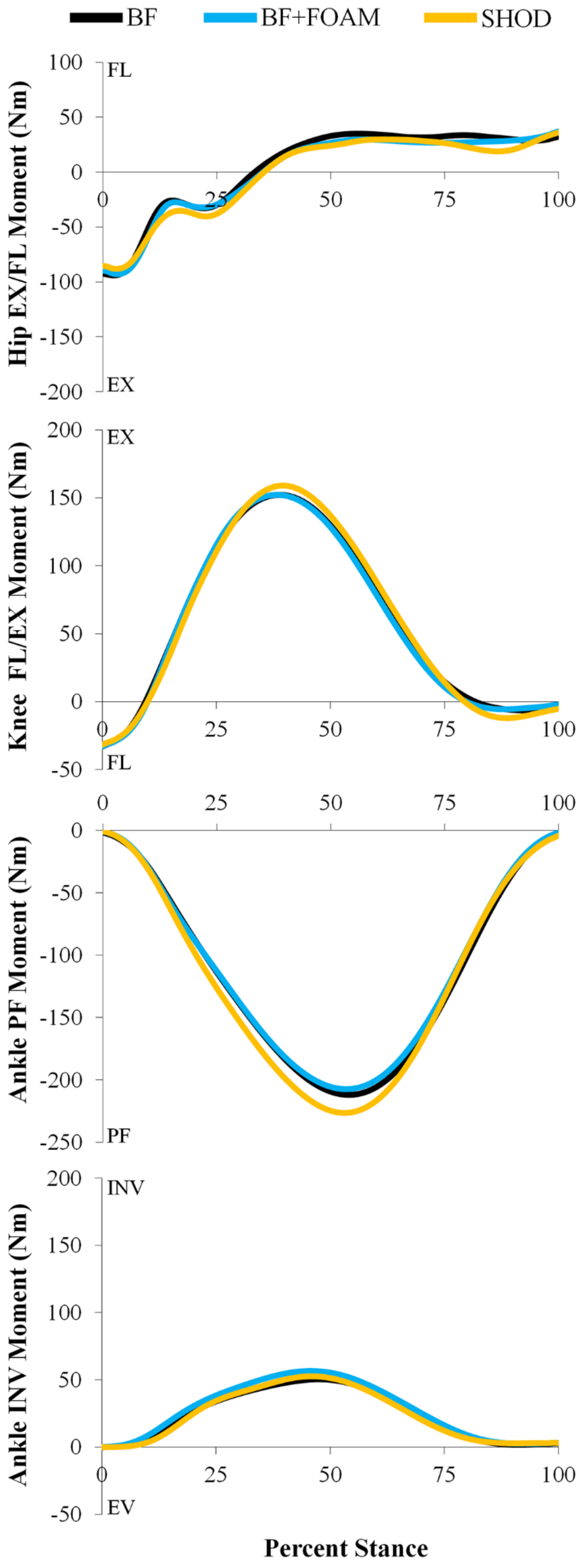


Figure 1. Vertical (top) and anteroposterior (bottom) ground reaction forces during running barefoot on the concrete lab floor (BF, black), barefoot on a foam surface (BF+FOAM, blue), and shod on the concrete lab floor (SHOD, yellow).


BF
BF+FOAM
SHOD
Hip EX/FL Moment (Nm)
100
50
0
-50
-100
-150
-200
FL
EX
0
25
50
75
100
Knee FL/EX Moment (Nm)
200
150
100
50
0
-50
EX
FL
0
25
50
75
100
Ankle PF Moment (Nm)
0
25
50
75
100
0
-50
-100
-150
-200
-250
PF
Ankle INV Moment (Nm)
200
150
100
50
0
-50
INV
EV
0
25
50
75
100
Percent Stance

661

Figure 2. Sagittal and frontal plane joint moments during running barefoot on the concrete lab floor (BF, black), barefoot on a foam surface (BF+FOAM, blue), and shod on the concrete lab floor (SHOD, yellow). Data includes sagittal hip (1st row), sagittal knee (2nd row), sagittal ankle (3rd row), and frontal ankle (4th row) internal joint moments. Positive moments indicate hip flexion (FL), knee extension (EX), ankle dorsiflexion (not observed), and ankle inversion (INV). Negative moments indicate hip extension (EXT), knee flexion (FLX), ankle plantarflexion (PF), and ankle eversion (peak eversion magnitudes across subjects were less than < 8 Nm).

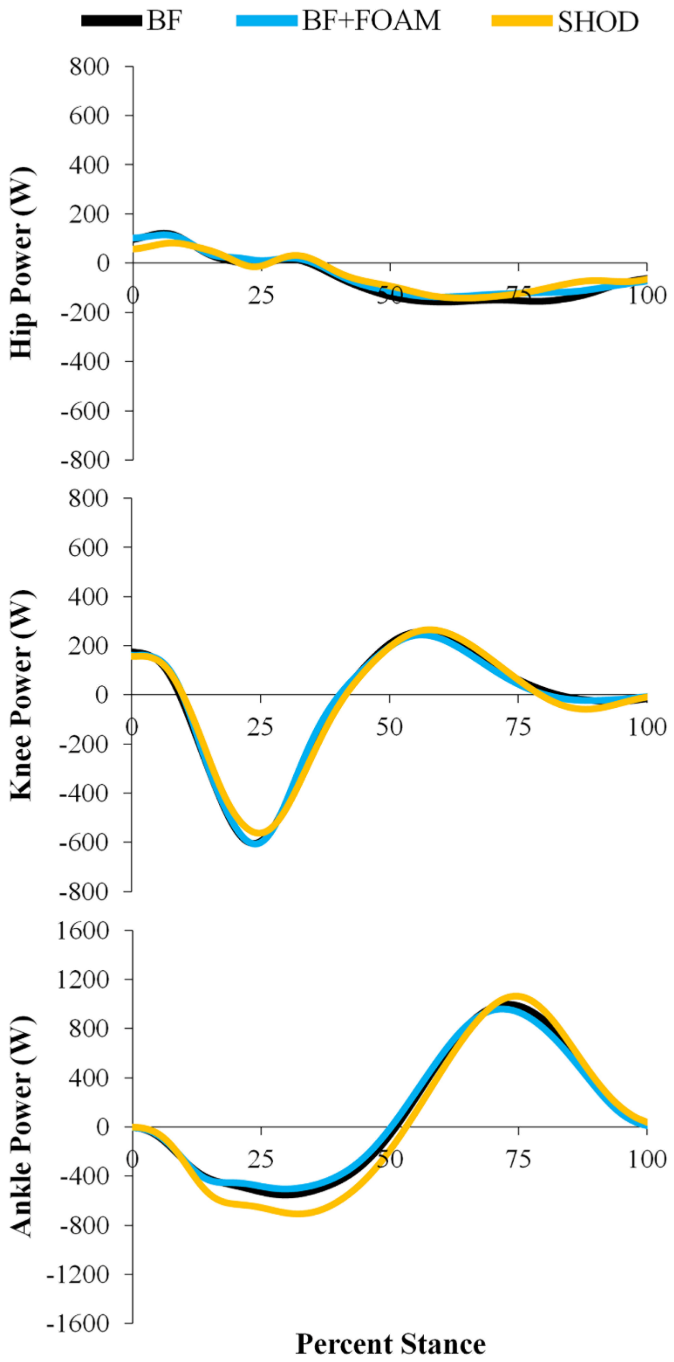


Figure 3. Sagittal plane joint power for the hip (top), knee (middle), and ankle (bottom) during running barefoot on the concrete lab floor (BF, black), barefoot on a foam surface (BF+FOAM, blue), and shod on the concrete lab floor (SHOD, yellow). Positive power indicates energy generation and negative power indicates energy absorption.

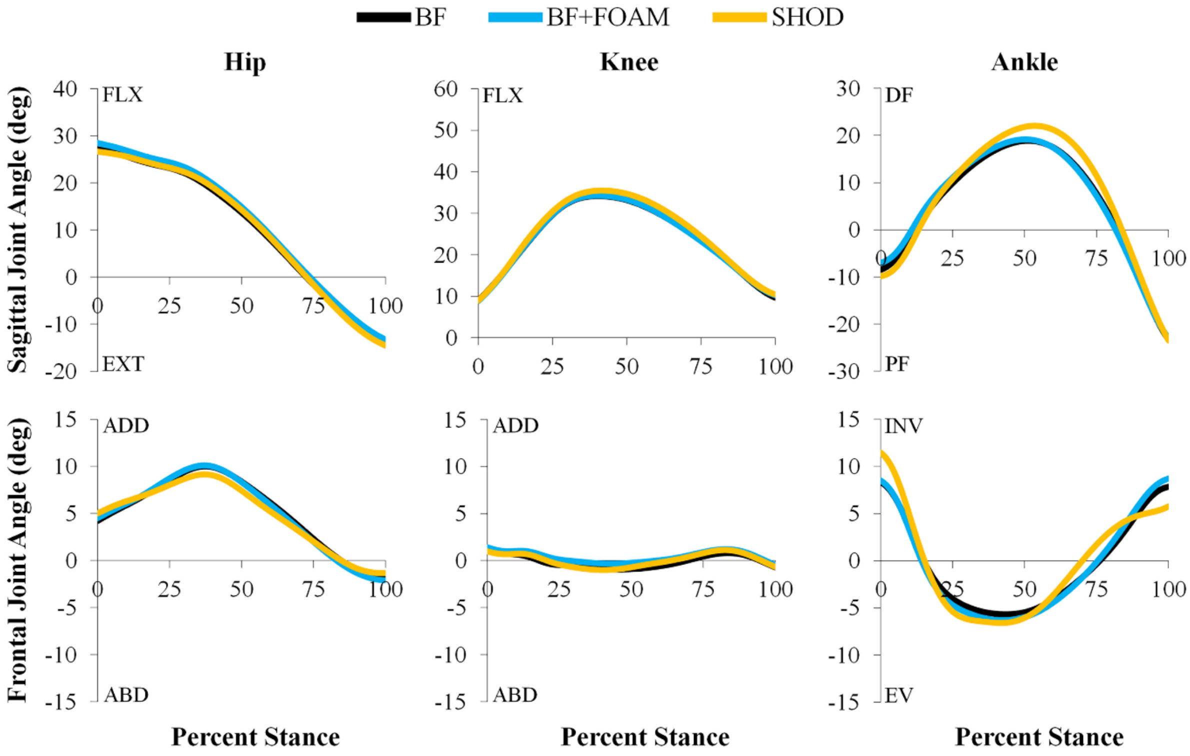


Figure 4. Sagittal plane (top row) and frontal plane (bottom row) joint angles for the hip (left), knee (middle), and ankle (right) during running barefoot on the concrete lab floor (BF, black), barefoot on a foam surface (BF+FOAM, blue), and shod on the concrete lab floor (SHOD, yellow). Positive angles indicate hip and knee flexion (FLX), ankle dorsiflexion (DF), knee and hip adduction (ADD), and ankle inversion (INV). Negative angles indicate hip extension (EXT), ankle plantarflexion (PF), hip and knee abduction (ABD), and ankle eversion.

Table 1. Descriptive statistics (Mean ± SD) for contact time, strike index, force platform variables, and joint kinetics for the barefoot (BF), barefoot with foam mats (BF+FOAM), and shod (SHOD) running conditions (N = 10).

		BF	BF+FOAM	SHOD
Ground Reaction Force, Strike Index, Contact Time	Peak active force (N)^{*,c}	1819.45±186.86	1786.19±194.72	1905.01±218.31
	Max. instantaneous loading rate (N·s^{-1})^{*,a}	91489.20±50538.31	70610.10±30806.01	48518.50±15473.24
	A-P Max. instantaneous loading rate (N·s^{-1})	19946.70±5532.78	20291.50±4496.96	21290.10±3237.45
	Strike Index (%)	58.95±14.57	54.92±15.57	59.52±11.14
	Contact time (s)^{*,a,b}	0.215±0.011	0.224±0.014	0.225±0.013
Joint Moments	Hip: peak flexion moment (Nm)	48.14±16.71	45.40±20.32	46.10±23.24
	Knee: peak extensor moment (Nm)	154.26±47.36	154.79±42.35	160.12±41.58
	Ankle: peak plantar flexor moment (Nm)^{*,ns}	-213.54±42.45	-208.45±40.43	-227.22±51.24
	Ankle: peak inversion moment (Nm)	51.74±18.99	57.44±21.14	53.42±18.67
Joint Work	Hip: positive work (J)	5.24±240	5.96±3.18	5.85±2.46
	Hip: negative work (J)	-19.40±6.90	-18.26±7.94	-15.23±7.81
	Hip: total work (J)	-14.15±7.92	-12.30±9.75	-9.38±9.09
	Knee: positive work (J)	18.75±4.96	18.21±3.78	18.73±6.07
	Knee: negative work (J)	-27.64±10.99	-28.92±9.67	-27.91±8.89
	Knee: total work (J)	-8.89±7.62	-10.71±7.47	-9.18±4.10
	Ankle: positive work (J)	65.87±14.47	64.12±14.33	67.72±21.0
	Ankle: negative work (J)^{*,b,c}	-44.64±15.21	-38.41±10.18	-58.98±16.92
	Ankle: total work (J)^{*a,c}	21.23±10.35	25.71±10.41	8.74±9.34

*: significant main effect of condition ($P \leq 0.05$)

a: significant pairwise comparison, SHOD vs. BF ($P \leq 0.05$)

b: significant pairwise comparison, BF vs. BF+FOAM ($P \leq 0.05$)

c: significant pairwise comparison, SHOD vs. BF+FOAM ($P \leq 0.05$)

ns: no significant pairwise comparisons between conditions

Table 2. The reported main effect of the repeated measures ANOVA and descriptive statistics for the differences in sagittal and frontal plane kinematics of the ankle, knee, and hip between barefoot (BF), barefoot with foam mats (BF+FOAM), and shod (SHOD) running conditions (N = 10). Descriptive statistics are presented in degrees as mean ± 1 standard deviation. IC = initial contact.

Joint	Variable	Main Effect for Condition	BF	BF+FOAM	SHOD
Hip	peak flexion angle	$F_{(2,18)} = 0.607$; $P = 0.487$; $\eta p^2 = 0.06$	27.22±9.33	28.32±7.82	26.87±11.49
	peak adduction angle	$F_{(2,18)} = 1.384$; $P = 0.276$; $\eta p^2 = 0.13$	10.23±2.72	10.38±3.30	9.39±3.36
Knee	peak flexion angle	$F_{(2,18)} = 2.385$; $P = 0.121$; $\eta p^2 = 0.21$	34.38±5.50	34.58±5.68	35.71±5.95
	peak adduction angle	$F_{(2,18)} = 0.600$; $P = 0.508$; $\eta p^2 = 0.06$	1.92±2.62	2.57±2.95	2.31±3.53
	peak abduction angle	$F_{(2,18)} = 0.870$; $P = 0.393$; $\eta p^2 = 0.09$	2.18±3.46	1.70±3.64	2.52±4.37
	flexion angle at IC	$F_{(2,18)} = 0.003$; $P = 0.997$; $\eta p^2 = 0.00$	8.98±4.41	8.89±3.90	8.94±5.42
Ankle	peak dorsiflexion angle^{*,a}	$F_{(2,18)} = 9.480$; $P = 0.006$; $\eta p^2 = 0.51$	19.07±4.98	19.34±4.93	22.2±4.08
	peak plantarflexion angle	$F_{(2,18)} = 0.160$; $P = 0.853$; $\eta p^2 = 0.02$	23.24±5.31	22.92±4.48	23.43±4.83
	peak eversion	$F_{(2,18)} = 0.534$; $P = 0.537$; $\eta p^2 = 0.06$	5.87±2.95	6.59±3.12	6.87±2.10
	sagittal plane plantarflexion angle at IC	$F_{(2,18)} = 0.714$; $P = 0.450$; $\eta p^2 = 0.07$	8.48±6.39	6.97±7.39	9.80±9.21
	frontal plane inversion angle at IC^{*,ns}	$F_{(2,18)} = 4.650$; $P = 0.024$; $\eta p^2 = 0.34$	8.32±3.42	8.52±4.28	11.44±2.14

*: significant main effect of condition ($P \leq 0.05$)
a: significant pairwise comparison, SHOD vs. BF ($P \leq 0.05$)
ns: no significant pairwise comparisons between conditions