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Differential effects of speed on two-dimensional foot strike pattern during barefoot and shod running in recreationally active men

Ran Wang[a,b], David H. Fukuda[b], Peng Cheng[c], Yang Hu[c], Jeffrey R. Stout[b] and Jay R. Hoffman[b]

[a]School of Physical Education & Sport Training, Shanghai University of Sport, Shanghai, China; [b]Institute of Exercise Physiology & Wellness, University of Central Florida, Orlando, USA; [c]Sport Science Research Centre, Beijing Sport University, Beijing, China

ABSTRACT

The majority of barefoot running studies have not considered speed as an influential factor on foot strike pattern. The aim of this study was to investigate differences in foot strike pattern and spatiotemporal characteristics between barefoot and shod overground running at varying speeds. We first determined maximal running speed (Vm) over 50 m in 15 recreationally active men who self-reported as habitual rearfoot strikers. Participants then completed shod and barefoot running trials at different speeds equivalent to approximately 90%, 80%, 70% and 60% of Vm. Sagittal plane two-dimensional (2D) foot-ground contact angle, ankle plantar-dorsi flexion angle, contact time, flight time, step length and step rate variables for each trial were recorded. A significant interaction effect of running speed and footwear condition ($p < 0.05$) on foot-ground contact angle, ankle plantar-dorsi flexion angle and contact time was observed. There was a main effect of running speed ($p < 0.01$) on flight time, step length and step rate. There was a main effect of footwear condition on step length ($p < 0.01$). Participants were more inclined to plantarflex the ankle and contact the ground with the forefoot at higher percentages of Vm, especially when running barefoot.

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KEYWORDS
Running technique; spatiotemporal characteristics; footwear; motion analysis

Introduction

The popularity of barefoot running has increased in the past few years and has been reported to result in improved running economy (Hanson, Berg, Deka, Meendering, & Ryan, 2011; Perl, Daoud, & Lieberman, 2012), as well as a decrease in injury risk for overuse injuries such as Achilles and patellofemoral tendinopathy (Azevedo, Lambert, Vaughan, O'Connor, & Schwellnus, 2009; Bonacci, Vicenzino, Spratford, & Collins, 2014; Pohl, Hamill, & Davis, 2009). The greatest distinction between shod and barefoot running occurs during initial stance (Lieberman et al., 2010). Foot strike pattern, generally categorised as rearfoot (RFS), midfoot (MFS) or forefoot (FFS) striking

CONTACT David H. Fukuda david.fukuda@ucf.edu

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(Nunns, House, Fallowfield, Allsopp, & Dixon, 2013) is the most obvious differentiator of barefoot and shod running techniques from a biomechanical perspective (Shih, Lin, & Shiang, 2013). According to Lieberman et al. (2010), habitually barefoot runners are more inclined to utilise a FFS pattern, and present with a more plantarflexed ankle at initial ground contact, compared with shod runners. Other reported barefoot running characteristics include shorter contact time and stride length (Squadrone & Gallozzi, 2009). An improvement in running economy attributed to the removal of shoes mass has also been reported (Franz, Wierzbinski, & Kram, 2012), however, existing evidence is mixed regarding the benefits of barefoot running from performance enhancement and injury prevention perspectives (Hamill & Gruber, 2017; Jenkins & Cauthon, 2011; Lorenz & Pontillo, 2012).

Previous research has predominantly instructed participants to run at either pre-set (Braunstein, Arampatzis, Eysel, & Brüggemann, 2010; Divert, Mornieux, Baur, Mayer, & Belli, 2005; Squadrone & Gallozzi, 2009; Tscharner, Goepfert, & Nigg, 2003; Williams Iii, Green, & Wurzinger, 2012) or a self-selected running speeds (Bates, Osternig, Mason, & James, 1979; Kurz & Stergiou, 2004; Lieberman et al., 2010; Morley et al., 2010) in order to access differences in running under barefoot and shod running, thereby failing to consider increasing running speed as a potential influencing factor in foot strike pattern adoption. Keller et al. (1996) reported that as running speed increased from 1.0 to 7.0 m/s, the foot strike patterns moved from a RFS to a non-RFS. Breine and colleagues (Breine, Malcolm, Frederick, & De Clercq, 2014) who accessed the foot strike speed relationship across four running speeds (3.2, 4.1, 5.1 and 6.2 m/s) reported similar alterations. While these studies only examined shod running, De Wit, De Clercq, and Aerts (2000) investigated the difference in the lower extremity kinetics and kinematics between barefoot and shod running across three speeds (3.5, 4.5 and 5.5 m/s) and found a significantly flatter (more neutral) foot placement at initial ground contact in barefoot running at higher speeds. It has been shown that the majority of shod runners use a RFS pattern over running long distances in contrast to sprinting, where initial contact is made almost universally with the forefoot (Novacheck, 1998). Indeed, Hasegawa, Yamauchi, and Kraemer (2007) reported a higher percentage of non-RFS runners in top performers of a half marathon. However, as Keller et al. (1996) and Breine et al. (2014) have shown, this may be attributable to the faster running speeds attained by these runners, and not a direct reflection on foot strike preference.

Fredericks et al. (2015) recently reported that foot strike pattern changed from RFS to non-RFS with footwear (traditional, minimalist and barefoot), but that this change was not reflected at running speeds equal or less than 4.0 m/s. However, as noted by the authors the study was conducted on a treadmill, limiting the applicability of these findings given that several investigations have shown differences in kinetics and kinematics, as well as electromyography findings, between treadmill and overground running (Van Caekenberghe, Segers, Aerts, Willems, & De Clercq, 2013; Sinclair et al., 2013; Van Caekenberghe et al., 2013; Wang, Hong, & Li, 2014). The findings from these studies indicate that treadmill running cannot be generalised to overground running and data from treadmill-based investigations should be interpreted with caution. Additionally, the extant literature references absolute speeds instead of relative speeds, under the assumption that biomechanical characteristics between running at absolute speeds and relative speeds may be similar among individuals with relatively homogeneous fitness levels. However, in more heterogeneous samples, relative speeds may result in a more appropriate comparison of biomechanical characteristics. To the author's knowledge, differences in foot strike pattern and spatiotemporal characteristics in barefoot and shod overground running at speeds relative to maximal speed have not been thoroughly investigated.

The aim of this study was to examine the influence of (1) running speed, (2) footwear condition (shod versus barefoot) and (3) the interaction between running speed and footwear condition on barefoot and shod running foot strike patterns of recreationally active men. We hypothesise that, with increasing speed, participants will decrease foot-ground contact angle and increase ankle plantar-dorsi flexion angle, indicating a shift from RFS towards non-RFS, in both shod and barefoot running conditions. A secondary aim of this study was to examine changes in spatiotemporal characteristics (contact time, flight time, step rate and step length) associated with changes in the foot strike technique.

Methods

Participants

Fifteen men (mean ± SD; age: 23.4 ± 2.2 yrs.; height: 176.4 ± 4.5 cm; weight: 68.7 ± 6.3 kg) volunteered to participate in this study. The study was approved by the Beijing Sport University's Institutional Review Board (BSUIRB-2013012). Testing procedures were fully explained before obtaining a signed informed consent from each participant. All participants were habitually active, according to the definition of the American College of Sports Medicine (Balady et al., 1998), and not habituated to running barefoot. In an attempt to eliminate the potential for residual fatigue, the participants were asked to refrain from any strenuous physical activity 72 h prior to the testing. In addition, participants were instructed to arrive at the testing session two hours fasted to avoid any gastrointestinal problems. Each participant completed a physical activity readiness questionnaire (PAR-Q) in order to identify any exclusion criteria, including the inability to perform physical exercise and any illness that required medical care, such as chest pain and joint problems.

Experimental design

Each participant completed all the tests in one single data collection session. After arriving at the laboratory, participants were instructed to select their comfortable size shoe from a selection of the same model of neutral-cushioned running shoes (Anta, Xiamen, China). This was to standardise the influence of shoe cushioning in the shod trial condition. The heel-to-toe differential, measured as the difference in thickness between the forefoot and rearfoot, was 10 mm. Participants were asked to perform a standardised warm-up consisting of lower body stretching and running. Immediately following the warm-up, participants completed three maximal effort running trials with a rest interval of three minutes between each, on a custom-made 50-m long digital track (Patent Number, China: CN1818569A) (Figure 1). The digital track is composed of a series of flexible pressure sensor arrays and coated with rubber particles. Extra space

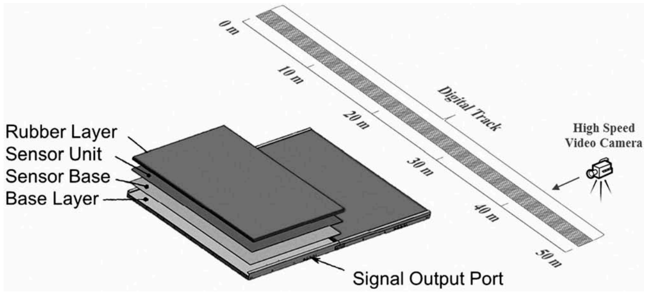

Figure 1. Illustration of data acquisition.

was provided for the participants to adequately decelerate after the 50 m line. The density of the sensor arrays was one per cm^2 and the sampling rate was 100 Hz. Running speed, contact time, flight time, step length and step rate was measured by the digital track throughout the running trials. The highest speed achieved over 50 m was considered the maximal achieved running speed (Vm). Participants were asked to complete multiple running trials at different speeds corresponding to 90%, 80%, 70% and 60% of Vm (a deviation of 5% was allowed). To ensure the frame captured was representative of the running technique at the required speed, participants were asked to maintain the speed after the initial acceleration until the 50 m line. Those trials during which the participants achieved and maintained a speed within 5% of their prescribed speed were analysed. The rest interval between each trial was three minutes to ensure the recovery of the phosphagen system and to minimise fatigue effects on normal running gait. Participants then repeated the protocol barefoot. The non-counterbalanced order was employed as; 1) shod running was the standard training condition for all participants at baseline, and 2) to minimise the possibility of motor pattern carry-over effects.

2D video acquisition

A high-speed video camera (A602fc, Balser, Ahrensburg, Germany) with a sampling rate of 200 Hz was positioned at the 40-m line (10 m from the finish line) separated from the track at a distance of 5-m and at a height of 1-m to allow for sagittal movement of the lower extremities to be centred within the video field of view (Figure 1).

Kinematic analysis

Kinematic data were analysed via a custom-made software by the same rater who was blinded to the speed of each trial, and the test-retest reliability for the digitising procedure was ICC = 0.98. Video files were imported into the software and screened frame by frame. The frame containing the initial landing phase was visually selected for the measurement of foot-ground contact angle and ankle plantar-dorsi flexion angle (Hein & Grau, 2014). According to Ghoussayni, Stevens, Durham, and Ewins (2004), visual determination of ground contact has a limited error. Therefore, the calcaneus, 5th

metatarsal, lateral malleolus and lateral tibial condyle were identified in both the shod and barefoot conditions via visual landmarks on the shoes and feet. The foot-ground contact angle was defined as the angle between the calcaneus-metatarsal vector and the ground, with a positive value indicating a RFS and a negative value indicating a non-RFS. The ankle plantar-dorsi flexion angle was defined as the angle between the shin and the foot formed by the intersection of the malleolus-condyle and malleolus-metatarsal vectors (Figure 2).

Data analysis

Data are presented as mean ± SD. Two-way [footwear condition (shod versus barefoot) x desired running speed (60–100% of Vm)] analysis of variance (ANOVA) with repeated measures were conducted to examine the change of observed running speed, foot-ground contact angle, ankle plantar-dorsi flexion angle, contact time, flight time, step length and step rate. Statistical significance was set at an alpha level of 0.05. In the case of a significant interaction, one-way repeated measures ANOVA with Bonferroni adjustment (Hopkins, Marshall, Batterham, & Hanin, 2009) were conducted to examine the simple main effect of desired running speed. Statistical significance was set at an alpha level of 0.01. Paired-sample t-tests were used to examine the simple main effect of footwear condition. Statistical significance was set at an alpha level of 0.05. In addition, correlation analysis was used to examine the relationship between absolute running speed and foot-ground contact angle. Statistical significance was set at an alpha level of 0.05. Interpretation of the correlation coefficients were based upon criteria published previously (Hopkins et al., 2009), where r values of 0.1, 0.3, 0.5, 0.7 and 0.9 represent small, moderate, large, very large and extremely large relationship, respectively.

Results

Shod and barefoot running speed

Descriptive statistics for running speed are presented in Table 1. The running speed corresponded to 87%, 78%, 67%, 59% Vm and 84%, 74%, 67%, 59% Vm for shod and

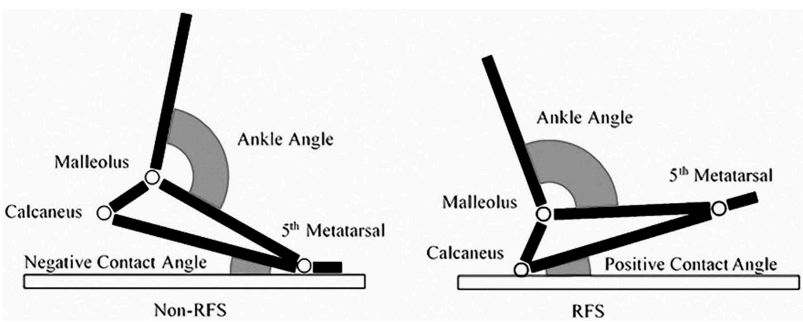

Figure 2. Illustration of foot-ground contact angle and ankle plantar-dorsi flexion angle of RFS and non-RFS.

Table 1. Descriptive statistics for running speed, contact time, flight time, step length and step rate.

Footwear condition	Desired speed	Observed speed (m/s)	Contact time (s)	Flight time (s)	Step length (m)	Step rate (step/s)
Shod	Vm	8.69 ± 0.65	0.13 ± 0.01	0.11 ± 0.02	2.02 ± 0.13	4.32 ± 0.45
	90% Vm	7.58 ± 0.65	0.14 ± 0.02	0.13 ± 0.02	2.02 ± 0.14	3.76 ± 0.35
	80% Vm	6.75 ± 0.54	0.16 ± 0.02	0.14 ± 0.02	1.97 ± 0.14	3.43 ± 0.26
	70% Vm	5.80 ± 0.65	0.16 ± 0.02	0.16 ± 0.03	1.87 ± 0.11	3.09 ± 0.26
	60% Vm	5.09 ± 0.73	0.19 ± 0.02	0.16 ± 0.04	1.75 ± 0.17	2.92 ± 0.30
Barefoot	Vm	8.62 ± 0.58	0.12 ± 0.01	0.10 ± 0.02	1.94 ± 0.13	4.45 ± 0.39
	90% Vm	7.23 ± 0.54	0.14 ± 0.01	0.12 ± 0.02	1.87 ± 0.13	3.87 ± 0.31
	80% Vm	6.38 ± 0.61	0.14 ± 0.01	0.14 ± 0.03	1.78 ± 0.11	3.59 ± 0.31
	70% Vm	5.79 ± 0.60	0.16 ± 0.02	0.15 ± 0.02	1.78 ± 0.12	3.25 ± 0.22
	60% Vm	5.06 ± 0.43	0.17 ± 0.02	0.15 ± 0.02	1.65 ± 0.12	3.08 ± 0.25

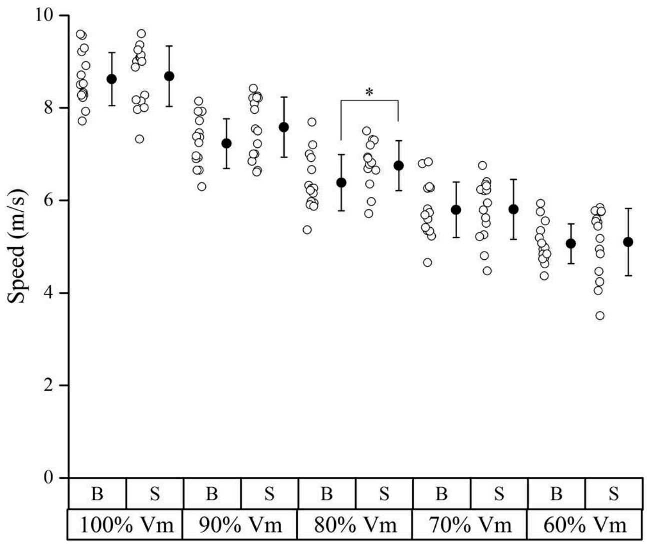

Figure 3. Comparison of individual (open circles) and mean (closed circles with standard deviation as error bars) speed values across running intensities in shod (S) and barefoot (B) conditions. * indicates significant difference between conditions.

barefoot conditions, respectively. The individual values for different running speeds between shod and barefoot conditions are depicted in Figure 3. Paired sample t-tests demonstrated that there was a difference in 80% Vm (p = 0.044) between shod and barefoot conditions.

The relationship between absolute running speed and foot-ground contact angle

As shown in Figure 4, correlation analysis revealed a significant negative relationship between foot-ground contact angle and absolute running speed in both shod (r = −0.466, p < 0.01) and barefoot (r = −0.394, p < 0.01) conditions. The coefficient of determination (r^2) results showed that absolute running speed explained 21.7% and 15.5% of the variance in foot-ground contact angle for shod and barefoot conditions, respectively.

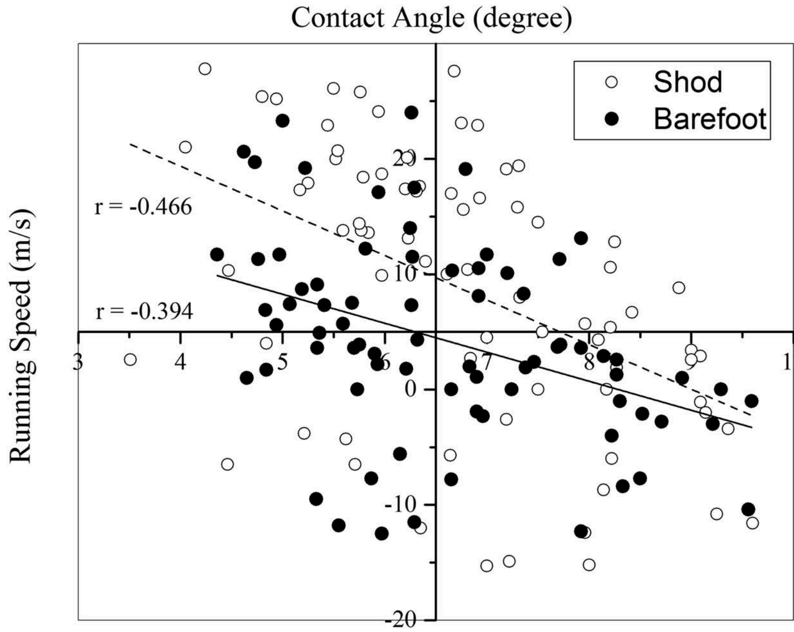

Figure 4. Scatter plot between foot-ground contact angle and running speed in shod and barefoot conditions. Dashed line represents shod condition; solid line represents barefoot condition.

Changes in Foot-Ground Contact Angle and Ankle Plantar-Dorsi Flexion Angle at Different Relative Running Speeds

The change in foot-ground contact angle and ankle plantar-dorsi flexion angle when running shod and barefoot across various running speeds are presented in Figures 5 and 6.

There was a statistically significant interaction between the effects of footwear condition and running speed on the change of foot-ground contact angle ($F_{(4, 56)} = 5.925$, $p = 0.001$, $\eta^2 = 0.297$). Results from one-way ANOVA with repeated measures indicated significant differences in foot-ground contact angle between various speeds for both shod ($F_{(4, 56)} = 29.014$, $p = 0.001$, $\eta^2 = 0.675$) and barefoot ($F_{(4, 56)} = 11.338$, $p = 0.001$, $\eta^2 = 0.447$) running. More specifically, when running shod, the foot-ground contact angle of 100% and 90% Vm were significantly less than that of 80% ($p = 0.001$ and $p = 0.011$), 70% ($p = 0.001$) and 60% ($p = 0.001$ and $p = 0.003$) Vm. When running barefoot, the foot-ground contact angle of 100% Vm was significantly lower than that recorded at 80% ($p = 0.004$), 70% ($p = 0.010$) and 60% ($p = 0.003$) Vm, and the foot-ground contact angle of 90% was significantly less than that of 70% ($p = 0.043$) and 60% ($p = 0.041$) Vm. Results from the paired-sample t-tests showed that the foot-ground contact angle in the barefoot condition was significantly lower than the shod condition when running at 60%, 70% and 80% of Vm ($p = 0.002$, $p = 0.001$ and $p = 0.005$, respectively).

For ankle plantar-dorsi flexion angle, a significant interaction existed for footwear condition and running speed ($F_{(4, 56)} = 2.974$, $p = 0.027$, $\eta^2 = 0.175$). Results of one-way ANOVA with repeated measures indicated that the significant differences in the

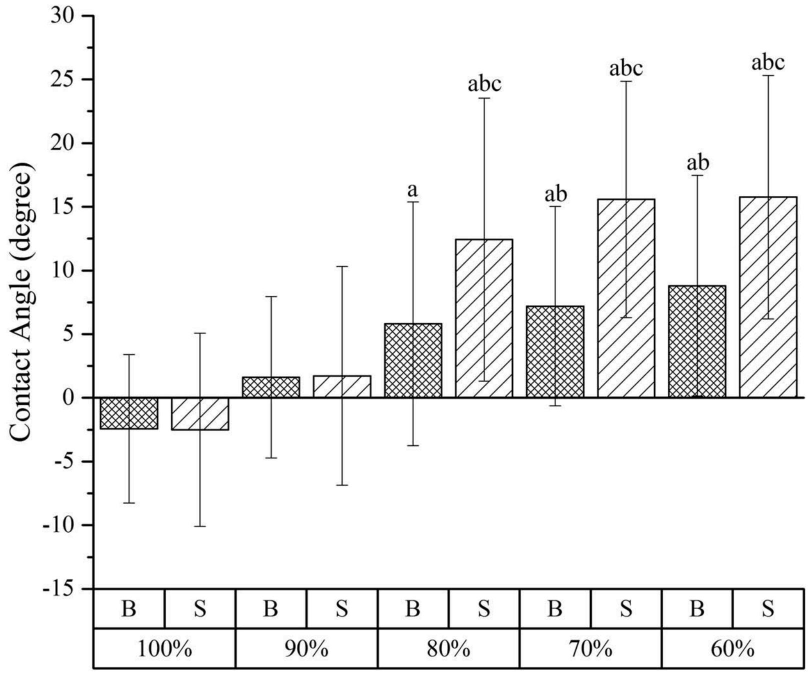

Figure 5. Mean foot-ground contact angle values (with standard deviation as error bars) when running barefoot (B) and shod (S) under different percentages of maximal 50 m running speed (Vm); a indicates significant difference with 100% of Vm (p < .01); b indicates significant difference with 90% of Vm (p < .01); c indicates significant difference between conditions (p < .05).

ankle plantar-dorsi flexion angle between various speeds only exist when running shod ($F_{(4,\ 56)} = 12.302$, $p = 0.001$, $\eta^2 = 0.468$). The ankle plantar-dorsi flexion angle of 100% Vm during the shod condition was significantly greater than that of 70% ($p = 0.001$) and 60% ($p = 0.003$) Vm, and the ankle plantar-dorsi flexion angle of 90% Vm was significantly greater than that of 80% ($p = 0.049$), 70% ($p = 0.008$) and 60% ($p = 0.008$) Vm. Results from the paired-sample t-tests showed that the ankle plantar-dorsi flexion angle in the barefoot condition was significantly greater than the shod condition when running at 60% and 70% of Vm ($p = 0.017$ and $p = 0.001$, respectively).

Changes in spatiotemporal characteristics at different relative running speeds

Descriptive statistics for spatiotemporal characteristics including contact time, flight time, step length, and step rate are depicted in Table 1.

A significant interaction ($F_{(4,\ 56)} = 2.888$, $p = 0.030$, $\eta^2 = 0.171$) was found for footwear condition and running speed on contact time. Results from one-way ANOVA with repeated measures indicated significant differences between various speeds when running both shod ($F_{(4,\ 56)} = 61.465$, $p < 0.001$, $\eta^2 = 0.814$) and barefoot ($F_{(4,\ 56)} = 38.439$, $p < 0.001$, $\eta^2 = 0.733$). More specifically, the contact time was significantly shorter at faster speeds with the exception of no significant difference between Vm and 90% Vm, between 80% Vm and 70% Vm when running shod, as well as between 90%

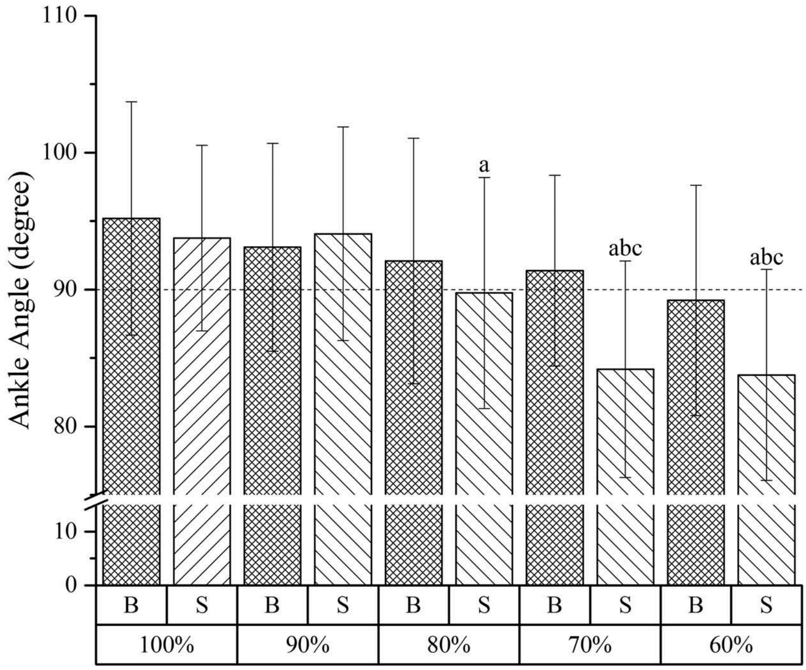

Figure 6. Mean ankle plantar-dorsi flexion angle values (with standard deviation as error bars) when running barefoot (B) and shod (S) under different percentages of maximal 50 m running speed (Vm); a indicates significant difference with 100% of Vm ($p < .01$); b indicates significant difference with 90% of Vm ($p < .01$); c indicates significant difference between conditions ($p < .05$).

Vm and 80% Vm, between 70% Vm and 60% Vm when running barefoot. Results from the paired-sample t-tests showed that contact time under the barefoot condition was significantly shorter than under the shod condition only when running at 80% of Vm ($p < 0.001$).

There was a significant main effect of running speed on flight time ($F_{(4, 56)} = 41.147$, $p < 0.001$, $\eta^2 = 0.746$). Pairwise comparisons showed that the flight time was significantly shorter at faster speeds except that there was no significant difference between 80% Vm and 60% Vm, and between 70% Vm and 60% Vm.

For step length, a significant main effect for footwear condition was noted ($F_{(4, 56)} = 41.195$, $p < 0.001$, $\eta^2 = 0.746$). Pairwise comparisons showed that step length was significantly shorter when running barefoot ($p < 0.001$). There was also a significant main effect of running speed on step length ($F_{(4, 56)} = 30.212$, $p < 0.001$, $\eta^2 = 0.683$). Pairwise comparisons showed that step length was significantly longer at faster speeds except that there was no significant difference between Vm and 90% Vm, and between 80% Vm and 70% Vm.

There was a significant main effect of running speed on step rate ($F_{(4, 56)} = 168.030$, $p < 0.001$, $\eta^2 = 0.923$). Pairwise comparisons showed that step rate was significantly higher at faster speeds with the exception of 70% Vm and 60% Vm. Noteworthy, though no significant ($F_{(4, 56)} = 4.369$, $p = 0.055$, $\eta^2 = 0.238$), footwear condition seemed to have an effect on step rate, with the step rate higher when running barefoot.

Discussion and implications

The aim of this study was to investigate the influence of running speed on the 2D foot strike pattern in barefoot and shod running in recreationally active men. We hypothesised that, as running speed increased, the participants would shift from a RFS towards a non-RFS, in both shod and barefoot running conditions. This hypothesis was supported by the changes in the foot strike pattern described by foot-ground contact angle and ankle plantar-dorsi flexion angle, as well as with spatiotemporal characteristics, such as contact time, flight time, step length and step rate. The primary finding of our study was that both running speed and footwear condition contribute to a change of foot strike pattern and associated spatiotemporal gait characteristics. More specifically, running speed and footwear condition had an interaction effect on selected variables such as foot-ground contact angle, ankle plantar-dorsi flexion angle and contact time; while flight time, step length and step rate were affected by individual factors.

The decrease in foot-ground contact angle and increase in ankle plantar-dorsi flexion angle indicated that participants were inclined to switch from RFS to non-RFS, which could have resulted from changing ankle plantarflexion with increasing speed in both footwear conditions. Previously, Keller et al. (1996) found that habitually shod runners predominantly used a RFS when running at speeds 5.0 m/s or slower, and switched to a MFS and FFS at 6.0 m/s or faster. The shod running speed in our study ranged from 3.5 to 9.6 m/s. Individual analysis showed that the speed at which participants changed from RFS to non-RFS ranged from 5.6 to 9.6 m/s. The large variance in this crossover point may be due to the heterogeneity of the participants in our study. Hatala, Dingwall, Wunderlich, and Richmond (2013) found an increased use of non-RFS at a higher speed among habitually barefoot participants from Kenya who tended to land on the rear foot at a slow jogging pace (2.0–3.0 m/s; 83% RFS), and the percentage of landing on midfoot and forefoot increased with running speed (60% of all foot strikes were classified as non-RFS at 6.0–7.0 m/s). One third of the participants in the present study employed non-RFS at 6.0–7.0 m/s when running barefoot, which is much lower than the previous findings. Apart from the surface interaction effect, the discrepancy could also be attributed to the difference in the participants with the current sample consisting of recreationally-active men who were not specialised in running. Moreover, Lieberman (2014) reported no effect of speed on foot strike pattern, though the range of speeds (2.3–4.8 m/s) employed was slower than both the present and previous studies.

In contrast to previous research, the current study investigated relative faster running speeds, ranging from 5.1 to 8.7 m/s on average and corresponding to 60% to 100% of Vm. The η^2 from ANOVA showed that relative running speed explained 67.5% and 44.7% of the variance in the change of foot-ground contact angle for shod and barefoot conditions, respectively. This is about three times as much as that explained by absolute running speed (21.7% for shod and 15.5% for barefoot condition). This highlights the importance of employing relative running speed in future studies aiming to examine changes in foot strike pattern, especially for a heterogeneous sample with large individual variability. Our study demonstrated that speed is an important factor when examining foot strike patterns, especially at higher running speeds. Results showed that foot strike pattern was predominantly non-RFS at near-maximal speeds (above 90% of Vm), and mostly RFS at moderate speeds (below 80% of Vm). When running at near-maximal speeds, there was no difference in foot strike pattern (mainly non-RFS) between footwear conditions. However, there was a foot strike pattern difference (more non-RFS in barefoot condition) when running at moderate speeds. Keller et al. (1996) explained that individuals running at higher speeds usually adopt a forward leaning posture to lower the centre of gravity. In the current study, it is possible that a forward leaning posture altered the hip and knee joint kinematics, which resulted in a downstream foot strike pattern shift.

When further comparing footwear conditions, the barefoot condition showed a more plantarflexed ankle than the shod condition at 60–70% of Vm. Therefore, the footwear condition may be a primary influencing factor for foot strike pattern at running speeds corresponding to 60–70% of Vm. This is in agreement with Fredericks et al. (2015), who employed a speed range of 2.5 to 4 m/s and reported that barefoot running exhibited greater plantar flexion during foot striking. Lieberman et al. (2010) speculated that increased plantarflexion may reduce the discomfort from the loading rate and impact force during barefoot RFS. Davis and colleagues (Davis, Rice, & Wearing, 2017) concluded that FFS, associated with increased plantarflexion, favours the 'spring-like' function of Achilles tendon. In the meanwhile, Jandacka and colleagues (Jandacka, Zahradnik, Farana, Uchytil, & Hamill, 2017) reported RFS as an adaptation to reduce the loading of Achilles tendon. Consistent with previous studies (Bonacci et al., 2013; Franz et al., 2012), our results showed that participants running barefoot had a smaller step length, indicative of a reduced knee flexion at initial contact, which may contribute to a greater shift in the foot strike pattern. The smaller step length explains the fact that barefoot runners often land with the foot more vertically aligned with the knee or even the hip (Lieberman, 2012). Korhonen et al. (2009) found that reduced stride length allows for reduced ground reaction forces, which may serve as a compensatory mechanism when running barefoot. Further, Tam, Astephen Wilson, Noakes, and Tucker (2014) concluded in a review that FFS is associated with greater plantar flexion and knee flexion at contact in order to cushion impact forces via distributing the force over multiple joints and muscles.

As previously stated, the greatest distinction between shod and barefoot running occurs during the stance phase (Lieberman et al., 2010). Our results showed that the contact time was shorter overall in the barefoot condition when compared with the shod condition while no differences were found in flight time between footwear conditions. Not surprisingly, step rate increased with increasing speed in both shod and barefoot conditions. Accompanied with the shorter contact time, participants tended to have a faster step rate when running barefoot, which is consistent with the findings of previous research (Bonacci et al., 2013; Squadrone & Gallozzi, 2009). This may partially explain the similar maximal running speeds observed between the two footwear conditions as the decrease in step length when running barefoot was compensated for by an increase in step rate.

Conclusion

Foot strike pattern and corresponding spatiotemporal characteristics are affected by both running speed and footwear condition when running over ground. Generally, participants switched from a RFS to a non-RFS with increasing running speeds, which was accompanied by simultaneous decreases in contact time and flight time as well as concurrent increases in step length and step rate. However, compared with shod running, participants running barefoot at moderate speeds (below 80% Vm) exhibited a shorter step length, which resulted in a clear shift from RFS to non-RFS, and a higher step rate. These findings underline the need for considering relative running speed as an influencing factor in future studies when examining foot strike patterns interactions with footwear and no footwear conditions.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Ran Wang http://orcid.org/0000-0002-7148-0764
David H. Fukuda http://orcid.org/0000-0002-4299-7764
Jeffrey R. Stout http://orcid.org/0000-0001-6114-1649

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