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Research article

Acute Differences in Foot Strike and Spatiotemporal Variables for Shod, Barefoot or Minimalist Male Runners

Ciara McCallion [1], Bernard Donne [1], Neil Fleming [2]✉ and Brian Blanksby [3]
[1] Departments of Anatomy and Physiology, Trinity College Dublin, Dublin 2, Ireland
[2] Department of Kinesiology, Recreation and Sport, Indiana State University, Indiana, USA
[3] School of Sport Science, Exercise and Health, University of Western Australia, Australia

Abstract
This study compared stride length, stride frequency, contact time, flight time and foot-strike patterns (FSP) when running barefoot, and in minimalist and conventional running shoes. Habitually shod male athletes (n = 14; age 25 ± 6 yr; competitive running experience 8 ± 3 yr) completed a randomised order of 6 by 4-min treadmill runs at velocities (V1 and V2) equivalent to 70 and 85% of best 5-km race time, in the three conditions. Synchronous recording of 3-D joint kinematics and ground reaction force data examined spatiotemporal variables and FSP. Most participants adopted a mid-foot strike pattern, regardless of condition. Heel-toe latency was less at V2 than V1 (-6 ± 20 vs. -1 ± 13 ms, $p < 0.05$), which indicated a velocity related shift towards a more FFS pattern. Stride duration and flight time, when shod and in minimalist footwear, were greater than barefoot (713 ± 48 and 701 ± 49 vs. 679 ± 56 ms, $p < 0.001$; and 502 ± 45 and 503 ± 41 vs. 488 ±4 9 ms, $p < 0.05$, respectively). Contact time was significantly longer when running shod than barefoot or in minimalist footwear (211±30 vs. 191 ± 29 ms and 198 ± 33 ms, $p < 0.001$). When running barefoot, stride frequency was significantly higher ($p < 0.001$) than in conventional and minimalist footwear (89 ± 7 vs. 85 ± 6 and 86 ± 6 strides·min^{-1}). In conclusion, differences in spatiotemporal variables occurred within a single running session, irrespective of barefoot running experience, and, without a detectable change in FSP.

Key words: Flight time, contact time, foot-strike pattern.

Introduction

Human bipedal running has been predominantly barefoot or in minimalist footwear for millions of years. Cushioned running shoes developed/appeared around the 1970s (Lieberman et al., 2010). Between 37 and 56% of runners suffer a musculoskeletal injury annually (van Mechelen, 1992), and despite shoe design advances, injury incidence has remained similar over the last 40 years (van Gent et al., 2007). These stable injury risks have influenced a trend back to shoes designed to mimic barefoot running with claims of improved performance and reduced injuries (Jenkins and Cauthon, 2011; Rothschild, 2012).Vibram Fivefingers (VFF) is a minimalist shoe that mimics barefoot running while providing a layer of protection. To date, VFF and Nike Free 3.0 are the only minimalist shoe designs that have undergone biomechanical evaluation (Bonacci et al., 2013; Squadrone and Gallozzi, 2009).

Athletes have recorded shorter step and stride lengths, and stride frequencies (De Wit et al., 2000; Divert et al., 2008; Kerrigan et al., 2009; Squadrone and Gallozzi, 2009) when running barefoot. In addition, mean contact time was reduced when running barefoot (Divert et al., 2005; Braunstein et al., 2010). However, Squadrone and Gallozzi (2009) found no differences in contact time between barefoot and shod running; and speculated that the degree of protection from the VFF minimalist shoes allowed athletes to push-off more vigorously, resulting in spatiotemporal variables being more aligned with shod running.

The gait cycle begins with contact, and occurs as a rear foot strike (RFS); a mid foot strike (MFS); or a fore foot strike (FFS), depending on which part of the foot contacts the ground first (Lieberman et al., 2010). A RFS occurs when the heel contacts the ground first, a MFS occurs when the ball of the foot and heel land simultaneously, and a FFS occurs when the ball of the foot lands before the heel (Lieberman et al., 2010).

Biomechanical research evaluating barefoot running has focused on ankle joint kinematics and, subsequently, cited foot-strike patterns (FSP) as possible reasons for observed differences (Bishop et al., 2006; Braunstein et al., 2010; De Wit et al., 2000; McNair and Marshall, 1994; Squadrone and Gallozzi, 2009). However, only one study has directly compared FSP between barefoot and shod running (Lieberman et al., 2010), and no study has examined FSP running in minimalist shoes.

Most analyses of barefoot and shod running have reported increased ankle plantarflexion at initial contact when barefoot which may be due to, or result in, changes in FSP (De Wit et al., 2000; Bishop et al., 2006; McNair and Marshall, 1994; Squadrone and Gallozzi, 2009). However, Lieberman et al. (2010) investigated habitually shod and habitually barefoot athletes and theorised that barefoot runners adopted a flatter foot placement at initial contact. De Wit (2000) reported that this flatter foot placement was brought about by significantly larger planterflexion and a significantly more vertical position of the shank at initial contact; the latter effect being brought about by increased knee flexion. In the study by Lieberman et al. (2010), habitually shod athletes mostly used a RFS pattern, with 100% of participants using a RFS when shod, and 83% adopting a RFS when barefoot. In contrast, athletes who habitually ran barefoot, mostly used a FFS pattern (75%) when barefoot, but changed to a RFS pattern when shod (50%). The majority of runners who grew up running barefoot, but subsequently switched to shod

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running, ran with a FFS pattern (91% barefoot vs. 51% shod). The authors hypothesised that differences in the FSPs were due to the cushioned shoes absorbing some of the "impact transient" and allowed a more comfortable RFS when running. However, statistical analysis of these data was not reported.

Hasegawa et al. (2007) documented that conventional running shoes facilitated a RFS. When examining the type of FSP adopted by shod runners at the 15 km point of a half-marathon, most athletes (74.9%) adopted a RFS pattern. But, more of the faster runners used a MFS pattern (36% of the top 50 runners vs. 19% for the last 50 runners; significance not reported). However, as running velocity was not controlled in this scenario, one can only speculate whether velocity or individual differences in running style contributed to this finding.

This study compared acute spatiotemporal variable changes in stride length and frequency, ground contact and flight times; when running barefoot, and in minimalist and conventional running shoes. In addition, kinematic determinations of FSP for each of the three conditions were made and the effects of condition and running velocity on FSPs were assessed.

Methods

Study design

This study used a repeated measures design to investigate differences in FSP and spatiotemporal variables during sub-maximal running in three different conditions, barefoot (BF), minimalist shoes (Vibram FiveFingers, VFF) and shod (participant's own running shoes); and at two individualised velocities. The velocities (V1 and V2) were nominated percentages (70 and 85%) of experienced runners' best race times from 5-km competition, the group mean velocities equated to 13.0 ± 1.0 and 16.1 ± 1.3 $km \cdot h^{-1}$, for V1 and V2, respectively.

Participants

Fourteen (n = 14) competitive, habitually shod male athletes (age 25 ± 6 yr; height 1.78 ± 0.06 m; mass 67.6 ± 5.8 kg, competitive running experience 8 ± 3 yr) were enlisted as participants. Participants were trained middle- (n = 8) or long- (n =6) distance runners, running at least 30 to 50 $km \cdot week^{-1}$, aged between 18-35 yr and free from any lower limb injuries in the six months prior to study commencement. Ethical approval was obtained from the Faculty of Health Science Research Ethics Committee, Trinity College Dublin.

Equipment

A Cartesian Optoelectronic Dynamic Anthropometric CX-1 (CODA) motion analysis system (Codamotion, Charnwood Dynamics, Rothley, UK) was used to capture real-time 3 dimensional (3-D) joint kinematics at 100Hz. Miniature infra-red light-emitting diodes (LEDs), each identifiable to indicate location, were placed on specific anatomical landmarks. Signals from the infra-red LEDs were picked up by two Codamotion sensor units. Two separate CX-1 measurement units were placed equidistant (3.5 m) and orthogonally to the left and right of the centre point of a motorised treadmill. Masked linear arrays in each sensor unit combined to measure the X, Y and Z coordinates of each infra-red LED. A Proform 700 ZLT treadmill (Icon Health and Fitness, Utah, USA) was positioned with the left posterior leg placed on an embedded AMTI force platform (Advanced Mechanical Technology, MA, USA). Synchronous recording of 3-D kinematic and ground reaction force data facilitated identification of initial contact for each stride cycle.

Experimental procedure

Participants attended the laboratory on two separate occasions with the initial visit for familiarisation. Participants completed a PAR-Q questionnaire, signed a consent form and ran on the treadmill for 4 min at a self-selected velocity, in each of the three footwear conditions, and wearing all the Codamotion equipment. The second visit was the testing session proper, consisting of 6 by 4 min bouts of treadmill running.

Upon arrival, anthropometric data were assessed and recorded. Stature was measured to the nearest 0.001m using a stadiometer (Holtain, Dyfed, UK), and body mass was measured to the nearest 0.1kg using a calibrated balance beam scale (Seca, Hamburg, Germany). Following anthropometric assessment, infra-red LEDs and wands were applied to the lateral aspect of the knee joint, the most lateral point of the lateral malleolus, the posterior inferior lateral aspect of the calcaneus, and the lateral aspect of the 5^{th} metatarsal head. The lateral calcaneus marker was located 2 cm posterior to the lateral malleolus marker and on the same level as the base of the 5^{th} metatarsal marker.

Test order was randomly determined by participants selecting sealed envelopes. Test condition and velocity were also randomised separately to ensure that two faster velocity trials (85% of 5-km best time) were non-consecutive. This was to avoid confounding results by possibly inducing fatigue. Each participant completed a series of 6 by 4-min treadmill running bouts, at 2 individualised velocities, in 3 conditions. A seated 10-min rest interval was provided between consecutive bouts and all kinematic data were recorded in the final minute of each 4-min bout.

Data reduction

Force data from the AMTI force platform, which supported the left posterior leg of the treadmill, were used to identify initial contact. Initial contact was identified as the time point at which vertical ground reaction force exceeded 20 N above baseline. This procedure has previously been used to quantify the onset of stride cycle during treadmill running (Bosco and Rusko, 1983). Toe-off was defined as the time point at which vertical ground reaction force dropped to within 20 N of baseline. The end of the stride cycle was determined to be the frame immediately before the next ipsilateral initial contact. Kinematic data for each stride cycle were saved as a discrete text file directly from the Codamotion software; in total, 5 consecutive strides were saved for each test condition. These data were transferred to Matlab (V7.14 R2012a, Mathworks, MA, USA) for data reduction via customised programs. Each individual's FSP was determined by comparing the time taken for the acceleration of the heel and toe markers in the Z plane to reach a minimum. Lieberman et al. (2010) described a MFS as the heel and ball of the foot landing simultaneously. However, due to the precision of the Codamotion equipment, a heel-toe latency of between -5 and +5 ms was classified as MFS. Consequently, heel-toe latencies of < -5 ms and > +5 ms were classified as FFS and RFS, respectively. These classifications were used for descriptive purposes only. Raw data consisting of time difference (ms) for heel and toe markers to reach their respective minima were used for statistical analysis. In addition, FSP data were temporally normalised to ground contact time, thereby, accounting for inter- and intra-individual variations in stride frequency. Stride duration was defined as the length of time (ms) from one initial contact to the next ipsilateral initial contact. Contact time was defined as the length of time (ms) from initial contact to toe-off, flight time was calculated as the remainder of the stride duration, and stride frequency was also computed.

Statistical analysis

Normality of the four spatiotemporal variables (stride duration, stride frequency, contact time and flight time) and FSP data (absolute and normalised) was assessed using Kolmogorov-Smirnov test. Subsequent analysis was performed using a 2-way repeated measures ANOVA to compare variables across velocity and condition. *Post-hoc* Tukey tests quantified detected differences. Statistical analyses were performed using SigmaStat (Systat Software, CA, USA) with $p < 0.05$ inferring statistical significance. All data are presented as group means and standard deviations.

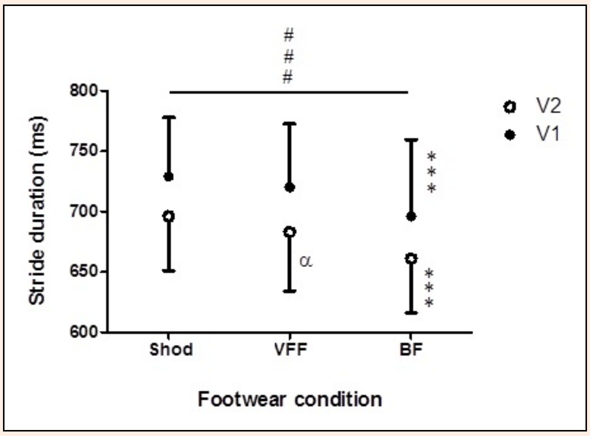

Figure 1. Mean stride duration across condition at V1 and V2, bars denote SD, n=14. Hash infers significant velocity effect (### $p < 0.001$), asterisk infers BF significantly less than shod or VFF (*** $p < 0.001$), alpha infers VFF significantly less than shod (α $p < 0.05$): Shod; traditional shoes: VFF; minimalist shoes: BF; barefoot.

Results

Spatiotemporal data

A significant main effect of condition on stride duration ($p < 0.001$) was detected. Overall, stride duration in traditional and minimalist shoes was significantly greater than barefoot (713 ± 48 and 701 ± 49 vs. 679 ± 56 ms, respectively, $p < 0.001$), see Figure 1. A similar outcome was independently evident at both assessed velocities, V1 (729 ± 50 and 720 ± 52 vs. 696 ± 63 ms, respectively, $p < 0.001$) and V2 (696 ± 46 and 683 ± 47 vs. 661 ± 46 ms, respectively, $p < 0.001$). Stride duration was significantly longer in shod than minimalist footwear overall (713 ± 48 vs. 701 ± 49 ms, $p < 0.05$) and at V2 (696 ± 46 vs. 683 ± 47 ms, $p < 0.05$). Although there was a trend towards a similar outcome at V1, it failed to attain statistical significance (729 ± 50 vs. 720 ± 52 ms, $p = 0.053$). In addition, there was a significant main effect of velocity on stride duration, as V1 was significantly greater than at V2 (715 ± 56 vs. 680 ± 45 ms, $p < 0.001$). *Post-hoc* analysis within condition revealed that stride duration was significantly greater at V1 than V2 across all conditions (shod: 729 ± 50 vs. 696 ± 46 ms; VFF: 720 ± 52 vs. 683 ± 47 ms; BF: 696 ± 63 vs. 661 ± 46 ms, $p < 0.001$), see Figure 1.

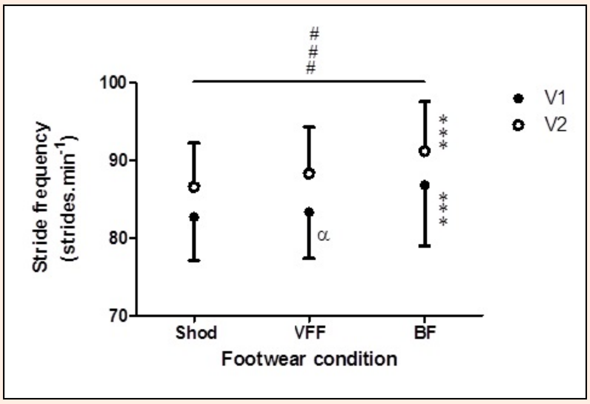

Figure 2. Mean stride frequency across condition at V1 and V2, bars denote SD, n=14. Hash infers significant velocity effect (### $p < 0.001$), asterisk infers BF significantly greater than shod or VFF (*** $p < 0.001$), alpha infers VFF significantly greater than shod (α $p < 0.05$): Shod; traditional shoes: VFF; minimalist shoes: BF; barefoot.

Significant main effects were detected for condition and velocity on stride frequency (Figure 2). For example, running barefoot resulted in higher ($p < 0.001$) stride frequencies when compared with shod and minimalist conditions overall (89.0 ± 7.1 vs. 84.7 ± 5.6 and 86.1 ± 6.0 strides·min^{-1}, respectively). Similar outcomes ($p < 0.001$) were detected at V1 (86.8 ± 7.8 vs. 82.7 ± 5.6 and 83.8 ± 6.1 strides·min^{-1}, respectively) and also at V2 (91.2 ± 6.3 vs. 86.6 ± 5.7 and 88.3 ± 6.0 strides·min^{-1}, respectively). Stride frequency in minimalist footwear was significantly higher ($p < 0.05$) than shod at V2 (88.3 ± 6.0 vs. 86.6 ± 5.7 strides·min^{-1}). *Post-hoc* testing revealed that stride frequency was significantly higher ($p < 0.001$) at V2 than at V1 within condition (shod: 86.6±5.7 vs. 82.7 ± 5.6 strides·min^{-1}; VFF: 88.3 ± 6.0 vs. 83.8 ± 6.1 strides·min^{-1}; BF: 91.2 ± 6.3 vs. 86.8 ± 7.8 strides·min^{-1}), see Figure 2.

Significant condition and velocity effects were also recorded for contact time data (Figure 3). Contact time was longer when running shod than barefoot, overall (211 ± 30 vs. 191 ± 29 ms, $p < 0.001$), and independently at V1 and V2 (V1; 231 ± 31 vs. 206 ± 34 ms and V2; 190 ± 30 vs. 176 ± 27 ms, $p < 0.05$). In addition, contact time, when shod, was longer than when in minimalist shoes overall (211 ± 30 vs. 198 ± 33 ms) and at V1 (231 ± 31 vs. 215 ± 37 ms, $p < 0.05$). When all conditions were combined for analysis, a significant main effect of velocity on contact time was detected, with significantly longer contact times noted at V1 compared to V2 (217 ± 34 vs. 182 ± 30 ms, $p < 0.001$). *Post-hoc* analysis revealed that the same outcome was evident within conditions (shod: 231 ± 31 vs. 190 ± 30 ms; VFF: 215 ± 37 vs. 181 ± 28 ms; BF: 206 ± 34 vs. 176 ± 27 ms, $p < 0.001$), see Figure 3.

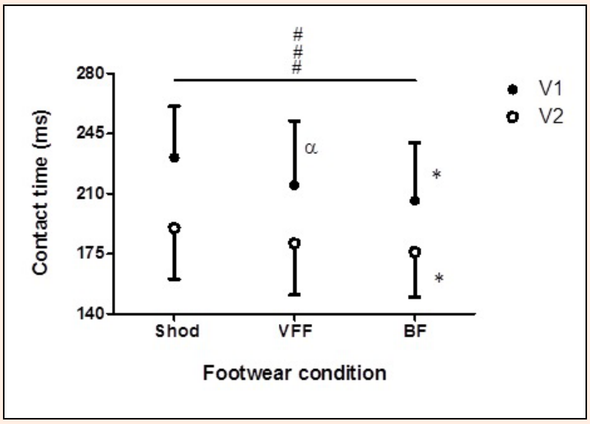

Figure 3. Mean contact time across condition at V1 and V2, bars denote SD, n=14. Hash infers significant velocity effect (### $p < 0.001$), asterisk infers BF significantly shorter than shod or VFF (*$p < 0.05$), alpha infers VFF significantly shorter than shod (α $p < 0.05$): Shod; traditional shoes: VFF; minimalist shoes: BF; barefoot.

A significant main effect of condition was observed for flight time. When all conditions were combined for analysis, flight time in minimalist footwear was greater ($p < 0.05$) than barefoot (503 ± 41 vs. 488 ± 49 ms). *Post-hoc* analysis revealed that a similar outcome was evident for V1 (505 ± 48 vs. 490 ± 57 ms) and V2 (502 ± 38 vs. 485 ± 40 ms). Flight time in traditional shoes was significantly greater than barefoot overall (502 ± 45 vs. 488 ± 49 ms, $p < 0.05$) and at V2 (505 ± 41 vs. 485 ± 40 ms, $p < 0.05$).

Table 1. Foot strike patterns in each condition at V1 and V2.

Velocity	V1			V2		
Condition	**Shod**	**VFF**	**BF**	**Shod**	**VFF**	**BF**
RFS	5	2	3	3	2	4
MFS	6	9	8	7	9	6
FFS	3	3	3	4	3	4

RFS; rear foot strike: MFS; mid foot strike: FFS; forefoot strike: Shod; traditional shoes: VFF; minimalist shoes: BF; barefoot.

Foot strike patterns

Table 1 presents the number of athletes adopting a RFS, MFS and FFS, respectively; in each shoe condition, and at both velocities. The majority of participants adopted a MFS pattern regardless of condition or velocity. There was no significant main effect of condition on absolute FSP data; however, a significant main effect of velocity was detected. A significant decrease in heel-toe latency at V2 when compared to V1 (-6 ± 20 vs. -1 ± 13 ms, $p < 0.05$) was reported, indicating a move towards a more FFS pattern. *Post-hoc* analysis revealed that this outcome was evident for the shod condition only (-7 ± 24 vs. 2 ± 8 ms, $p < 0.05$). A similar overall trend was noted for normalised FSP data when comparing V2 to V1 (-8 ± 23 vs. -2 ± 12 %). However, differences were not statistically significant ($p = 0.054$), which inferred that the changes detected in absolute FSP data may be a product of stride frequency and/or reduced contact time.

Discussion

Foot-strike patterns

No significant differences were recorded in FSPs between any of the conditions tested. This was the first study to directly examine FSP in minimalist footwear. Previously, Lieberman et al. (2010) examined FSPs in shod and BF running. The habitually shod participants in this study recorded data that were consistent with that previously reported for habitually shod athletes by Lieberman et al. (2010), with no significant differences detected in FSPs between shod and BF running. However, most participants in the current study used a MFS pattern, regardless of shoe condition, and not a RFS when shod, as reported by Lieberman et al. (2010).

Firstly, the treadmill itself might possibly have influenced the high number of MFS patterns demonstrated, because the FSPs were not assessed during over-ground running in the current study. Mixed results are reported regarding over-ground and treadmill running being similar (Fellin et al., 2010; Riley et al., 2008); or that treadmill running can alter FSPs from RFS to MFS (Nigg et al., 1995). Secondly, enlisted participants were competitive athletes with a group mean personal best for 5-km of 15.9 ± 0.3 min. Hasegawa et al. (2007) reported that a higher percentage of fast runners in a half marathon (15.5 min pace per 5-km) used a MFS pattern when compared to the slower runners (pace unspecified). Participants in the present study were national level competitors who could be expected to use a MFS pattern based on the data of Hasegawa et al. (2007). The calibre of volunteers assessed by Lieberman et al. (2010) was unspecified and potentially variations in performance capability were a possible reason for the greater occurrence of a MFS gait in the present study. In addition, over half of the current study participants were middle-distance runners, a factor which may also influence FSP, as sprinters mainly FFS, whereas endurance runners typically RFS (Lieberman et al., 2010). Sprinters attain fast running velocities by adopting a FFS gait to reduce contact time (Ardigo et al., 1995). Therefore, the larger number of middle-distance than endurance runners in the current study could possibly explain the high percentage of MFS gaits recorded.

The above rationale involves intrinsic factors accounting for the greater occurrence of MFSs in the shod condition. Consequently, it is postulated that, since no differences were observed in FSP between assessed conditions, motor patterns laid down through years of running were not immediately altered by simply changing footwear on a single occasion. Over half (n = 8) of the current study participants used the same FSP across all 3 conditions. This may be due to the creation of specific neural connections within the reticulospinal neurons and central pattern generators by repetitive actions such as running (Sinnatamby, 2006). Previously, Lieberman et al. (2010) reported that runners who grew up training barefoot, but later switched to running shod, mainly adopted a FFS pattern when running barefoot or shod. As the majority of habitually barefoot athletes in their study used a FFS, it is likely that these athletes maintained the same running style, including FSP, even after transitioning from barefoot to running shod.

The current study and Lieberman et al. (2010) lend some credence to the theory that FSP could be a learned motor pattern. It is not immediately altered by removing or changing footwear, and, consequently, induced alterations in FSPs are likely to require a period of time to occur. For this reason, to prevent adverse effects when switching from shod to barefoot or minimalist footwear, such as metatarsal stress fractures (Giuliani et al., 2011), a gradual transition period is advised. Robbins and Hanna (1987) suggested that adapting to barefoot running could take several weeks. However, the length of time necessary for changing FSPs requires future research to clarify the optimum duration of such a transitional period.

Spatiotemporal variables

When running barefoot, stride duration, flight time and contact time were significantly shorter, and stride frequency significantly higher, than the other two conditions. No significant differences in these spatiotemporal variables were recorded when comparing minimalist footwear with shod (see Figures 1, 2 and 3). Stride frequency is inversely proportional to stride duration multiplied by velocity, and velocity was controlled in this study. Thus, it would be expected that if one variable increased, the other should decrease, and *vice versa;* as was recorded in the present study.

An increased flight time when shod might be attributable to the shoe sole providing stronger propulsion at toe-off, thereby prolonging the airborne phase of the stride (Squadrone and Gallozzi, 2009). The increased contact time when shod (Figure 3) may be partially attributable to the mass of the traditional shoe (Divert et al., 2008). Although shoe mass was not recorded in the present study, it is likely that the minimalist shoes (150g each) weighed significantly less than the traditional shoes. Therefore, this could possibly explain the increased contact time recorded when running shod than when running at the same velocity in minimalist footwear. As stride duration is the sum of flight and contact times, it would logically follow that stride duration was greater when shod than barefoot, as both flight and contact times were higher in the shod condition. Previously, De Wit et al. (2000) reported that the horizontal distance travelled during the stance phase was greater when running shod than barefoot.

Shorter flight time data when running barefoot than shod is consistent with Squadrone and Gallozzi (2009) and Divert et al. (2005). Mean reductions in flight time between barefoot and shod were similar between the current study (14ms), Squadrone and Gallozzi (2009) (14ms) and Divert et al. (2005) (18ms). Contact time was also significantly reduced when barefoot running was compared with shod (Braunstein et al., 2010; Divert et al., 2005). The mean difference recorded in the current study was slightly greater than reported by Divert et al. (2005) and Braunstein et al. (2010), 20 vs. 6 and 10 ms, respectively. However, Divert et al. (2005) requested participants to RFS, and Braunstein et al. (2010) conducted their trials on a 20-m runway rather than on a motorised treadmill. Consequently, protocol issues may partly account for the differences in findings between previous research and this study.

Stride frequency when running barefoot has been compared with running in traditional shoes by Divert et al. (2008) and Squadrone and Gallozzi (2009). Squadrone and Gallozzi (2009) reported stride frequencies of experienced barefoot runners to be 91.2 strides·min^{-1} when barefoot and 86.0 strides·min^{-1} when shod. This was slightly higher than recorded in the current study (89.0 ± 1.9 vs. 84.7 ± 1.5 strides·min^{-1}, barefoot vs. shod, respectively). The fact that the Squadrone and Gallozzi (2009) participants were habitually barefoot, as opposed to the habitually shod participants in the current study, could possibly account for these small differences. This study and that by Squadrone and Gallozzi (2009) both reported significantly higher stride frequencies in the barefoot condition (mean difference of 4.3 and 5.2 strides·min^{-1}, respectively). However, in runners with no barefoot running experience, stride frequencies similar to the current results have been reported (Divert et al., 2008). The mean stride frequency reported by Divert et al. (2008) when athletes ran barefoot, was 87.6 strides·min^{-1}. This decreased to 84.6 and 84.0 strides·min^{-1}, when athletes ran in light (150g) and heavy (350g) shoes, respectively ($p < 0.01$). These data support the findings of this research.

Overall, spatiotemporal data recorded when running in minimalist shoes more closely resembled data obtained using traditional shoes. The only exception was contact time which was significantly longer when shod, than in both minimalist footwear and barefoot (see Figure 3). Only Squadrone and Gallozzi (2009) and Bonacci et al. (2013) have examined spatiotemporal variables in minimalist footwear. Bonacci et al. (2013) reported that stride length was shorter, and stride frequency higher when running in minimalist compared with traditional shoes. However, stride length was also shorter and stride frequency higher when barefoot was compared with the minimalist shoe. Their results conflict with those reported here, but this may be due to a different minimalist shoe being investigated (the Nike Free 3.0), or protocol differences (over-ground vs. treadmill running). Only Squadrone and Gallozzi (2009) have biomechanically investigated VFF minimalist shoes. They agreed with the results of this study by reporting that spatiotemporal variables (stride length, stride frequency and flight time) in minimalist footwear were closer to those recorded in traditional shoes. More specifically, stride length and flight times were longer, and stride frequency was lower, in VFF than barefoot, and no significant differences were detected for these variables comparing VFF and shod conditions.

Study limitations

Before drawing definitive conclusions from the current results, certain limitations of the study must be considered. Firstly, the lack of standardisation of the traditional shoes used may have impacted the results in the shod condition. Participants were tested in their regular training shoes, in order to most accurately represent the normal running mechanics exhibited in training. However, this meant that both the mass of the shoe and the degree of cushioning and the vertical distance from the ground to the lateral calcaneal marker was not standardised. Therefore, a study of similar design using a standardised cushioned running shoe with a clearly defined hell-to-toe drop would be useful.

Secondly, although studies have compared over-ground and treadmill running and reported that treadmill running was representative of over-ground running (Fellin et al., 2010; Riley et al., 2008) the two are not necessarily identical. Therefore, if a study of similar design was conducted on an indoor running track, or a non-motorised treadmill, would more closely replicate typical training scenarios (over-ground running). Alternatively, an instrumented treadmill would be useful as force data could help to explain differences found in other study variables; a valuable biomechanical variable in its own right.

Conclusion

Results of this study indicate that differences in spatiotemporal variables can occur almost immediately (within a single running session), irrespective of previous barefoot running experience, and without a change in FSP. Additionally the data suggests that when running in minimalist footwear, most spatiotemporal variables more closely resembled shod than barefoot running. This may be an important consideration for athletic performance and injury prevention. Furthermore, the data suggests that FSP could be a learned motor pattern which is not immediately altered by removing or changing footwear, and, therefore, induced alterations in FSPs are likely to require time to occur

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References

Ardigò, L., Lafortuna, C., Minetti, A., Mognoni, P. and Saibene, F. (1995) Metabolic and mechanical aspects of foot landing type, forefoot and rearfoot strike, in human running. *Acta Physiologica Scandinavica* **155**, 17-22.

Bishop, M., Fiolkowski, P., Conrad, B., Brunt, D. and Horodyski, M. (2006) Athletic footwear, leg stiffness, and running kinematics. *Journal of Athletic Training* 41, 387-392.

Bonacci, J., Saunders, P., Hicks, A., Rantalainen, T., Vicenzino, G. and Spratford, W. (2013) Running in a minimalist and lightweight shoe is not the same as running barefoot: A biomechanical study. *British Journal of Sports Medicine* **47**, 387-392.

Bosco, C. and Rusko, H. (1983) The effect of prolonged skeletal muscle stretch shortening cycle on recoil of elastic energy and on energy expenditure. *Acta Physiologica Scandinavica* **119**, 219-224.

Braunstein, B., Arampatzis, A., Eysel, P. and Bruggemann, G. (2010) Footwear affects the gearing at the ankle and knee joints during running. *Journal of Biomechanics* **43**, 2120-2125.

De Wit, B., De Clercq, D. and Aerts, P. (2000) Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics* **33**, 269-278.

Divert, C., Mornieux, G., Baur, H., Mayer, F. and Belli, A. (2005) Mechanical comparison of barefoot and shod running. *International Journal of Sports Medicine* **26**, 593-598.

Divert, C., Mornieux, G., Freychat, P., Baly, L., Mayer, F. and Belli, A. (2008) Barefoot-shod running differences: Shoe or mass effect? *International Journal of Sports Medicine* **29**, 512-518.

Fellin, R., Rose, W., Royer, T. and Davis, I. (2010) Comparison of methods for kinematic identification of foot strike and toe-off during over-ground and treadmill running. *Journal of Science and Medicine in Sport* **13**, 646-650.

Giuliani, J., Masini, B., Alitz, C. and Owens, B. (2011) Barefoot-simulating footwear associated with metatarsal stress injury in 2 runners. *Orthopaedics* **34**, 320-323.

Hasegawa, H., Yamauchi, T. and Kraemer, W. (2007) Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *Journal of Strength and Conditioning Research* **21**, 888-893.

Jenkins, D. and Cauthon, D. (2011) Barefoot running claims and controversies: A review of the literature. *Journal of the American Podiatric Medical Association* **101**, 231-246.

Kerrigan, D., Franz, J., Keenan, G., Dicharry, J., Croce, U. and Wilder, P. (2009) The effect of running shoes on lower extremity joint torques. *American Academy for Physical Medicine and Rehabilitation* **1**, 1058-1063.

Lieberman, D., Venkadesan, M., Werbel, W., Daoud, A., D'andrea, S., Davis, I., Mang'Eni, R. and Pitsiladis, Y. (2010) Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* **463**, 531-535.

McNair, P. and Marshall, R. (1994) Kinematic and kinetic parameters associated with running in different shoes. *British Journal of Sports Medicine* **28**, 256-260.

Nigg, B., De Boer, R. and Fisher, V. (1995) A kinematic comparison of over-ground and treadmill running. *Medicine and Science in Sports and Exercise* **27**, 98-105.

Riley, P., Dicharry, J., Franz, J., Della Croce, U., Wilder, R. and Kerrigan, D. (2008) A kinematic and kinetic comparison of over-ground and treadmill running. *Medicine and Science in Sports and Exercise* **40**, 1093-1100.

Robbins, S.E. and Hanna, A.M. (1987) Running-related injury prevention through barefoot adaptations. *Medicine and Science in Sports and Exercise* **19(2),** 148-156.

Rothschild, C. (2012) Primitive running: A survey analysis of runners' interest, participation, and implementation. *Journal of Strength and Conditioning Research* **26**, 2021-2026.

Sinnatamby, C. (2006) *Last's Anatomy: Regional and applied.* 10th edition. Churchill Livingstone Elsevier, China. pp. 468-473.

Squadrone, R. and Gallozzi, C. (2009) Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of Sports Medicine and Physical Fitness* **49**, 6-13.

Van Gent, R., Siem, D., van Middelkoop, M., van Os, A., Bierma-Zeinstra, S. and Koes, B. (2007) Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *British Journal of Sports Medicine* **41**, 469-480.

Van Mechelen, W. (1992) Running injuries. A review of the epidemiological literature. *Sports Medicine* **14**, 320-335.

Key points

- Differences in spatiotemporal variables occurred within a single running session, without a change in foot strike pattern.
- Stride duration and flight time were greater when shod and in minimalist footwear than when barefoot.
- Stride frequency when barefoot was higher than when shod or in minimalist footwear.
- Contact time when shod was longer than when barefoot or in minimalist footwear.
- Spatiotemporal variables when running in minimalist footwear more closely resemble shod than barefoot running.

AUTHORS BIOGRAPHY

Ciara McCALLION
Employment
Dublin Spine and Sports Physiotherapy, Dublin, Ireland. Human Performance Laboratory, Trinity College, Dublin, Ireland
Degree
BSc (Physiotherapy) MSc (Sports Medicine)
Research interests
Biomechanics, injury prevention, running injuries
E-mail: mccallic@tcd.ie

Bernard DONNE
Employment
Senior Experimental Officer and lecturer in Physiology Department, Trinity College Dublin, Ireland.
Degree
MSc
Research interest
Physiological testing and training of elite athletes
E-mail: bdonne@tcd.ie

Neil FLEMING
Employment
Assistant Professor, Department of Kinesiology, Recreation and Sport, Indiana State University, Indiana, USA.
Degrees
BSc, PhD
Research interest
Biomechanics and physiology of sport performance
E-mail: neil.fleming@indstate.edu

Brian BLANKSBY
Employment
Professor Emeritus, School of Sport Science, Exercise and Health, University of Western Australia, Australia
Degrees
MSc, PhD
Research interest
Biomechanics of running and swimming
E-mail: brian.blanksby@uwa.edu.au

✉ **Neil Fleming, PhD**
Dept. Kinesiology, Recreation & Sport, Indiana State University, Arena Bldg C19, Terre Haute, In 47809, USA