Effects of a seven-week minimalist footwear transition programme on footstrike modality, pressure variables and loading rates

1. Introduction

The recent interest in barefoot (BFT) and minimalist shod (MS) running has led many researchers to consider whether it brings biomechanical and physiological benefits. Equivocal results have been reported regarding the physiological effects of minimalist running, with the majority of research investigating acute footwear manipulations, using either runners with BFT/MS experience (Franz *et al.* 2012; Perl *et al.* 2012; Squadrone & Gallozzi 2009) or habitually shod runners with no previous BFT experience (Burkett *et al.* 1985; Hanson *et al.* 2011). The biomechanical gait modifications to such acute manipulations tend to focus on kinematic and/or kinetic adjustments. Typically when compared to shod (SH) running, BFT and/or MS running has been associated with reduced impact attenuation if a rearfoot strike pattern is maintained, which has manifested in greater loading rates of force (De Wit *et al.* 2000, Paquette *et al.* 2013, Sinclair *et al.* 2013), higher impact accelerations (McNair & Marshall 1994, Sinclair *et al.* 2013) and earlier impact peaks (De Wit *et al.* 2000). There is also evidence of runners adopting a midfoot or forefoot strike when running in BFT or MS, which has been associated with a flatter foot and greater ankle plantarflexion upon initial ground contact (De Wit *et al.* 2000) and greater knee flexion at touchdown and during stance (De Wit & De Clercq 2000, De Wit *et al.* 2000). Additionally, stride length and ground contact time are shortened when running BFT (Franz *et al.* 2012, Squadrone & Gallozzi 2009). There is evidence that long-term habituation to BFT running leads to some individuals adopting a forefoot strike pattern (Lieberman *et al.* 2010). However, considering footstrike modality to only be a function of footwear is over-simplistic, as recent evidence argues that the strike pattern adopted is dependent upon factors such as surface stiffness, running speed and stride length (Hatala *et al.* 2013; Gruber *et al.* 2013, Moore *et al.* 2014).

Approximately 75% of SH runners are rearfoot strikers (Hasegawa *et al.* 2007), which some researchers argue is a result of the raised heel lift present in traditional trainers compared with barefoot running (Lieberman *et al.* 2010). In contrast to this suggestion, Dixon and Kerwin (2001) reported that a controlled increase in heel lift reduced ankle dorsi-flexion at initial ground contact through a flatter foot orientation to the ground, whilst Hamill and colleagues (2011) observed a consistent rearfoot strike running style across three footwear conditions with different heel lift. Another key component of traditional trainers thought to affect running mechanics, is the external cushioning layer that is often not present in minimalist footwear and absent when BFT. An increased stiffness (or absence) of such cushioning has been reported to increase loading rates and peak pressures (De Wit *et al.* 1995, Heidenfelder *et al.* 2010, Shorten & Mientjes 2011). Furthermore, observations have shown that reducing the level of shoe cushioning can increase peak plantar pressures at the midfoot and toe regions (Wiegerinck *et al.* 2009). However, Squadrone and Gallozzi (2009) reported higher peak pressures at the heel, midfoot and toe regions when running in a cushioned trainer compared to BFT and in minimalist footwear with no external cushioning. Previously only acute effects of changing footwear have been investigated. However, the transition period requires greater understanding, particularly as it has recently been reported that individuals may experience lower limb pain when undertaking a transition to minimalist footwear (Giandolini *et al.* 2013). Additionally, understanding whether acute adaptations to different footwear conditions represent gait changes present after several weeks of exposure or whether, in fact, they differ is important.

Prior to the current study only three studies have documented the transition period, considering footstrike modality, touchdown ankle angles, physiological responses and bone edema (Lieberman *et al.* 2010, Ridge *et al.* 2013, Warne & Warrington 2012). From these studies, it appears that the number of runners using a rearfoot strike pattern halves as a result of MS running and the number of forefoot strikers quadruples (Lieberman *et al.* 2010). Additionally, a four week MS transition programme has been shown to improve running economy by up to 8% (Warne & Warrington 2014). Notwithstanding such a positive performance implication, Ridge and colleagues (2013) provided evidence that transitioning to MS running can increase an individual's chance of sustaining a stress fracture. They reported an increase in bone edema in the metatarsals and calcaneous after 10 weeks of MS running. However the underlying kinetic and pressure parameters were not recorded, therefore the biomechanical mechanism cannot be determined.

Evidence shows that training in minimalist footwear increases the strength of intrinsic foot muscles and can result in greater force production of the toe flexors (Goldmann *et al.* 2013; Miller *et al.* 2014). One suggested explanation for these results is that that the flexible midsoles, characteristic of minimalist footwear, lead to a greater recruitment of intrinsic foot muscles that are needed to stabilize the foot arch during push-off (Goldmann *et al.* 2013; Miller *et al.* 2014). For habitually SH runners BFT is likely to place greater stress on the foot muscles, which may have weakened due to inactivity as a result of wearing shoes (Lieberman *et al.* 2010). Therefore, minimalist footwear manufacturers recommend following a foot-strengthening programme prior to the initiation of MS running. Yet, to-date, no investigation has incorporated such a programme into their transition to MS running.

The aim of the current study was to assess the impact of a seven-week transition programme to minimalist footwear on footstrike patterns, kinetic measures and pressure variables. The programme included a two-week foot-strengthening programme, which was then followed by a five-week running programme. Each runner was assessed running in traditional running shoes (SH), MS and BFT at the start and end of the seven-week test period. It was hypothesised that after the transition programme runners would demonstrate a greater proportion of trials classified as midfoot/forefoot strike in the BFT and MS condition compared with at the start of the test period. No changes to footstrike modality were expected within the SH condition. Furthermore it was hypothesised that the SH condition would exhibit the lowest peak pressures and loading rates compared to the BFT and MS conditions.

2. Methods

Ten recreational athletes (nine males and one female) volunteered for the study training programme (Table 1). Participants provided informed consent and were required to be free from injury for at least six months before pre-testing, prior to the initiation of the seven week training programme. Additionally, participants were only selected for inclusion if they had at least one year's experience of running traditional shoes and had no previous experience of running barefoot or in minimalist footwear. Ethical approval was granted from the Ethics Committee of Sport and Health Sciences, University of Exeter.

Each participant attended two laboratory visits. These were completed both before and after the transition programme (pre and post, respectively). Right foot pressure and force data were simultaneously collected during both visits. Height (SEC-225, Seca, Hamburg, Germany) and mass (SEC-170, Seca, Hamburg, Germany) were recorded during the first laboratory visit.

2.1.Experimental procedure

To simultaneously record the ground reaction force and pressure data a pressure plate (300 Hz; RSscan USB plate, RSscan international, Belgium) was positioned on top of the force plate (500 Hz; Advanced Mechanical Technologies Inc, Watertown, MA, USA). Participants ran over the pressure and force plate, which were set flush 5 m along a 10 m EVA runway (Shore A rating of 60). To record the participants' running speeds timing gates were positioned either side of the pressure plate.

Participants were given several familiarisation trials and five minutes to warm-up in each footwear condition [BFT, MS (Komodo Sport, Vibram FiveFingers) and SH (Gel 1500, Asics)] prior to the collection of the experimental data. The three footwear conditions were performed in a randomised order to minimise the impact of potential learning effects on recorded data. Five successful trials for each footwear condition were collected for each participant. A trial was deemed successful if the whole of the right foot contact was within the pressure plate, the test velocity of 3.8 $m{\cdot}s^{-1}$ (± 5%) was met and no gait adjustments were made to target the pressure plate. This process was then repeated after the transition programme.

2.2. Transition Programme

The transition programme commenced immediately after pre-testing. During the first two weeks of the transition programme participants were instructed to refrain from running and complete foot-strengthening exercises, based on recommendations from the VibramFiveFingers website, to help increase the strength of their foot muscles (VibramFiveFingers 2012). Six exercises were described to participants, in addition to photographic examples of the exercises being performed. Participants were instructed to perform three sets of 20 repetitions of each exercise 3-5 times per week, for two weeks. The exercises were: heel raise, toe grip, dorsiflexion and plantarflexion, toe spread, exaggerated eversion and inversion, and grabbing a towel off the floor with their toes. Only during the final five weeks of the transition programme were participants instructed to run in the minimalist footwear. Additionally, participants were encouraged to increase the distance covered per week in the minimalist footwear by no more than 20% each week (Lieberman *et al.* 2010) and were not given any guidance or instruction regarding footstrike modality. Descriptives regarding the number of days and miles ran per week using the minimalist footwear are recorded in Table 1.

2.3 Data analysis

Footstrike modality was determined using the pressure profiles recorded during each trial. Each footstrike modality was classified through inspecting the initial two frames of ground contact, following the procedure recommended by Nunns and colleagues (2013). Four footstrike categories were identified across all the trials: rearfoot (only heel contact within first two frames), midfoot (initial contact at midfoot, or several regions within first two frames), forefoot (only forefoot contact in the first two frames, followed by contact with the rest of the foot) and toe runner (contact made only with the forefoot). The foot was divided into 10 regions (medial and lateral heel (HM and HL, respectively), midfoot (MF), the five metatarsals (M1, M2, M3, M4 and M5), hallux (HX) and toes 2-5 (T2-5)) with the magnitude and time of peak pressure, along with the force-time integral (impulse) of each region determined for each trial.

Using the force plate data, the magnitude and timing of the impact force was calculated only for rearfoot and midfoot strike patterns, as both strike patterns demonstrate a distinguishable impact peak. Additionally, the average (avLR) and instantaneous (iLR) loading rates were only computed for these strike patterns. For all strike patterns the peak active force, braking force ($-F_y$) and propulsive force ($+F_y$) were calculated. All kinetic variables were normalized to body weight prior to statistical analysis.

Individual footstrike modality responses were assessed by identifying the most common footstrike modality used by each participant during their running trials. To accommodate individuals who exhibited a ‘mixed’ footstrike pattern, numerical categories were used to allow half-scores. Footstrike was coded as follows: 1 = rearfoot; 2 = midfoot; 3 = forefoot; 4 = toe runner.

2.4 Statistical analysis

Means (± standard deviations) of the five trials of each footwear condition were calculated for each kinetic and pressure variable. Footstrike modality was determined for each trial and chi-squared tests assessed whether footstrike modality and time, and footstrike modality and footwear were significantly related ($p < 0.05$). Additionally, individual footstrike responses were descriptively examined. A two-way (time x footwear condition) repeated measures ANOVA was performed using PASW Statistics version 18.0.0 (SPSS Inc, Chicago, IL, USA) to determine within-subject effects. Where Mauchley's test of sphericity was violated, a Greenhouse-Geisser correction factor was used. Post-hoc T-tests with bonferroni corrections were performed on any variables found to exhibit significant main effects ($p < 0.05$). Additionally effect size (ES) was estimated using squared partial eta (n^2) and was calculated for all significant main effects and interaction effects.

3. Results

Chi-square analysis revealed that footstrike modality and time were significantly related ($X^2(3) = 87.611$, $p < .001$), similar results were also found within each footwear condition (BFT: $X^2(3) = 22.555$, $p < .001$; MS: $X^2(3) = 36.482$, $p < .001$; SH: $X^2(3) = 87.611$, $p < .001$). When all trials were included regardless of footwear condition, the distribution of the number of trials exhibiting each footstrike modality were spread more evenly post transition, with 79% of pre trials classed as rearfoot, 13% midfoot, 8% forefoot and 0% toe runner, whereas post transition 30%, 15% and 30% were classed as rearfoot, midfoot and forefoot trials respectively, in addition to 25% being toe runner style. Footstrike modality was also related to footwear ($X^2(6) = 17.023$, $p < .05$), with the greatest number of rearfoot trials exhibited during SH running (63%), the greatest number of midfoot and forefoot trials exhibited when BFT (17% and 27%, respectively) and the greatest number of toe runner steps during MS running (14%) (Figure 1).

When individual footstrike responses were assessed, seven participants demonstrated a consistent response pre- to post-intervention across all three footwear conditions. Of these, six adopted a more anterior footstrike modality (e.g. initial contact moving forward, towards the toes) for all conditions (participants 2, 3, 4, 7, 8, 9) and one retained the same footstrike modality (participant 6) (Figures 2, 3, and 4). The footstrike modalities demonstrated by the other three participants (1, 5 and 10) showed a varied response. When considering the footwear conditions, participants either retained the same footstrike or adopted a more anterior footstrike in the SH and MS conditions post-intervention compared to pre-intervention. When BFT two participants retained their footstrike modality post-intervention, six adopted a more anterior footstrike and two adopted a more posterior footstrike (e.g initial contact moving back, towards the heel).

An interaction effect between time and footwear condition ($p < 0.05$) was found for time to impact (Table 2); time of HM and HL peak pressure, peak pressures at the HM, HL, MF, M1, M2 and M4; and impulses at HM, M2 and MF (Table 2). A main effect for time ($p < 0.05$) was revealed for several kinetic variables. Both avLR and iLR were shown to decrease from pre to post (31.3 and 43.2% respectively), whereas active force was shown to increase by 6.1%. All peak pressure variables were found to decrease with time except the M1, M5 and HX. An earlier occurrence of peak pressure at M5 was found post transition (87.3 ± 24.2 and 61.0 ± 39.9 ms, pre and post respectively). Impulses at HL and M4 decreased with time (53.1 and 33.2%, respectively). Furthermore heel off occurred significantly earlier post transition compared to pre transition (68.5 ± 39.2 and 111.3 ± 16.9 ms, respectively).

There was a significant main effect for footwear for both avLR and iLR, with the SH condition exhibiting the lowest loading rates and the BFT condition exhibiting the highest (Table 2). SH running also resulted in the latest occurrence of peak impact force, however the magnitude of peak impact force remained unchanged across the footwear conditions. Ground contact time was found to be significantly different between all types of footwear, with BFT running producing the shortest times and SH the longest (Table 2). BFT braking force ($-F_y$) was greater than the SH braking force, as well as MS propulsive force ($+F_y$) being greater than the SH propulsive force.

All peak pressures showed a significant main effect for footwear (Table 3). The SH condition had significantly lower peak pressures at the M1, M2, M3, M4 and HX than both BFT and MS conditions, and lower peak pressures at the HL (51.9 %) and HM (48.3 %) when compared to MS. However, the SH condition had significantly higher peak pressures at the MF and T2-5. BFT and MS conditions produced similar peak pressures, except for at the MF and M5, where MS had greater peak pressures (24.3 and 17.4 %, respectively). Time of peak pressure was found to be significantly earlier when BFT and MS than SH at the HM (21.4 ± 9.6 and 23.6 ± 9.7 vs. 29.3 ± 6.8 ms, respectively), as well as BFT running producing an earlier occurrence of peak pressure than SH running at the HX (135.5 ± 22.9 vs. 155.0 ± 28.9 ms, respectively). Impulses at M1, M3, M4 and HX were significantly lower when SH than BFT and MS (Table 4). However at MF and T2-5, SH running resulted in higher impulses than both MS and BFT, in addition to significant differences between MS and BFT running (Table 4).

4. Discussion

This study aimed to assess the effect of a seven-week minimalist footwear transition programme on ground reaction forces, pressure and footstrike modality when SH, MS and BFT. There were both time and footwear-dependent effects on loading rates, peak pressures and footstrike modality. After the transition programme runners demonstrated lower loading rates, reduced peak pressures and a trend towards adopting a more anterior footstrike. When comparing footwear, SH running resulted in the lowest loading rates (avLR and iLR) and peak pressures at the heel (HL and HM), metatarsals (M1, M2, M3, M4 and M5) and hallux, but greatest peak pressures at the MF and T2-5 regions compared to BFT and MS running.

During BFT running the distribution of footstrike modalities pre-transition programme were similar to previous reports investigating acute responses to BFT running (Nunns *et al.* 2013). In regards to post-transition, there was a general trend for runners to adopt a more anterior footstrike in all three conditions (Figures 2, 3 and 4). Interestingly though, only during the BFT condition did some individuals adopt a more posterior footstrike post-transition compared to pre-transition. This could have resulted from runners being cautious pre-transition, unaccustomed to the heightened somatosensory feedback, despite the habituation period provided. Notwithstanding these individual responses, it was apparent that there was no dominant footstrike modality across any footwear condition when all the individual trials post-intervention were considered (Figure 1). This finding is in contrast to Lieberman and colleagues (2010) who found over half (57%) of their participants adopted a forefoot strike after a MS transition programme. It is likely that the different runway surface used in the current study and in Lieberman and colleagues (2010) study and time spent accommodating to this surface influenced strike patterns and running mechanics

(Divert *et al.* 2005, Gruber *et al.* 2013, Moore & Dixon, 2014). Forefoot striking can help attenuate shock through eccentric contraction of the gastrocnemius (Pratt 1989), such a shock attenuation strategy is possibly the reason why some habitual BFT runners forefoot strike (Lieberman *et al.* 2010). However other kinematic alterations may have been present during midfoot and rearfoot strikes that acted to absorb impact, such as greater ankle plantarflexion (without a change in foot angle), a more vertical shank and/or greater knee flexion (De Wit *et al.* 2000, Derrick *et al.* 2002). It is suggested that future transition studies should include kinematic data to allow investigation of these suggestions.

Whilst the observed change in footstrike pattern was expected within the BFT and MS conditions after the transition programme, the alteration towards a more anterior footstrike observed for SH running was unexpected. It is conceivable that due to the reduced cushioning offered by minimal footwear individuals adopt certain running mechanics to attenuate the mechanical stress underfoot (Robbins *et al.* 1989, Robbins & Hanna 1987) and that after a transition period these gait modifications are adopted regardless of footwear as runners look to self-optimise their running technique (Moore *et al.* 2012, 2014). However, it was also apparent that seven runners exhibited two different footstrike modalities during the five trials post-intervention when SH, compared to only one runner pre-intervention. This suggests that transitioning back to SH running after MS running produces a more variable running gait in the previous habitual running condition, conceivably due to reacting to reduced somatosensory feedback and greater external cushioning when SH compared to MS.

The later occurrence of peak impact force and lower loading rates for SH running is consistent with findings regarding the effectiveness of compliant materials in footwear (De Wit *et al.* 1995, Heidenfelder *et al.* 2010, Shorten & Mientjes 2011) and supports our second hypothesis. It is this external cushioning layer, present only in the SH condition, which is likely to be the mechanism behind the reduction in loading rates and delayed time to peak impact, particularly as the BFT and MS conditions are relying on the heel fat pad that provides very limited shock reduction and attenuation (De Clercq *et al.* 1994). Whilst the transition programme was successful at lowering loading rates (possibly due to the fact there were fewer rearfoot strikes and more midfoot strikes), the impact magnitudes were still greater in the BFT and MS conditions than SH. It is conceivable that this may always be the case when an impact peak is present as the heel pad reaches maximal deformation upon ground contact (De Clercq *et al.* 1994) and therefore no amount of training is likely to change this. It is conceivable that this explanation relates to both rearfoot and midfoot strike modalities, because although the heel is not the only part of the foot to make initial contact with the ground during midfoot striking, the contribution of heel pad deformation to impact attenuation is likely to be a consistent, and possibly a critical, factor. Similar changes to loading rates have been observed during gait re-training investigations, whereby participants are provided with verbal and visual feedback regarding specific gait parameters to potentially reduce their risk of tibial stress fractures (Crowell & Davis 2011, Davis *et al.* 2009; Milner *et al.* 2006). It is therefore conceivable that runners could use MS running to re-train their own gait. However, footstrike modality will not always be affected and for those who retain a rearfoot strike when BFT and/or MS loading rates will be greater. The potential effect that this may have upon injury risk for these runners should not be overlooked.

In general, BFT and MS running resulted in similar peak pressures, which were higher than for SH running, in accordance with our second hypothesis. Whilst it is acknowledged that the pressure plate used is not directly measuring foot pressures in the MS and SH conditions, this result supports previous evidence from in-shoe pressure insoles that higher pressures occur for minimalist footwear compared to a traditional trainer (Dixon, 2008; Wiegerinck *et al.* 2009). The lower peak pressures when SH are likely to be a result of the external cushioning layer and the dissipation of force over a greater surface area in contact with the ground. The design of the minimal footwear used, which has a similar shaped sole to that of a human foot with individual toe compartments, lends itself to having a similar contact surface area to BFT, except at the MF where contact surface area is increased in the minimalist footwear. Based on this design and lack of cushioning, it does not seem surprising that similar peak pressures were observed for BFT and MS conditions. Interestingly, peak pressures did differ between the BFT and MS conditions in the MF region. BFT running had lower MF peak pressures and impulses than MS. It seems likely that this is due to the lack of surface contact area when BFT, although this will differ based on individual foot arch. The other observed difference is at the M5, where the MS condition has the highest peak pressures, which occur during early stance (approximately 33%), compared to BFT and SH. Whereas, for the other metatarsals (M1, M2, M3 and M4) peak pressures occurred during midstance (approximately 55%). This finding may highlight the inter-play between reducing cushioning (SH to MS) and reducing somatosensory feedback (BFT to MS). With less external cushioning, pressures cannot be dissipated to the same degree and with less somatosensory feedback runners are less aware of the pressure they are exerting.

Collectively, reduced cushioning and somatosensory feedback would result in MS having the highest peak pressures. However, it seems that such an inter-play between cushioning and somatosensory feedback is less apparent when the peak pressures occur during midstance and push-off, particularly for BFT and MS comparisons that demonstrated similar peak pressures during this phase, suggesting that perhaps the heightened somatosensory feedback experienced when BFT has the greatest effect upon initial ground contact. Exerting greater peak pressures is likely to increase the stress placed upon the fifth metatarsal, thus the greater pressure at M5 for MS may be an explanation for the greater bone edema in the metatarsals previously observed in runners after a 10-week transition to minimalist footwear (Ridge *et al.* 2013). Furthermore, the earlier heel off observed post-transition has been found in acute conditions when running BFT and MS compared to SH (Moore *et al*, 2014) and would mean the metatarsals were loaded for longer than pre-transition and could also explain greater bone edema. However, the link between earlier heel off and risk of metatarsal stress fracture has been questioned (Nunns *et al*, 2012). Additionally, peak pressures were higher at the heel when BFT and MS, even after the transition period. Again, this may explain the greater bone edema, this time at the calcaneus, reported by Ridge and colleagues (2013).

Peak pressures decreased from pre to post, except at the medial and lateral metatarsals (M1 and M5) and the HX. The reduced peak pressures under the heel (HL and HM) possibly result from gait modifications whereby a greater number of mid and forefoot strikes were observed. Such a strategy, where runners produce a flatter foot, accompanied by a lower plantarflexion velocity and greater knee flexion at ground contact when running with reduced cushioning underfoot, has been suggested as an adaptation to avoid excessive, localised forces through the heel (De Wit *et al.* 2000, Dixon *et al.* 2005, Robbins *et al.* 1989, Squadrone & Gallozzi 2009). It is evident from the current study that a similar impact attenuation strategy is necessary wearing minimal footwear, probably due to the lack of cushioning, and that this strategy can transfer across to SH running.

Interestingly, runners increased their average weekly mileage from pre- to post-transition. This suggests that runners were comfortable with increasing their running mileage whilst using novel footwear. It is conceivable that the two-week foot strengthening programme led to muscular adaptations to the intrinsic foot muscles, which helped gear the foot for running in novel footwear by stabilizing the foot arch (Miller *et al*. 2014). . Although, the change in running mechanics found in this study could be attributed to the minimalist footwear intervention, it could also be argued that they resulted from the runners becoming more experienced. However, collective evidence suggests that changes to running mechanics are likely to occur between 6 and 10 weeks of running, with very few kinetic changes being made overall (Lake & Cavanagh, 1996, Moore *et al.* 2012). So whilst it is impossible to distinguish between the effect of increased running mileage and the effect of the minimalist intervention within the current study, previous evidence suggests the findings were not purely a result of an increase in running mileage. Nevertheless, the total mileage post-transition is relatively low for runners, but reflects the athletic population used (recreational athletes) within this study. Yet, caution must be raised over such an increase in running mileage over a five week period as it may expose the runner to greater injury risk. It has previously been suggested that a gradual transition, covering low mileage, over a period longer than ten weeks will reduce the risk of bone stress injuries (Ridge *et al.* 2013). Although data regarding bone stress was not included in this study, no injuries were reported.

It must be noted that whilst this study implemented an initial foot strengthening programme, which is encouraged by the manufacturers, no attempt was made to quantify changes to foot strength. This initial programme was deemed necessary to provide a realistic transition to minimalist footwear. However, as the focus of the study was on changes in footstrike modality and kinetics due to footwear and/or the transition programme, foot strength was not measured. Future research may seek to include measures of foot strength for investigation of the mechanism by which observed changes occur.

5. Conclusions

In conclusion, a seven-week transition programme to minimal footwear led to reduced loading rates, lowered peak pressures and trend towards adopting a more anterior footstrike. Whilst it appears that most of the impact attenuation gait modifications occurring as a result of the MS transition were able to transfer across to both BFT and SH running, several runners also exhibited a more variable footstrike when transitioning back to the SH condition. Furthermore, there were consistently greater loading rates and higher peak pressures when running BFT and MS compared to running SH. This is particularly important regarding whether or not to recommend/advocate BFT or MS running to individuals.

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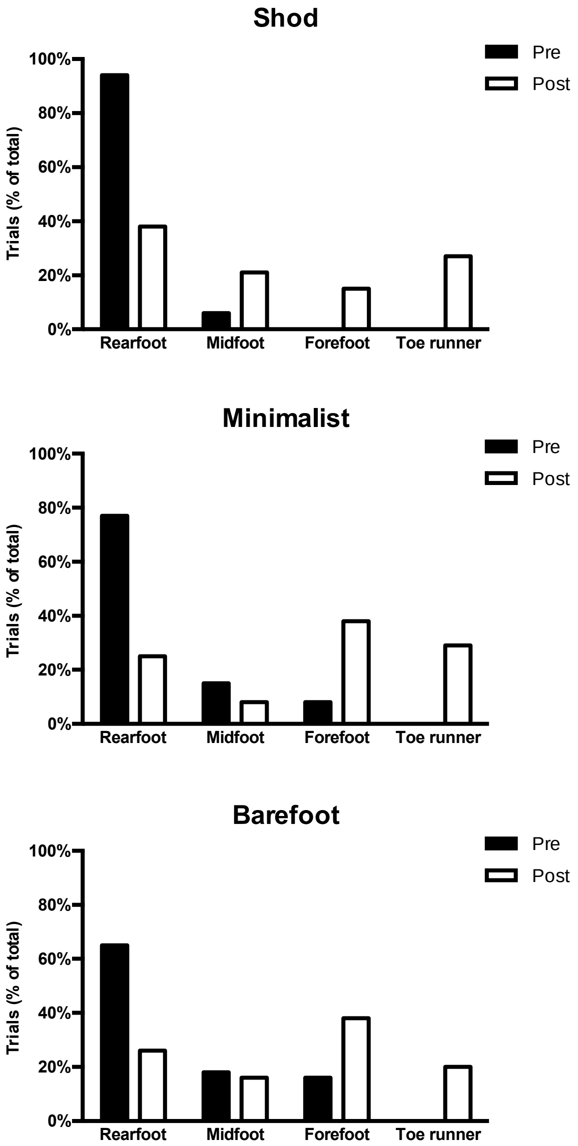


Figure 1. Percentage of trails for each footstrike modality during all three footwear conditions. Pre-transition represented by black bars. Post-transition represented by white bars.

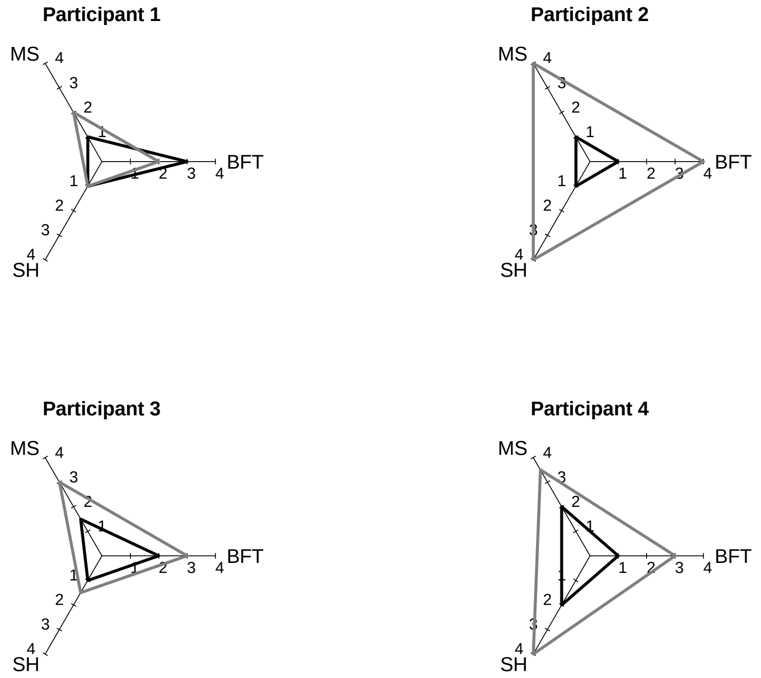


Figure 2. Dominant footstrike modality during all three conditions, pre- and post-transition, for participants 1, 2, 3 and 4. Pre-transition represented by black lines. Post-transition represented by grey lines. Footstrike was coded as follows: 1 = rearfoot; 2 = midfoot; 3 = forefoot; 4 = toe runner.

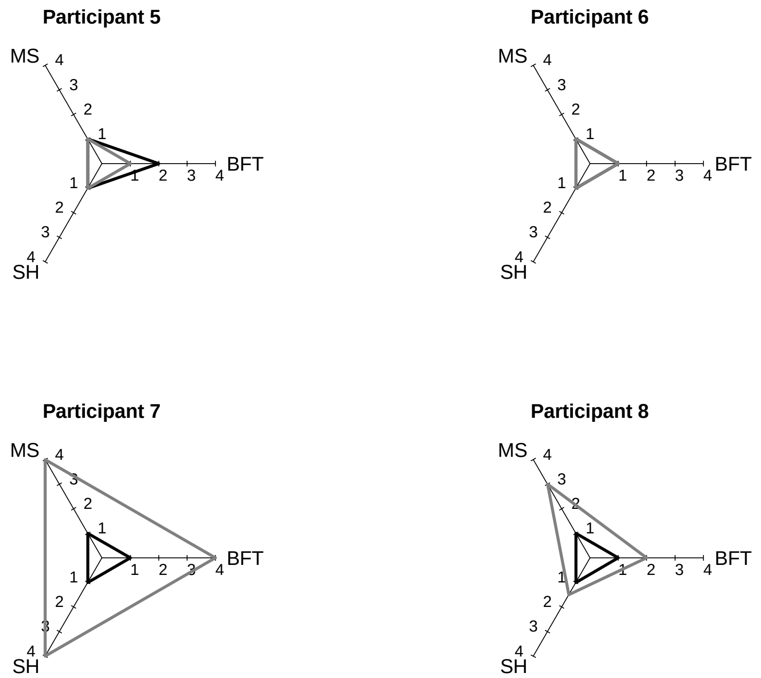
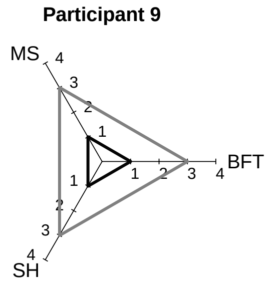


Figure 3. Dominant footstrike modality during all three conditions, pre- and post-transition, for participants 5, 6, 7 and 8. Pre-transition represented by black lines. Post-transition represented by grey lines. Footstrike was coded as follows: 1 = rearfoot; 2 = midfoot; 3 = forefoot; 4 = toe runner.



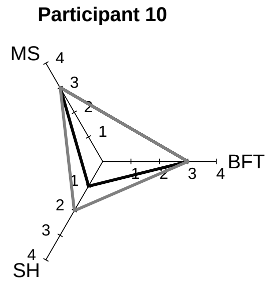


Figure 4. Dominant footstrike modality during all three conditions, pre- and post-transition, for participants 9 and 10. Pre-transition represented by black lines. Post-transition represented by grey lines. Footstrike was coded as follows: 1 = rearfoot; 2 = midfoot; 3 = forefoot; 4 = toe runner.

Table 1. Descriptive data [means (SDs)] for each participant

Ages (years)	Height (cm)	Mass (kg)	Use per week of Vibrams (days)	Average number of miles ran per week	
				Pre	Post
21.0 (0.7)	179.4 (7.6)	78.6 (8.7)	2 - 7	3-10	10-30

Table 2. Means (SDs) and statistical results of ground contact time and kinetic variables for each footwear condition, pre and post transition programme

Variable	BFT		MS		SH		Footwear effect	Time effect	Interaction effect
	Pre	Post	Pre	Post	Pre	Post			
GCT (ms)	216.23 (10.13)	215.04 (19.24)	224.43 (14.68)	221.21 (22.17)	232.36 (15.90)	226.12 (23.10)	$p < .001$, ES = 0.64 BFT < MS < SH	$p = .432$	$p = .571$
Impact force (BW)	2.32 (0.48)	2.20 (0.47)	2.15 (0.40)	1.97 (0.23)	2.02 (0.35)	1.72 (0.49)	$p = .548$	$p=.507$	$p = .358$
Time to impact (ms)	13.18 (6.55)	25.52 (12.35)	17.08 (3.14)	26.27 (9.01)	38.20 (6.65)	32.49 (7.70)	$p = .010$, ES = 0.60 MS < SH	$p = .116$	$p = .015$ ES = 0.57
Active force (BW)	2.38 (0.18)	2.55 (0.28)	2.43 (0.20)	2.56 (0.27)	2.43 (0.21)	2.58 (0.25)	$p = .382$	$p = .017$ ES = 0.48	$p = .560$
avLR ($BW·s^{-1}$)	206.38 (80.57)	106.24 (43.19)	134.52 (38.85)	122.04 (20.25)	54.83 (13.62)	55.80 (10.09)	$p < .001$ ES = 0.74 BFT > MS	$p = .013$ ES = 0.64	$p = .818$
iLR ($BW·s^{-1}$)	445.99 (156.18)	234.91 (82.32)	379.26 (178.75)	196.71 (45.90)	105.79 (36.83)	110.64 (24.27)	$p < .001$ ES = 0.74 BFT, MS > SH	$p = .029$ ES = 0.65	$p = .086$
$-F_y$ (BW)	-0.37 (0.11)	-0.37 (0.14)	-0.32 (0.09)	-0.34 (0.13)	-0.30 (0.09)	-0.34 (0.10)	$p = .014$ ES = 0.38 BFT < SH	$p = .098$	$p = .125$
$+F_y$ (BW)	0.34 (0.07)	0.37 (0.07)	0.34 (0.07)	0.37 (0.05)	0.32 (0.06)	0.36 (0.07)	$p = .030$ ES = 0.32 MS > SH	$p = .335$	$p = .0.78$

Table 3. Means (SDs) and statistical results of peak pressures for each footwear condition, pre and post transition programme.

Variable	BFT		MS		SH		Footwear effect	Time effect	Interaction effect
	Pre	Post	Pre	Post	Pre	Post			
HL	24.24 (10.98)	12.03 (11.87)	36.50 (6.90)	10.05 (8.32)	14.22 (5.00)	8.99 (7.29)	p < .001, ES = 0.68 MS > SH	p = .001 ES = 0.73	p < .001 ES = 0.72
HM	26.35 (13.58)	12.58 (10.52)	35.53 (10.80)	10.97 (9.25)	14.94 (4.99)	9.97 (5.76)	p = .001, ES = 0.56 MS > SH	p < .001 ES = 0.79	p < .001 ES = 0.64
MF	7.01 (15.64)	4.33 (3.93)	9.54 (3.47)	4.56 (3.24)	15.04 (1.79)	9.19 (3.89)	p < .001, ES = 0.77 SH > MS > BFT	p < .001 ES = 0.77	p = .045 ES = 0.29
M1	24.46 (8.35)	21.94 (9.17)	32.10 (7.07)	20.01 (6.49)	14.76 (4.89)	12.47 (5.71)	p < .001, ES =0.79 BFT, MS > SH	p = .067	p = .003 ES = 0.48
M2	44.38 (15.43)	36.41 (15.26)	45.32 (12.45)	30.28 (8.99)	23.06 (5.00)	19.36 (7.49)	p < .001, ES = 0.75 BFT, MS > SH	p = .039, ES = 0.39	p =.003, ES 0.47
M3	38.75 (13.90)	31.00 (14.49)	39.02 (12.96)	26.19 (10.03)	23.60 (6.00)	17.71 (8.91)	p < .001, ES = 0.68 BFT, MS > SH	p = .036	p = .097
M4	29.18 (7.75)	23.00 (12.33)	32.64 (7.85)	19.69 (9.23)	22.42 (7.52)	15.85 (9.30)	p < .001, ES = 0.62 BFT, MS > SH	p = .025 ES = 0.45	p = .015 ES = 0.37
M5	17.17 (8.65)	14.25 (10.15)	21.22 (8.52)	15.76 (12.43)	13.65 (5.77)	12.57 (9.22)	p = .004, ES = 0.59 MS > BFT, SH	p = .251	p = .309
HX	21.78 (7.93)	18.41 (8.58)	22.69 (4.97)	16.40 (8.78)	14.07 (5.89)	11.37 (5.11)	p < .001, ES = 0.64 BFT, MS > SH	p = .096	p = .331
T2-5	6.04 (2.22)	4.74 (2.27)	8.75 (1.87)	5.04 (2.79)	11.30 (2.49)	8.59 (4.93)	p < .001, ES = 0.73 SH > MS, BFT	p = .041 ES = 0.39	p = .175

Table 4. Means (SDs) and statistical results of impulses for each footwear condition, pre and post transition programme

Variable	BFT		MS		SH		Footwear effect	Time effect	Interaction effect
	Pre	Post	Pre	Post	Pre	Post			
HL	18.55 (10.84)	9.77 (12.69)	20.98 (7.93)	6.52 (8.92)	19.13 (9.17)	11.32 (12.36)	p = .631	p =.004 ES = 0.79	p = .181
HM	30.56 (18.99)	11.82 (16.74)	42.63 (23.71)	12.37 (23.31)	22.13 (12.20)	10.73 (12.50)	p =.015, ES = 0.37	p < .001 ES = 0.82	p =.002 ES = 0.57
MF	25.90 (15.64)	15.03 (17.05)	28.31 (13.00)	10.36 (10.57)	68.92 (19.19)	42.37 (26.61)	p < .001, ES = 0.79 SH > MS > BFT	p < .001 ES = 0.81	p = .043 ES = 0.30
M1	45.96 (15.99)	47.12 (24.45)	55.99 (16.78)	41.89 (20.74)	38.86 (12.51)	32.09 (17.63)	p =.002, ES = 0.49 BFT, MS > SH	p =.273	p = .041 ES = 0.30
M2	69.33 (21.31)	54.12 (21.66)	67.90 (22.56)	42.57 (12.38)	42.64 (12.15)	31.81 (15.03)	p < .001, ES = 0.75 BFT, MS > SH	p =.021, ES = 0.46	p = .029 ES =0.33
M3	51.13 (16.82)	42.81 (20.61)	50.13 (19.31)	35.41 (12.61)	35.22 (11.02)	25.73 (13.34)	p < .001, ES = 0.74 BFT, MS > SH	p =.085	p = .401
M4	37.46 (11.56)	27.23 (14.15)	38.73 (13.72)	23.75 (10.00)	31.51 (12.40)	21.00 (11.05)	p =.001, ES = 0.526 BFT, MS > SH	p =.041 ES = 0.39	p =.415
M5	22.20 (14.61)	18.85 (15.05)	23.08 (11.79)	25.24 (16.10)	21.68 (13.76)	16.38 (11.73)	p = .256	p = .325	p =.898
HX	40.72 (17.95)	41.40 (21.20)	41.19 (10.39)	36.53 (21.02)	21.20 (8.63)	21.96 (11.19)	p < .001, ES = 0.72 BFT, MS > SH	p = .846	p =.588
T2-5	23.27 (11.44)	20.28 (9.54)	35.49 (9.37)	24.28 (15.21)	51.90 (15.13)	50.39 (31.36)	p < .001, ES = 0.73 SH > MS > BFT	p = 4.12	p = .434