



Do Strike Patterns or Shoe Conditions Have a Predominant Influence on Foot Loading?

by

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This study aimed to explore the effects of strike patterns and shoe conditions on foot loading during running. Twelve male runners were required to run under shoe (SR) and barefoot conditions (BR) with forefoot (FFS) and rearfoot strike patterns (RFS). Kistler force plates and the Medilogic insole plantar pressure system were used to collect kinetic data. SR with RFS significantly reduced the maximum loading rate, whereas SR with FFS significantly increased the maximum push-off force compared to BR. Plantar pressure variables were more influenced by the strike patterns (15 out of 18 variables) than shoe conditions (7 out of 18 variables). The peak pressure of midfoot and heel regions was significantly increased in RFS, but appeared in a later time compared to FFS. The influence of strike patterns on running, particularly on plantar pressure characteristics, was more significant than that of shoe conditions. Heel-toe running caused a significant impact force on the heel, whereas wearing cushioned shoes significantly reduced the maximum loading rate. FFS running can prevent the impact caused by RFS. However, peak plantar pressure was centered at the forefoot for a long period, thereby inducing a potential risk of injury in the metatarsus/phalanx.

Key words: foot strike patterns, impact force, plantar pressure, shod/barefoot running.

Introduction

Running is considered to be one of the most important recreational activities (De et al., 2000). It is an increasingly popular activity worldwide due to its high accessibility and low cost. However, the majority of recreational as well as elite runners experience a high incidence of running injury (Fredericson and Misra, 2007). Up to 79% of endurance runners are injured annually, and 46% of these injuries are recurrences (Van Gent et al., 2007). Nearly 80% of running injuries are overuse injuries, which are caused by overloading of the musculoskeletal system of lower extremities (Davis et al., 2017).

Repetitive impact forces experienced during long distance running normally reach the level of magnitude ranging from two to three times the body mass and are considered to induce damage

to the musculoskeletal system of the lower extremity (Nordin et al., 2017). In order to reduce the magnitude of impact force and a corresponding high loading rate, the concept of “cushioning” was proposed in shoe manufacturing to reduce such impacts and potential impact-related running injuries. However, no scientific consensus with regard to the effect of cushioned shoes on the impact force and external loading currently exists. Clarke et al. (1983) showed that highly-cushioned shoes did not significantly change the peak impact force during heel-toe running, whereas Shorten and Mientje (2011) found that the peak impact force in cushioned shoes was significantly reduced during running compared with that in standard shoes. During the past 50 years, the incidence of running

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injuries has not decreased significantly in spite of the emergence of cushion sports shoes (Nigg, 2001). Thus, the role of cushioned shoes in reducing impact force and the rate of running injury remains controversial.

Recently, professional runners and researchers have advocated barefoot running in training, recreation activities, and competitions (Hamill and Gruber, 2017; Lieberman et al., 2010), claiming that it is an effective approach to reduce impact-related injuries (Altman and Davis, 2016; Bonacci et al., 2014). From a biomechanical perspective, one of the clearest differences between barefoot and conventional shod running is the way the foot strikes the ground. Specifically, most barefoot runners use a forefoot strike pattern (Lieberman et al., 2015), whereas approximately 90% of shod runners land on their heels (Hasegawa et al., 2007). Thus, the foot strike pattern was considered to be a key factor that contributed to the benefit of barefoot running (Shih et al., 2013). The forefoot strike decreases effective mass in the lower extremities, prevents the occurrence of repetitive impact forces during running, and reduces injury rates in runners (Lieberman et al., 2010), particularly patellofemoral pain (Bonacci et al., 2014). However, forefoot runners have higher Achilles tendon loading (Kulmala et al., 2013) and greater ankle joint contact forces (Rooney, 2013) than rearfoot runners. Therefore, the appropriateness for traditionally shod amateur runners to convert to a forefoot strike pattern or barefoot running is questionable. Furthermore, little evidence on the predominant influences of shoe conditions or foot strike patterns on foot loading during running is available. Plantar pressure measurement has been widely used to examine the actual loading applied to the feet (Mei et al., 2015; Queen et al., 2007). Knowledge on how plantar pressure combined with impact forces occur in response to different foot strike patterns and shoe conditions would be useful to better understand variations in foot and lower extremity loading and running-related injuries from both movement control and shoe roles.

The purpose of this study was to determine whether strike patterns or shoe conditions had a significant influence on foot loading. Under different strike patterns, ground reaction force, plantar pressure, and impulse during barefoot

running (BR) were compared with those during shod running (SR). We hypothesized that 1) SR would significantly reduce the maximum loading rate, and 2) foot strike patterns would have a more pronounced influence than shoe conditions on overall plantar pressure characteristics during running.

Methods

Participants

Twelve healthy male recreational runners (age: 21.0 ± 1.3 years, body height: 177.1 ± 4.2 cm, and body mass: 68.1 ± 7.4 kg) volunteered to participate in this study. They all had 3-4 years of running experience and ran with regular RFS. All subjects reported no history of lower extremity injury within the previous 6 months and no vigorous exercise within 24 hours before the experiment. Before the start of the study, participants were familiarized with the experimental protocol and potential risks. Informed written consent was obtained from each participant and approved by the Institutional Review Board of the Shanghai University of Sport.

Instrumentation

Two $90 \times 60 \times 10$ cm 3D force plates (9287B, Kistler Corporation, Switzerland) embedded in the laboratory floor were used to register the ground reaction force (GRF) data at 1200 Hz. An in-shoe plantar pressure measuring system (T&T Medilogic Medizintechnik GmbH, Schönefeld, Germany) was used to collect plantar pressure data at 120 Hz during SR and BR with rearfoot and forefoot strike patterns (RFS and FFS, respectively). An insole contained a maximum of 240 force sensors, the number of which depended on insole size and shape, with dimensions of 0.6×0.4 cm and a working dynamic range of 6–640 kPa (Figure 1). Each insole was calibrated using the manufacturer's calibration device prior to the study. A small portable datalogger was attached to the waist of each subject to transfer data to a computer through a wireless connection. The size of the pressure insole was selected according to the shoe code, and the thickness of the insole was 1.2 mm. A timing system with two sets of photocells (Witty-Manual, Microgate, Italy) was used to monitor the running speed. It collected the time elapsed while the participants ran at $3 \text{ m/s} \pm 5\%$ along a 20 m runway (Figure 2). The standard running shoes, each with a full-length

highly-cushioning unit, were used in this study (Figure 3). All the participants adopted the same lacing pattern and wore the same type of running socks to avoid the influence of various shoelaces and socks.

Experimental procedure

Prior to the test, the participants were required to warm up on a treadmill at a running speed of 2.2 m/s for 3 min. They then ran at 3 m/s for 1 min to familiarize themselves with the target speed in the formal test. Subsequently, each performed BR and SR with FFS or RFS at 3 m/s \pm 5% along a 20 m runway (Figure 4). The order of the foot strike patterns and the barefoot/shod condition was randomized. For each participant, three successful trials in which the foot was completely on the force plate were included for each condition.

Data reduction

GRF data were normalized to body mass (BM). Figure 5 presents a representative vertical GRF (vGRF) time curve during the stance phase of running in different foot strike and shod conditions. The stance phase was identified when vGRF exceeded a threshold of 10 N. The variables of interest included: 1) total contact time (CT); 2) the first peak vGRF (FP), that is, the local maximum vGRF that was commonly obtained from the first 25% of the stance phase, and the occurrence time (t_{FP}); 3) the second peak vGRF (SP), that is, the overall maximum vGRF, and its occurrence time (t_{SP}); and 4) the peak vertical loading rate (LR) and its occurrence time (t_{LR}), which was defined as the peak instantaneous slope of the vGRF time curve before the occurrence of FP.

The plantar pressure data were analyzed using Medilogic software (version 4.4). The plantar pressure was calculated dividing the insole area. A regional analysis of each insole was performed by dividing the plantar surface into five regions, namely, forefoot (40% of the foot length), midfoot (30% of the foot length), rearfoot (30% of the foot length), medial (50% of the foot width), and lateral (50% of the foot width). Plantar pressure variables of interest included the following: 1) the peak pressure (PP) of each region and its occurrence time (t_{PP}); and 2) the pressure-time integral (PTI_{50}), which was defined as the impulse of pressure, and was calculated from 0 to 50 ms after the foot contact.

Statistics

All the data were presented as mean \pm standard deviation (SD). A two-way ANOVA with repeated measures was used to examine the effect of foot strike patterns and barefoot or shod conditions on running forces and plantar pressure characteristics (SPSS 17.0, SPSS Inc., Chicago, IL, USA). The intra-class correlation coefficient (ICC) was calculated using absolute agreement in a two-way model. The significance level α was set at 0.05.

Results

Ground reaction force

Overall, the FP and SP were approximately 2 and 2.5 times BM during running with RFS at 3 m/s, respectively. However, the t_{FP} occurred earlier in the barefoot condition than in the shod condition. SP occurred during running with FFS, but FP did not (Figure 5). A significantly less CT with FFS was observed compared with RFS during both SR and BR (Table 1).

No significant differences in FP were found between BR and SR with RFS. Moreover, t_{FP} occurred earlier during BR than SR with RFS ($p < 0.01$, ICC > 0.5 , Figure 6), whereas LR was higher and t_{LR} occurred earlier during BR compared to during SR ($p < 0.01$, ICC > 0.6).

The SP was significantly higher in SR than in BR with both RFS and FFS ($p = 0.008$, ICC > 0.7 , Table 1). The t_{SP} occurred later in the shod condition than in the barefoot condition with RFS ($p = 0.001$, ICC > 0.6) and during BR with FFS compared to RFS ($p = 0.001$, ICC > 0.6), but occurred earlier during SR ($p = 0.028$, ICC > 0.5).

Plantar pressure

In summary, foot strike patterns (15 of the 18 variables) had a more significant effect on the plantar pressure characteristics (Figure 7) than shod conditions (7 of the 18 variables).

First, a significant effect of the foot strike pattern on the PP was found at all plantar regions (Figure 7). Specifically, the PP at the entire foot ($p = 0.012$, ICC > 0.7), midfoot ($p < 0.001$, ICC > 0.6), rearfoot ($p = 0.004$, ICC > 0.8), and lateral ($p = 0.004$, ICC > 0.6) regions was lower in FFS than in RFS in both BR and SR, except for an increased PP at the forefoot ($p = 0.002$, ICC > 0.6) region in FFS. Additionally, the PP at the medial foot was higher in FFS compared with RFS in SR ($p = 0.018$, ICC > 0.6), and a significant shoe effect on the PP was

found at the midfoot ($p = 0.013$, $ICC > 0.6$), rearfoot ($p < 0.001$, $ICC > 0.8$), and medial regions ($p = 0.003$, $ICC > 0.6$). Specifically, the PP at these regions was higher in SR than in BR with RFS. Only the PP at the midfoot region was higher in SR than in BR with FFS ($p = 0.013$, $ICC > 0.6$).

Second, foot strike patterns also had a significant effect on t_{PP} at four plantar regions (Figure 7). Specifically, the t_{PP} at the forefoot ($p < 0.001$, $ICC > 0.6$), midfoot ($p = 0.038$, $ICC > 0.5$), and rearfoot ($p = 0.001$, $ICC > 0.6$) regions occurred later in RFS compared to FFS in SR and BR. However, the t_{PP} at the medial foot ($p < 0.001$, $ICC > 0.6$) region occurred earlier in RFS than in FFS during BR. A significant shoe effect on the t_{PP} was found at the forefoot ($p = 0.039$, $ICC > 0.6$) and medial ($p < 0.001$, $ICC > 0.6$) foot regions, that is, the t_{PP} at these regions occurred later in SR than in BR with RFS. The t_{PP} at the forefoot occurred later

in SR than in BR with FFS ($p = 0.005$, $ICC > 0.6$), whereas the t_{PP} at the medial region occurred earlier ($p = 0.038$, $ICC > 0.6$).

Similar to the PP results, a significant effect of the foot strike pattern on the PTI_{50} was found at the five plantar regions (Figure 7). Specifically, the PTI_{50} at the entire foot ($p = 0.004$, $ICC > 0.6$), rearfoot ($p = 0.013$, $ICC > 0.7$), lateral ($p = 0.044$, $ICC > 0.6$), and medial ($p = 0.004$, $ICC > 0.6$) foot regions was lower in FFS than in RFS in both BR and SR, except for a higher PTI_{50} at the forefoot ($p < 0.001$, $ICC > 0.7$). Moreover, a significant shoe effect on the PTI_{50} was found at the forefoot and rearfoot regions. Specifically, the PTI_{50} at the forefoot region was higher in BR than in SR both with RFS and FFS ($p = 0.011$, $ICC > 0.7$); however, the PTI_{50} at the rearfoot region was lower in BR compared to SR ($p < 0.001$, $ICC > 0.7$).

Table 1

Comparison of the 2nd peak vGRF (SP), the occurrence time (t_{SP}), and contact time (CT) among the four conditions

Variables	BR		SR	
	RFS	FFS	RFS	FFS
SP (BM) ^{cd}	2.49 ± 0.13	2.54 ± 0.34	2.62 ± 0.20	2.81 ± 0.14
t_{SP} (ms) ^{abc}	100.3 ± 5.4	113.1 ± 7.7	116.6 ± 10.9	108.8 ± 7.1
CT (ms) ^{ab}	255.5 ± 19.7	241.3 ± 18.2	272.1 ± 17.5	242.1 ± 13.4

BR, barefoot running; SR, shod running; RFS, rearfoot strike pattern; FFS, forefoot strike pattern.

^a Significant difference between RFS and FFS in SR.

^b Significant difference between RFS and FFS in BR.

^c Significant difference between BR and SR with RFS.

^d Significant difference between BR and SR with FFS.

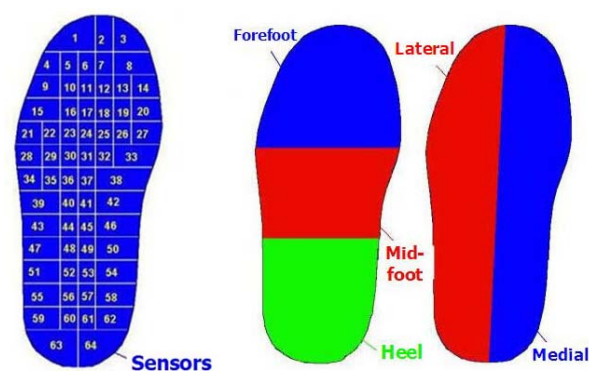


Figure 1

Insole pressure sensors and plantar regions.

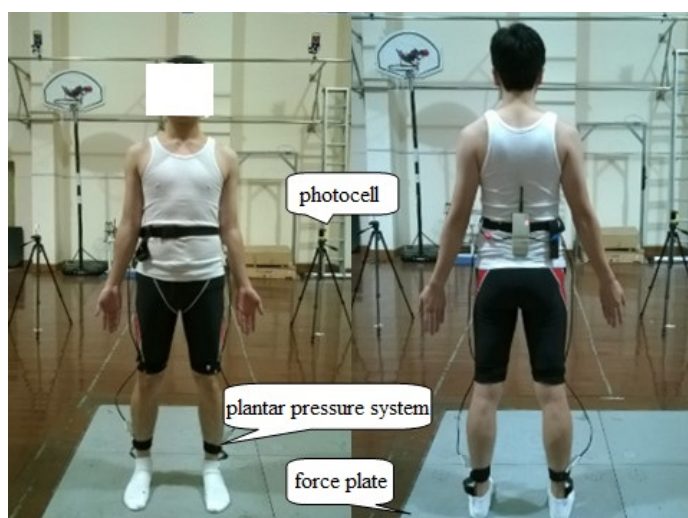


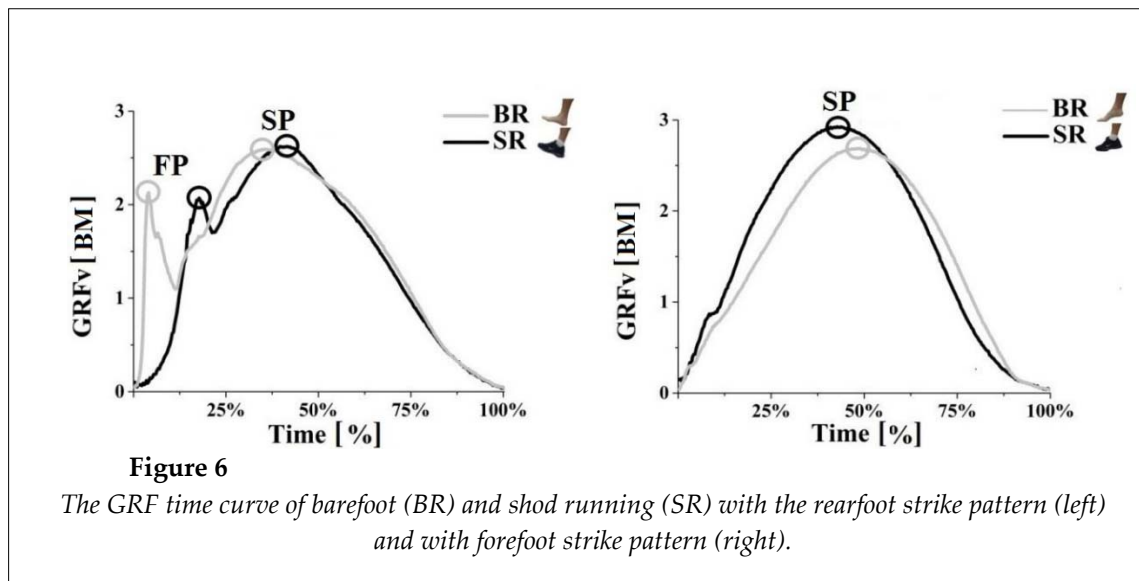
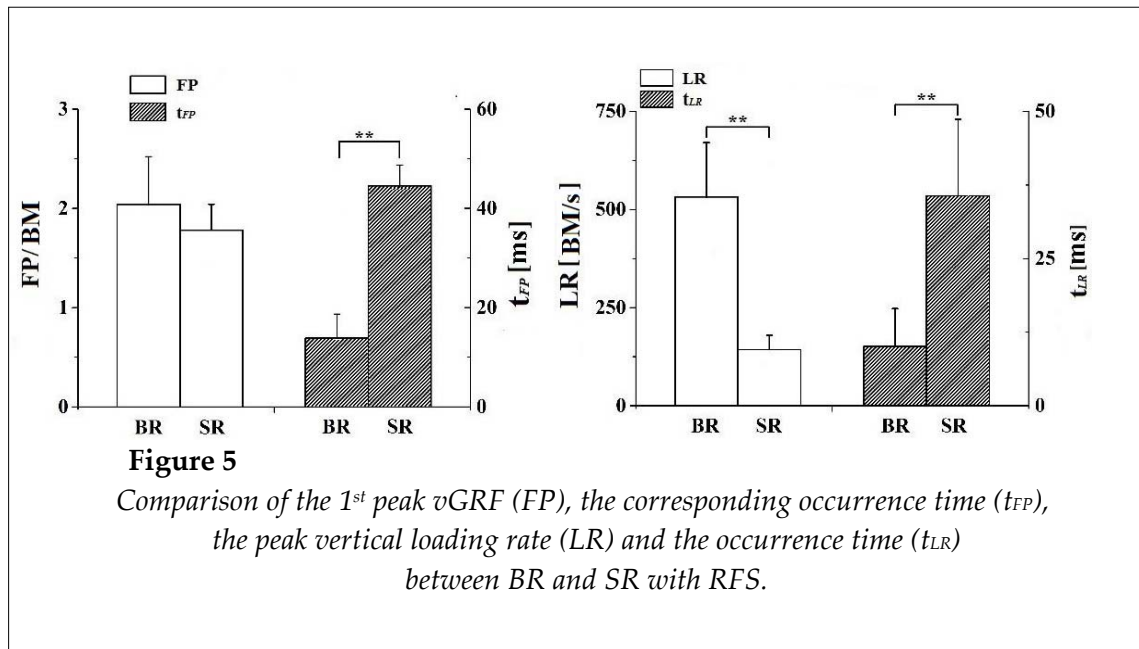
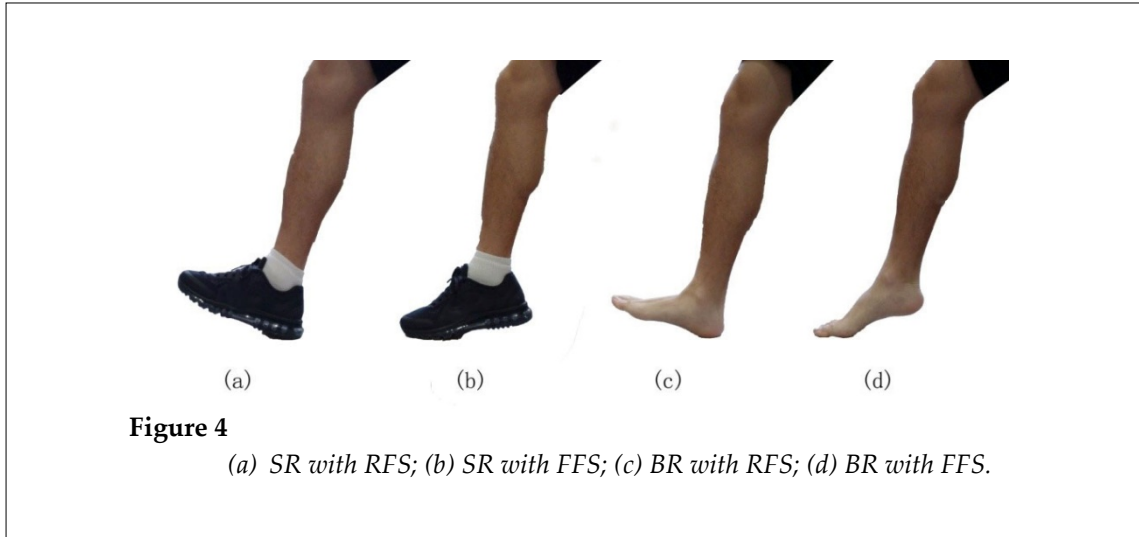
Figure 2

Experimental set-up.



Figure 3

Experimental shoes (left), barefoot (right), and the set-up of the plantar pressure system.



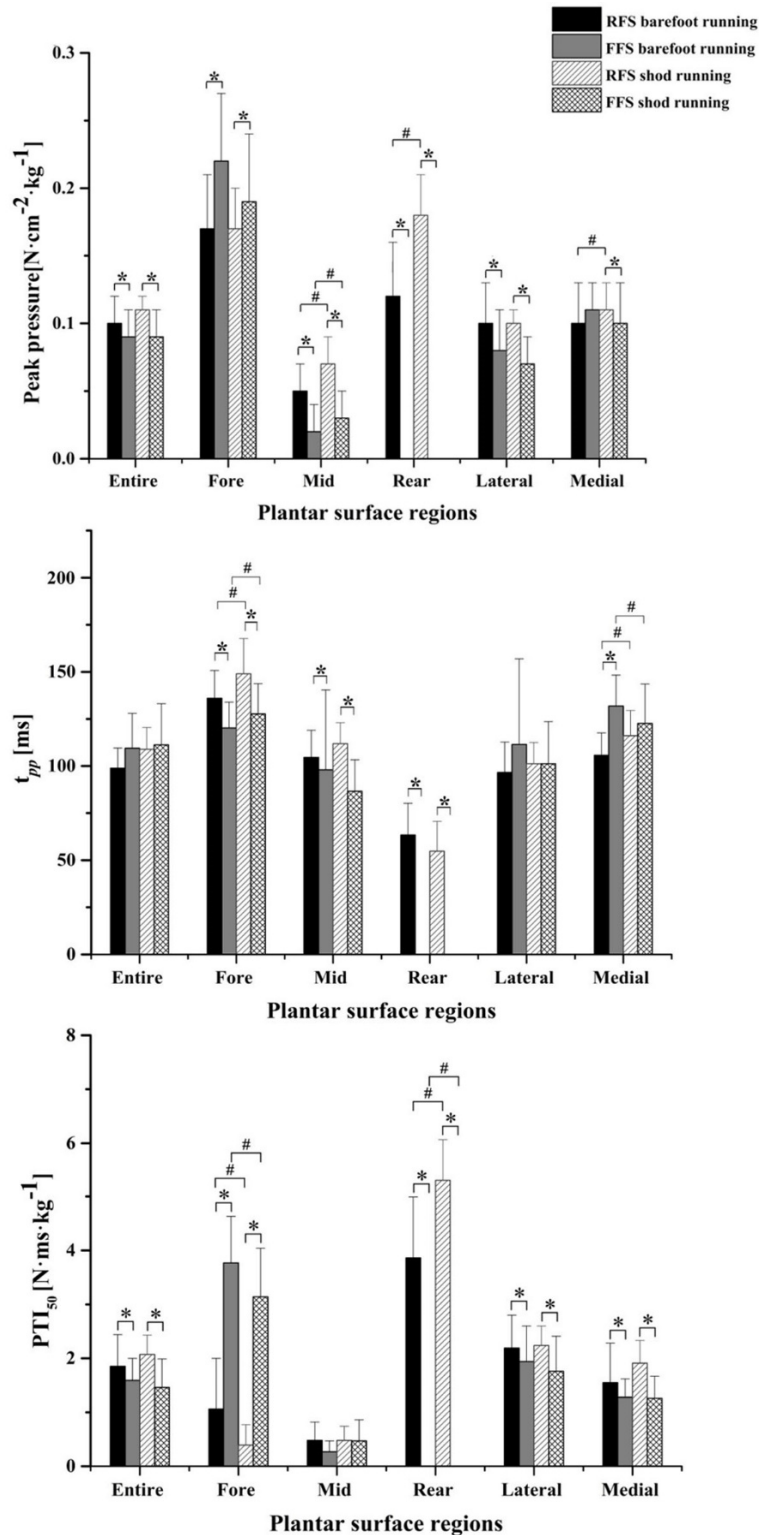


Figure 7

Comparison of peak pressure, occurrence time of peak pressure (t_{pp}), and pressure-time integral during BR and SR with FFS and RFS. Note: Entire, entire foot; Fore, forefoot; Mid, midfoot; Rear, rearfoot; Lateral, lateral foot; Medial, medial foot. Meanwhile, no plantar pressure data in the rearfoot region was available during running with FFS.

* Significant difference between FFS and RFS in running.

Significant difference between SR and BR.

Discussion

The purpose of this study was to examine whether strike patterns or shoe conditions had a significant influence on foot loading. Our hypothesis was supported by the results which indicated that SR significantly reduced the maximum LR and extended the occurrence of t_{FP} and t_{LR} . Moreover, the foot strike patterns (15 out of 18 variables) had a more significant influence than shoe conditions (7 out of 18 variables) on overall plantar pressure characteristics during running.

For the impact forces, no significant difference on FP was observed between BR and SR at RFS; however, t_{FP} appeared earlier during BR compared to SR. The lack of significant differences for the FP between shoe conditions supports the results from the majority of impact-related studies. For instance, De et al. (2000) observed no significant main effect of condition (barefoot vs. shod) for the impact force, which may be because the impact force varies substantially for different effective masses (Lieberman et al., 2010), touchdown speeds (Bruggemann et al., 2011), and lower limb postures (Derrick et al., 2002), but is relatively insensitive to changes in shoe cushioning (Henniget al., 1996). The cushioned shoes were originally designed to attenuate impact force and reduce impact-related injuries (Clarke et al., 1983). Our results, together with those previously mentioned, indicate that cushioned running shoes do not significantly change the FP. On the other hand, LR and t_{LR} were higher and occurred earlier during BR than SR. Similarly, the external loading rate was significantly higher in BR than in SR (De et al., 1994; Komi et al., 1987; Lees, 1988). More compliant shoe cushioning has been found to delay the time at which the t_{FP} occurs and hence reduced the overall loading rate, whereas the magnitude of the impact force was unaffected (Heidenfelder et al., 2010; Wit et al., 2010). In addition, a meta-analysis reported a significant relationship between vertical load rates and tibial stress fractures in RFS runners (Zadpoor and Nikooyan, 2011). Our results suggest that SR does not change peak impacts, yet reduces the LR and extends the occurrence of t_{LR} , indicating that RFS is not suitable for BR, whereas cushioned shoes can be beneficial in reducing the LR for runners with RFS.

For the FFS, no FP occurred (Figure 5). Thus, switching the foot strike to FFS may prevent vertical peak impact and decrease the peak loading rate, reducing the risk for impact-related injuries compared with RFS (Boyer et al., 2014; Cheung and Davis, 2011; Crowell and Davis, 2011; Giandolini et al., 2013; Lieberman et al., 2010). Some studies reported the benefits of using FFS. Daoud et al. (2012) reported that in a collegiate cross country team, RFS runners sustained medically diagnosed repetitive stress injuries twice as often as FFS runners. Moreover, transitioning from RFS to FFS prevents running injuries. Diebal et al. (2012) investigated a group of U.S. military cadets who presented anterior compartment syndrome and high intracompartmental pressures and who underwent transition to FFS. All the subjects demonstrated significant reduction in their intracompartmental pressure and were able to complete a 5 km run without pain.

On the other hand, our findings showed the SP was significantly larger in SR than in BR with FFS. A possible explanation is that the cushioning attribute in the forefoot of shoes enables forefoot landing with a flat placement and stimulates the foot to push off the ground rapidly and heavily (Keijsers et al., 2013; Shorten, 2011). Meanwhile, a significantly less CT occurred with FFS compared with RFS during SR and BR. These results indicate that SR with FFS can prevent peak impact, that is, FP, and produce large active forces, that is, SP, which may reduce the incidence of running injuries and improve performance.

The PP, its occurrence time (t_{PP}), and PTI_{50} were also recorded for the analysis of foot loading characteristics. Based on the results, we found that foot strike patterns had a more significant effect on plantar pressure characteristics compared with shod conditions. In particular, of the 18 variables, 15 were significantly affected by the foot strike pattern, and seven were significantly affected by shoe conditions.

During RFS running, the pressure center moved from the rearfoot to the forefoot, whereas during FFS running, the pressure was concentrated in the forefoot region (Figure 7). Generally, plantar pressure provides information on the distribution of force, and this information can be related to potential damaging effects to local tissues (Rosenbaum and Becker, 2010). In the

current study, we found that the PP in the forefoot was the greatest (Figure 7). The higher forefoot loads may be relevant to metatarsal stress fractures (Hockenbury, 1999). With regard to the effect of foot strike patterns on regional pressure in our study, significant reductions in PP and PTI₅₀ were observed in the entire foot, rearfoot, and lateral regions in FFS in both BR and SR, except for an increased PP at the forefoot region in FFS. Similar findings were reported by Kernozek et al. (2014), who showed that PP and PTI at heel and midfoot regions were higher in RFS than in FFS during running when a minimalist footwear was used, but were lower in PP and PTI at the forefoot. Furthermore, Warne et al. (2013) found that the increase in plantar pressure in the forefoot region during running altered the foot strike pattern from RFS to FFS with barefoot-simulated minimalistic shoes on a treadmill. Changes in plantar pressure can provide accurate data on how the foot is loaded with respect to the supporting surface, given that unnatural or localized loading may predict or indicate injury risk (Orlin and Mcpoil, 2000), particularly tibial and metatarsal stress fractures (Davis et al., 2011). The reduction in plantar pressure during running may represent a possibility for injury reduction as impact and pressure have been linked to running-related injury (Davis et al., 2004; Macdermid et al., 2017). Collectively, our findings indicate that FFS may reduce the risk of impact-related injuries in contrast to RFS. However, transitioning from RFS to FFS acutely may also increase forefoot loading.

Regarding the shoe effect on regional pressure with RFS, the PPs at midfoot, rearfoot, and medial regions were significantly reduced in BR compared to SR. The PP at the midfoot region was lower in BR than in SR with FFS, and the PTI₅₀ at the forefoot region was higher in BR than in SR with both RFS and FFS. However, the PTI₅₀ at the rearfoot region was lower in BR than in SR. These findings are partially supported by the study of Bergstra et al. (2015), who showed that the PP and PTI of the forefoot region increased with the minimalist shoes in contrast to those in standard shoes. The PP and PTI in the heel region did not differ between the two shoe types. In the midfoot region, PP was reduced in minimalist running shoes. The difference between our results and those of Bergstra et al. (2015) may be attributed to differences in gender, testing shoes,

and running speed.

The key outcome of this study was that the average PP and average PTI₅₀ of the entire foot were significantly reduced with FFS compared to RFS. Moreover, the lowest PP and PTI₅₀ were obtained during SR with FFS. Combined with the results of the impact and maximum vertical GRF, SR with FFS may prevent impact and improve performance. The current findings indicate that FFS may be the main factor that contributes to the benefit of BR. Meanwhile, the pressure concentrated at the forefoot for a long time with FFS increases the risk of overuse injury at the metatarsal area (Shakoor and Block, 2006). Therefore, a suitable pair of running shoes is needed for runners with either FFS or RFS to reduce plantar pressure during running.

The limitations of the current study are acknowledged along with proposed future directions for research. First, we only considered the acute effects of shoe and foot strike pattern condition on running impacts. Therefore, the assessment of lower limb kinematics, accompanied with joint kinetics and muscle forces or activation, is warranted to provide further evidence of neuro-musculoskeletal reactions. Second, a long-term effect of the shoe and foot strike pattern should be considered. Highlighting the effect of gender is highly recommended.

Conclusion

The influence of strike patterns on running is more significant than shoe conditions, which was observed in plantar pressure characteristics. Heel-toe running caused a significant impact force on the heel, but cushioned shoes significantly reduced the maximum loading rate. Meanwhile, although forefoot running can prevent impact, peak plantar pressure was centered at the forefoot for a long period, inducing a potential risk of injury in the metatarsus/phalanx. Plantar pressure on the forefoot with RFS was lesser and push-off force was greater when cushioned shoes were used than when running barefoot.

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