Footwear matters: Influence of footwear and foot strike on loadrates during running

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Abstract

Introduction: Running with a forefoot strike (FFS) pattern has been suggested to reduce the risk of overuse running injuries, due to a reduced vertical loadrate compared with rearfoot strike (RFS) running. However, resultant loadrate has been reported to be similar between foot strikes when running in traditional shoes, leading to questions regarding the value of running with a FFS. The influence of minimal footwear on the resultant loadrate has not been considered. This study aimed to compare component and resultant instantaneous loadrate (ILR) between runners with different foot strike patterns in their habitual footwear conditions.

Methods: 29 injury-free participants (22 males, 7 females) ran at 3.13m.s^{-1} along a 30m runway, with their habitual foot strike and footwear condition. Ground reaction force data were collected. Peak ILR values were compared between three conditions; those who habitually run with a RFS in standard shoes, with a FFS in standard shoes, and with a FFS in minimal shoes.

Results: Peak resultant, vertical, lateral and medial ILR were lower ($P < 0.001$) when running in minimal shoes with a FFS than in standard shoes with either foot strike. When running with a FFS, peak posterior ILR were lower ($P < 0.001$) in minimal than standard shoes.

Conclusions: When running in a standard shoe, peak resultant and component instantaneous loadrates were similar between footstrike patterns. However, loadrates were lower when running in minimal shoes with a FFS, compared with running in standard shoes with either foot strike. Therefore, it appears that footwear alters the loadrates during running, even with similar foot strike patterns.

Key Words: ground reaction force; resultant; overuse injury**;** minimalist; forefoot

Introduction

The relationship between foot strike pattern and injury during running has been the subject of much discussion in recent years. This is because the vertical impact transient characteristic of a rearfoot strike (RFS) (3) is associated with a high rate of loading experienced by the body. The musculoskeletal system is viscoelastic in nature and therefore sensitive to high rates of loading. This was underscored by earlier animal studies that demonstrated that impulsive impact loading was associated with both bony (22) and cartilaginous (23) injuries. In humans, high loadrates during running have since been associated with lower extremity overuse injuries in retrospective studies (17, 21, 31). A recent prospective study suggests that high loadrates can distinguish between those who develop any medically diagnosed running-related injury, and those who have never been injured, further strengthening this relationship (8).

It has previously been reported that a forefoot strike (FFS) pattern is missing the impact transient in the vertical ground reaction force that is characteristic of a RFS pattern (15). This FFS pattern has been associated with markedly lower vertical loading rates (15). In a recent study, Daoud and colleagues reported that collegiate cross-country runners who habitually FFS experience fewer repetitive stress running injuries compared with those who habitually RFS (7). Additionally, transitioning to a FFS pattern has been reported to resolve a variety of chronic running-related injuries including patellofemoral pain syndrome (4) and anterior compartment syndrome (9). However, footwear was not considered in these studies. Additionally, all of these studies focused only on the vertical component of the ground reaction force.

While the vertical ground reaction force is the largest component of the total ground reaction force, forces in the anteroposterior (AP) and mediolateral (ML) directions also contribute to the loading forces the body experiences. Yet, the resultant ground reaction force, and its associated loadrate, has received little attention in the running literature. The resultant loadrate may be important in terms of injury risk, as this is the total rate of loading that is applied to the body, and was found to be at least as high as the vertical instantaneous loading rate (ILR) by Boyer et al. (2). These authors reported that the resultant ILR was similar between habitual RFS and FFS runners in standard running shoes, despite slightly lower vertical ILR when running with a FFS compared with a RFS. They also found that ILR in the posterior and medial directions were higher when running with a FFS than a RFS, likely due to impact peaks in these directions that are characteristic of traditionally shod FFS running. These increases in posterior and medial ILR may explain why the resultant ILR was similar between foot strikes. If there is no difference in the total rate of loading to the body between a FFS and a RFS, it is reasonable to question the overall value of FFS running. However, this similarity in resultant ILR has only been observed during running in traditional, cushioned running shoes with a heel-toe drop.

Minimal shoes are often recommended when transitioning to a FFS pattern, as their lack of cushioning discourages landing on the heel. In fact, running in minimal shoes has been shown to encourage a more anterior foot strike than running in traditional shoes (20, 27). Landing on stiffer surfaces has been shown to result in more compliant landings (1, 10, 16), thus running in minimal shoes may have a similar influence. Running in minimal shoes has been shown to result in lower vertical impact loading than running in standard shoes (27) but resultant loadrates were not examined in this study. These authors also noted a more anterior foot strike in minimal shoes, but comparisons to running with a FFS pattern in standard shoes were not made. It should be noted that running barefoot or in minimalist footwear has been associated with stress reactions in the metatarsals (11, 24, 25). However, it remains unclear whether this was the influence of footwear, or was confounded by the brief transition these runners underwent. Boyer et al. (2) reported that when runners were asked to transition to a novel RFS or FFS, they immediately exhibited exaggerated RFS or FFS characteristics compared with the characteristics of runners in their habitual group. This suggests the novel condition was not representative of the habitual state and highlights the need for more ecologically valid research in which participants run in their typical condition.

The aim of this study was to assess the component, as well as the resultant GRF and ILR during running in three distinct groups of runners. These groups were: those who habitually run in standard shoes with a RFS those who habitually run in standard shoes with a FFS; and those who habitually run in minimal shoes with a FFS. It was hypothesized that FFS runners would demonstrate a lower peak vertical ILR than RFS runners. It was also hypothesized that running with a FFS pattern in minimal shoes would result in lower posterior, medial and lateral ILR, and therefore a lower peak resultant ILR, than running with a FFS pattern in standard shoes.

Methods

Participants

Twenty nine participants, aged 18 – 60 years were included in the study (Table 1). These participants were part of a larger study of healthy runners. Participants were required to run at least 10 miles per week, with a minimum running pace of 8.5 minutes per mile (3.12 $m.s^{-1}$). Participants were injury-free at the time of data collection, and had been injury-free for at least six months prior. Habitual footwear was recorded. Foot strike was determined from frame-by-frame observation of videos (125 frames per second) capturing force plate contact from a sagittal plane view. Only one camera was used, allowing observation of either the medial right foot, or the lateral left foot. Foot strike pattern was observed from the video analysis for each trial, and the participant was categorized as running with either a RFS (heel first landing) or a FFS (forefoot first landing) based on observation of all of their recorded trials. No participants demonstrated a combination of both RFS and FFS running in this study. Runners with a midfoot strike (flat foot landing), were not included in this study, as there were fewer than five midfoot strike runners in each footwear condition. Once footstrike pattern was classified, those who ran with a FFS pattern in traditional shoes and those who ran with a FFS pattern in minimal shoes (defined as having minimal cushioning and heel-toe drop ≤ 4 mm) were included. An equal number of those who run with a RFS pattern in traditional shoes were randomly selected and were also included. The study was approved by the Institutional Review Board, and all participants provided written informed consent.

Protocol

Each participant was provided with a shoe consistent with the type of shoe they habitually wore for at least 50% of their running miles. The standard neutral lab shoe was the Nike Air Pegasus and the minimal lab shoe was the inov-8™ BARE–X–200. Participants warmed up on a treadmill, running at 2.24 $m.s^{-1}$ for three minutes, followed by overground running familiarization trials. Force data were collected at 1500 Hz using two AMTI force plates (AMTI, Watertown, MA). Data were collected while participants ran at 3.13 $m.s^{-1}$ (± 5%) along a 30 meter runway. Five trials per side in which the foot was completely on the force plate were included. Participants were not aware that force data were being collected, or that foot strike was being assessed, thus minimizing the likelihood of plate targeting or alteration of foot strike.

Data analysis

Force data were filtered using a 4^{th} order 50Hz low-pass Butterworth filter in Visual3D (C-motion, Rockville, MD). Variables were extracted for each trial using customized Matlab (Mathworks, Natick, MA) codes. Data from only those trials in which the right leg contacted the force plate were used throughout. Stance was identified when vertical GRF > 10N. Variables were obtained from each trial. Time series data were then time normalized and averaged across trials for visualization purposes only. Comparisons were made between those who habitually run with a RFS in a standard shoe (SRFS), those who habitually run with a FFS in a standard shoe (SFFS), and those who habitually run with a FFS in a minimal shoe (MFFS).

Variables

Component ILRs were determined by calculating the derivative of the corresponding GRF with respect to time. Resultant ILR was the resultant of component ILRs (rather than the derivative of the resultant GRF). This ensured that positive ILR values were obtained, so that the resultant magnitude would be more easily interpreted. GRF and ILR values were normalized to body weight (BW). The percentage of foot strikes which included a vertical impact peak (VIP) was determined for each group, where a VIP was defined as a local maximum in vertical GRF that occurred prior to the overall maximum vertical GRF. These percentages were provided for reference, and were not included in statistical analyses. Ground contact times were also compared across groups.

Peak medial (negative direction) and lateral (positive direction) GRF values were obtained from the first 25% of stance. In the posterior (negative direction) GRF, an initial peak is often observed prior to the greatest peak value, particularly when FFS running. This posterior impact peak was defined as the greatest local minimum in the first 15% of stance. The maximum ILR value in the first 25% of stance was obtained for the resultant, as well as in the vertical, lateral and medial directions, while the posterior ILR was the maximum value in the first 15% of stance. Previous studies of RFS running have obtained the vertical loadrate between 20% and 80% of the time of the vertical GRF impact peak (6, 14, 17, 19, 21, 29, 32). However, when running with a FFS pattern, an impact peak may not be present, in which case an alternative method is required to calculate loadrate. Samaan et al. (26) utilized 13% of stance (the average time of an impact peak in the RFS pattern) over which to calculate the loadrates in FFS runners. Boyer (2) used a similar approach, but used 14% of stance. Goss (12) considered the loadrate for runners without impact peaks between 3% and 12% of stance. As we have found vertical loadrate peaks in FFS to occur later in the stance cycle, we calculated these over the first 25% of stance. However, for comparison to other studies, we also calculated peak vertical loadrates in FFS runners in the first 13% of stance (**Peak vILR$_{13}$**).

Statistical analyses

The data were determined to be non-normally distributed according to Kolmogorov-Smirnov tests and the observation of histograms. Nonparametric Kruskal-Wallis tests were used to identify whether there was a main effect of group on GRF and ILR variables, with $P < 0.05$ indicating a significant main effect. Where there was a main effect, Mann Whitney U tests identified where differences between groups occurred. A post-hoc sub-analysis was also conducted on the minimal footwear group. This is because half of the shoes classified as minimal had some cushioning (partial minimal, n=5) and half had no cushioning (full minimal, n=5). The vertical and resultant ILR, as well as the percentage of foot strikes with impact peaks in these two minimal footwear subgroups were compared descriptively to the two standard shoe groups.

Results

Demographic characteristics of the participants are presented in Table 1. There were 22 male and 7 female participants. The majority of those who habitually ran with a FFS in either footwear condition were male (89%). There were no differences in age, height, body mass or BMI between groups.

There was a main effect for ground contact time ($P < 0.001$), which was lowest in the SFFS group, and highest in the SRFS group [mean (SD) SRFS: 270 (23) ms; SFFS: 246 (20) ms; MFFS: 260 (10) ms, $P < 0.001$ for all comparisons]. Impact peaks, defined as local maxima during early stance, were present in 96% of foot strikes in the SRFS group, compared with 16% in the SFFS group and 32% in the MFFS group. Group mean GRF and ILR time histories are presented in Figures 1 (resultant and vertical) and 2 (AP and ML directions). Peak GRF and ILR values are presented in Figures 3 and 4 respectively. There were main effects for posterior, lateral, and medial impact peaks ($P < 0.001$ in all cases). Posterior impact peak was lowest in the SRFS group, and highest in the SFFS group. Lateral impact peak was lower in the MFFS group than both standard shoe groups. Medial impact peak was higher in the SFFS group than both the SRFS and MFFS groups.

There were main effects for ILR in all directions, including the resultant ($P < 0.001$ in all cases). Resultant and vertical ILR were lower in MFFS than both standard shoe groups. Posterior ILR values were higher in the SFFS group than both the SRFS and MFFS groups. Lateral and medial ILR values were lower in MFFS than both standard shoe groups. Peak vertical ILR calculated over the first 13% of stance (Peak $vILR_{13}$) was higher in the SRFS group than both the SFFS ($P = 0.007$) and MFFS ($P < 0.001$) groups [mean (SD) SRFS: 71.12 (27.70) $BW.s^{-1}$; SFFS: 55.24

(14.22) $BW.s^{-1}$; MFFS: 47.10 (12.00) $BW.s^{-1}$]. Time of peak vertical ILR (mean (SD) values as a percentage of stance) occurred at 9.0 (2.2) % in SRFS; 14.4 (4.2) % in SFFS; and 10.6 (7.5) % in MFFS runners. The range of values for time of peak vertical ILR for the SRFS, SFFS and MFFS groups respectively were 4.4 – 12.7 %; 5.0 – 20.3 %; and 1.7 – 24.5 %.

Sub-analysis results

Both partial and full minimal shoe subgroups exhibited lower resultant and vertical loadrates than the groups who either RFS or FFS in standard shoes. However, vertical and resultant ILR were 17% and 15% lower respectively in those who habitually FFS in *full* minimal shoes compared with those who habitually FFS in *partial* minimal shoes (Figure 5). Additionally, all of the impact peaks noted in the minimally shod group (32% of footstrikes) were found in those who habitually run in partial minimal shoes. Those habituated to full minimal shoes exhibited no impact peaks.

Discussion

The purpose of this study was to determine the influence of foot strike and footwear on component and resultant ground reaction forces and loadrates in runners in their habitual conditions. Results of this study suggest that forefoot striking in shoes with the least cushioning results in the lowest rates of loading.

Ground Reaction Force

GRF time histories displayed patterns that differed according to foot strike pattern. When running with a RFS, the majority of foot strikes displayed a distinct impact peak, which was not the case when running with a FFS in either shoe. This is consistent with previous findings (12, 13). Distinct posterior and medial impact peaks were observed in both FFS groups which were less evident when running with a RFS, also consistent with previous findings (2, 3, 18, 29). Boyer et al., (2) suggested that the initial posterior and medial impact peaks that occur during FFS running may result from a rapid change in direction of the foot center of mass during stance, which does not occur during RFS running. The lower lateral GRF when running in minimal shoes compared with standard shoes may be the result of a smaller lateral flare in minimal shoes than standard shoes. This results in a smaller moment arm for the vertical ground reaction force, thereby reducing the pronatory moment on the foot. This may minimize the amount of change in direction of the center of pressure at contact. The mechanical characteristics of the shoe, particularly the rigidity, likely also influence the amount of change in direction of the center of pressure throughout stance. The magnitude of GRF in the AP and ML directions is considerably lower than in the vertical direction for all groups. Nonetheless, these components contribute to the shear forces applied to the body and may be important in terms of injury. For example it is known that bone is weaker in shear than compression (28).

Instantaneous loadrates

Our results were consistent with a previous study, demonstrating similar resultant ILR between habitual RFS and FFS runners in traditional footwear (2). In their study, Boyer et al. (2) found a significantly lower vertical ILR in FFS runners, but the resultant was similar due to higher posterior and medial ILR. In our study, the component ILR values were similar between foot strikes when running in standard running footwear, with non-significantly lower vertical ILR but higher posterior ILR contributing to a similar resultant ILR. In the current study, runners who habitually use minimal shoes and run with a FFS had lower component and resultant loadrates than runners using standard footwear with either foot strike. This finding is likely due to an interaction of footstrike pattern and footwear, as running with a RFS pattern in minimal shoes results in higher loadrates than in standard shoes (20). Those who habitually run in *full* minimal shoes had lower vertical and resultant loadrates than those who habitually run in *partial* minimal shoes. Additionally, only those running in partial minimal shoes exhibited impact peaks in their vertical ground reaction forces. This further emphasizes the importance of footwear, and suggests that even being habituated to a small amount of cushioning can lead to harder landings. To date, only the vertical ILR component has been associated with injury in runners. However, the resultant warrants investigation as these loadrates are at least as high as the vertical ILR, and represent the total loading experienced by the body.

When running with a FFS, the foot contacts the ground in a more plantarflexed (30) and inverted (2) position than when running with a RFS. To achieve a FFS in standard shoes, these characteristics may be exaggerated in order to overcome both the heel height and lateral flare of the standard shoe, that are not present in a true minimal shoe. This may increase both the braking and mediolateral forces in early stance, and could lead to higher loadrates. Furthermore, the midsole of a standard shoe extends to the forefoot and provides additional cushioning. Several studies have demonstrated that individuals land harder when landing on cushioned surfaces (1, 10, 16).

While the vertical loadrate was lower in the SFFS compared with the SRFS, this was not statistically different, contrary to our hypothesis and to previous studies (2). The current study identified the maximum loadrate within the first 25% of stance, while previous studies used only the first 13% of stance (4, 6, 13, 17, 19, 21, 26, 29). When assessing vertical loadrates within the first 13% of stance, our findings also indicated significantly lower vertical ILR when running with a FFS compared with a RFS. However, our findings demonstrate that the time of peak vertical ILR ranged from 1.7% to 24.5% of stance when running with a FFS, thus the maximum vertical loadrate may not have been obtained in previous studies including FFS runners.

Vertical ILR for FFS runners in both shoe conditions demonstrated two local maxima, with the first local maximum being lower than the second. Boyer et al. (2) also found a double peaked vertical ILR for the FFS group, however, they found the second peak to be lower than the first. The source of this second peak may be associated with the acceleration of the remainder of the body's mass throughout stance, following initial foot contact (5). The difference observed between the present study, and the study by Boyer et al. may be due to the combining of MFS and FFS data in the previous study, while our study included only FFS runners. Furthermore, the study by Boyer et al. included competitive runners, whereas our study included recreational runners. Both of these factors likely influenced the acceleration of the remainder of the body's mass after foot impact. All other studies of FFS running, because of the range over which they assessed loadrates, captured the first peak in vertical ILR, but not the second. Therefore, they may have underestimated the true vertical instantaneous loadrate during the loading phase of stance. Future studies of FFS running should consider the maximum vertical ILR that occurs throughout the first 25% of stance, rather than determining this according to the typical time of impact peak when running with a RFS pattern.

This study has a number of strengths. First, including runners in their habitual running conditions increases the ecological validity of the results. Additionally, including an assessment of resultant ILR provides information about the total loading experienced by the body. Finally, extending the range of stance over which instantaneous loadrates are assessed in FFS runners improves the validity of the data. This study may have been limited by the uneven distribution of gender between the groups, although there is no evidence that this factor affects impact loading. This observed difference may be interesting in itself, and warrants further investigation. Additionally, while habitually running with a FFS pattern in a minimal shoe resulted in lower loadrates than in a standard shoe, further studies are required to determine if these differences are important in terms of injury.

Conclusions

The results of this study suggest that running with a FFS pattern in standard shoes results in similar resultant loadrates as running with a RFS pattern in standard shoes. However, resultant loadrates are significantly lower when running with a FFS pattern in minimal shoes. Preliminary analysis of the minimal footwear group revealed that runners who are habituated to full minimal shoes (no cushioning) have the lowest impacts at landing. Additional studies are under way to further examine these differences.

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Conflict of Interest

We report no known conflicts of interest.

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Table 1: Mean (SD) demographics for each group

Variable	**SRFS (n=10)**	**SFFS (n=9)**	**MFFS (n=10)**	**Main Effect (P)**
Male: Female	5:5	7:2	10:0	
Age (years)	32.2 (9.1)	30.7 (10.0)	41.0 (10.9)	>0.05
Height (m)	1.72 (0.11)	1.76 (0.08)	1.82 (0.05)	>0.05
Body mass (kg)	69.3 (15.6)	70.3 (7.3)	78.0 (13.1)	>0.05
BMI ($m.kg^{-2}$)	23.2 (3.7)	22.7 (1.7)	23.6 (2.9)	>0.05

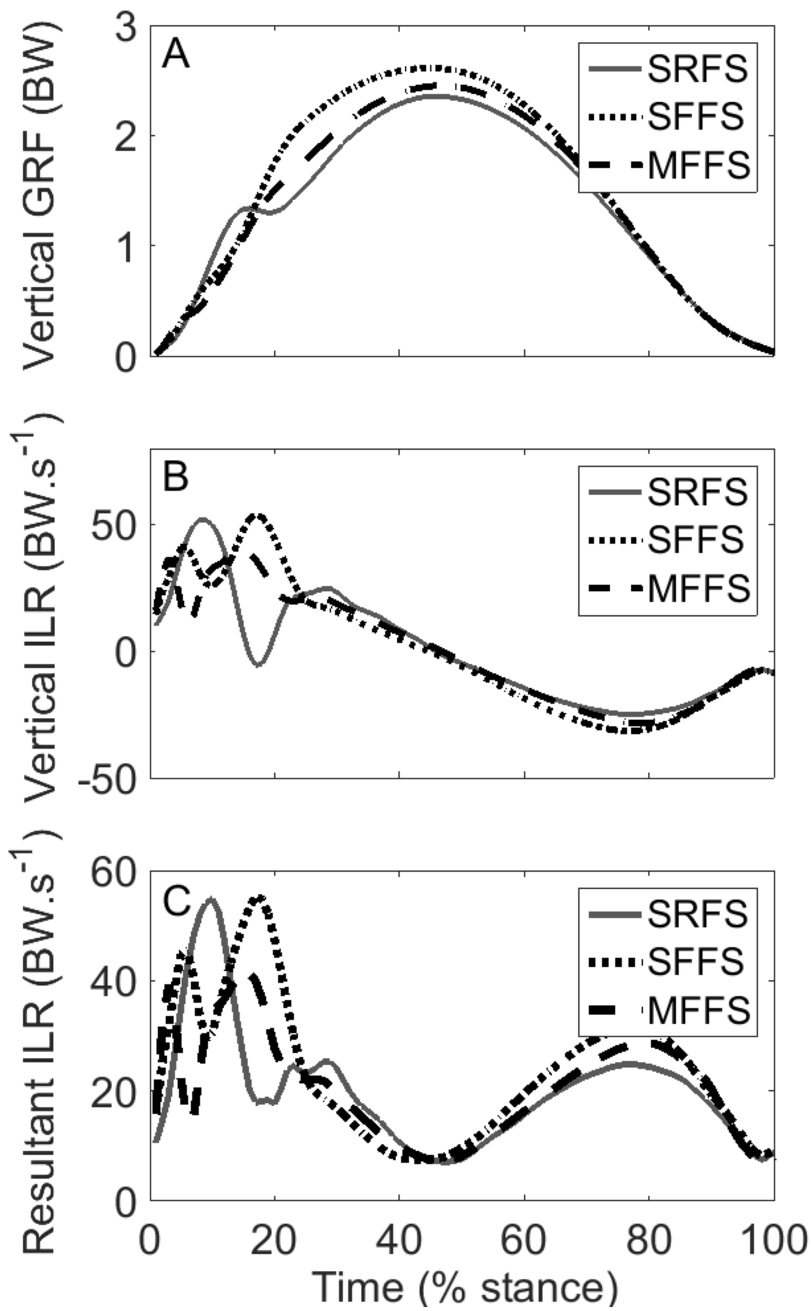

Figure 1: Group mean vertical GRF (A), vertical ILR (B) and resultant ILR (B) throughout stance.

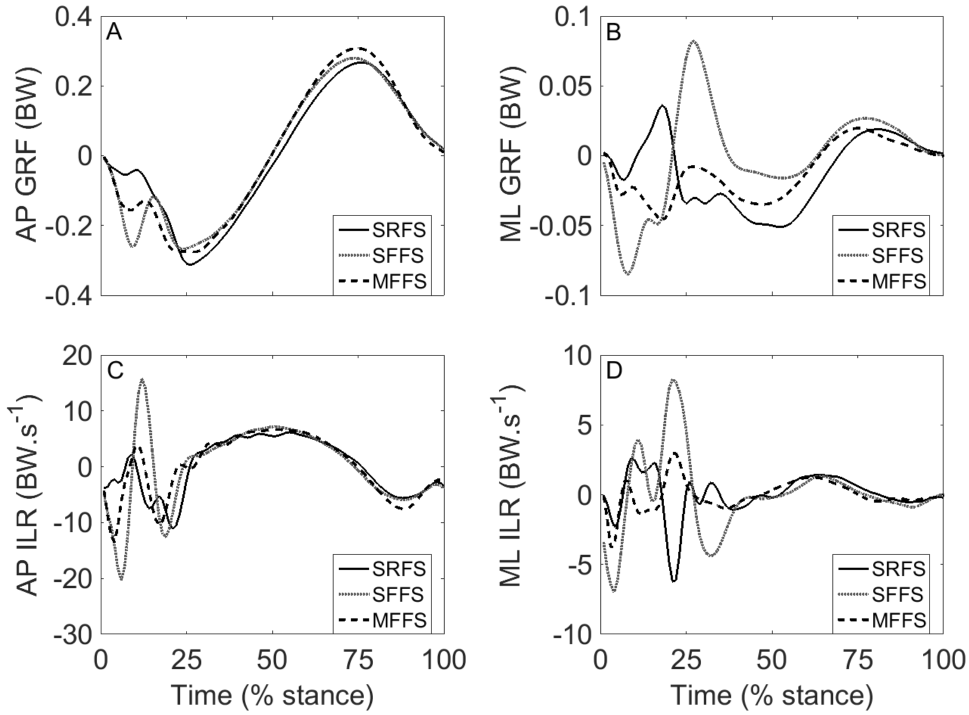

Figure 2: Group mean GRF (A and B) and ILR (C and D) throughout stance in the AP (A and C) and ML (B and D) directions. Positive values represent lateral and anterior directions, respectively.

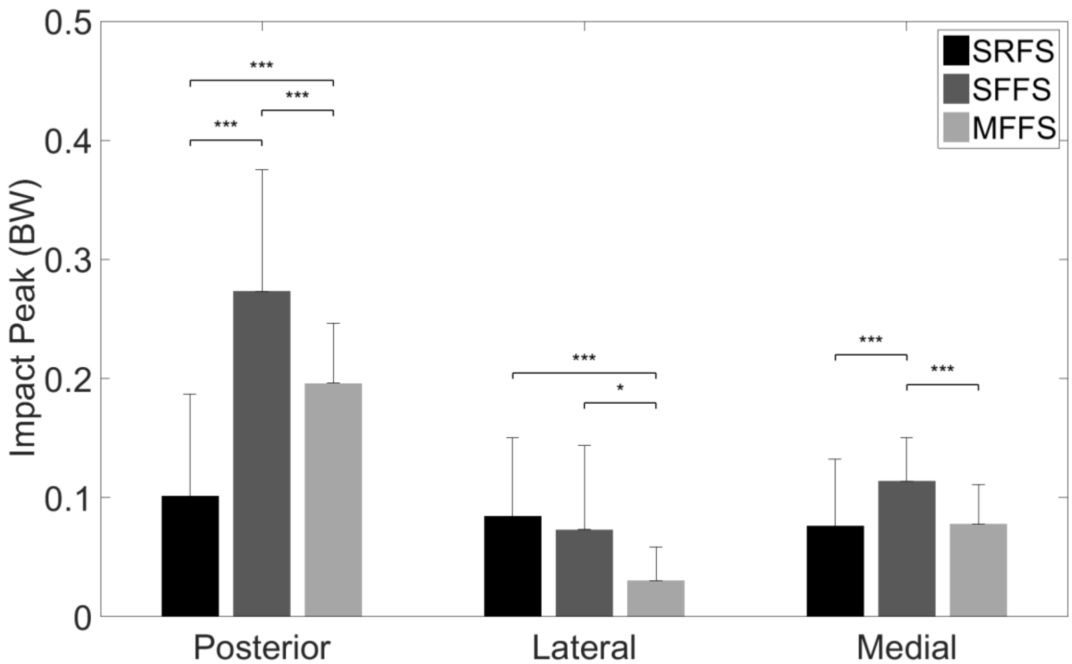

Figure 3: Group mean (SD) GRF impact peaks in the posterior, lateral and medial directions.

* indicates significant difference between groups, P < 0.05

*** indicates significant difference between groups, P < 0.001

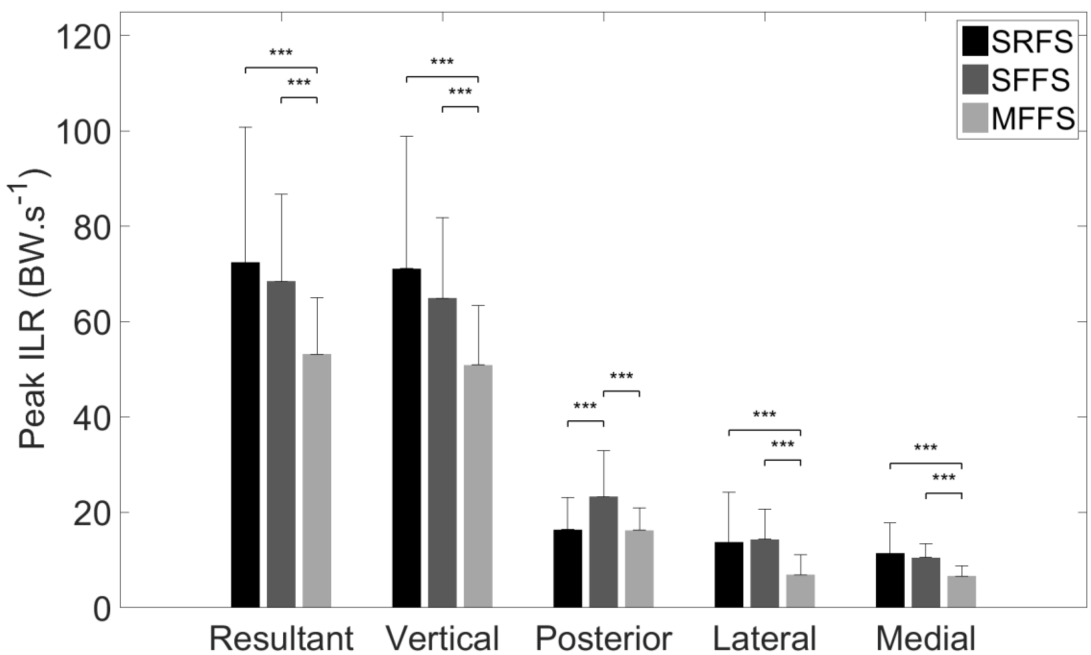

Figure 4: Group mean (SD) values for resultant and component peak ILR.

*** indicates significant difference between groups, $P < 0.001$

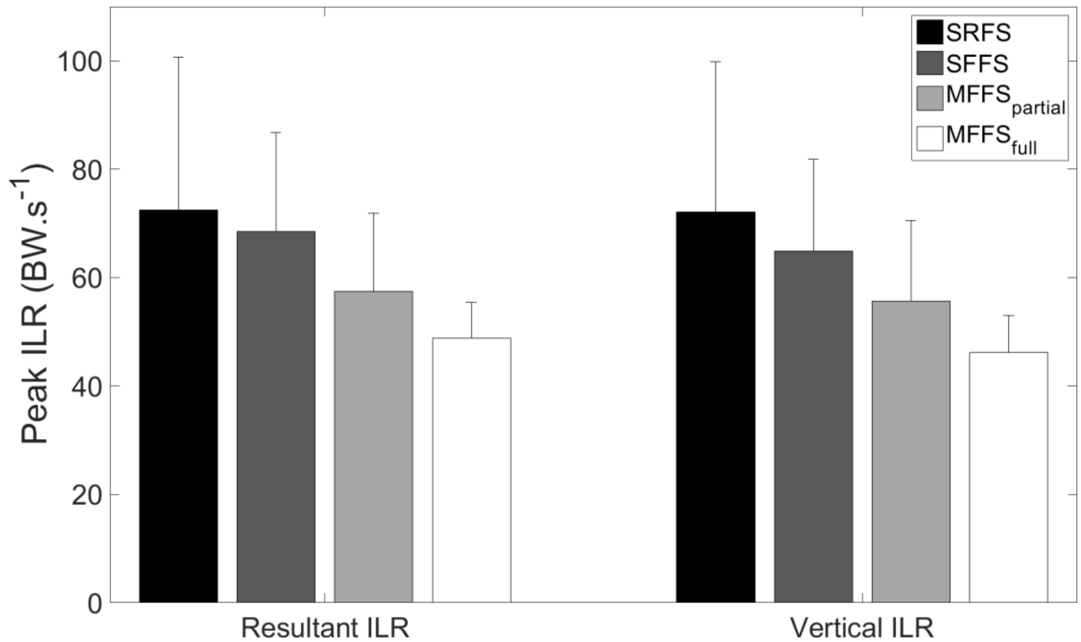

Figure 5: Group mean (SD) peak resultant ILR and vertical ILR values. MFFS subgroup values are presented, where $MFFS_{partial}$ represents those who habitually run in partial minimal shoes, and $MFFS_{full}$ represents those who habitually run in full minimal shoes.