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Original article

Comparison of foot strike patterns of barefoot and minimally shod runners in a recreational road race

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Abstract

Background: Previous studies of foot strike patterns of distance runners in road races have typically found that the overwhelming majority of shod runners initially contact the ground on the rearfoot. However, none of these studies has attempted to quantify foot strike patterns of barefoot or minimally shod runners. This study classifies foot strike patterns of barefoot and minimally shod runners in a recreational road race.
Methods: High-speed video footage was obtained of 169 barefoot and 42 minimally shod distance runners at the 2011 New York City Barefoot Run. Foot strike patterns were classified for each runner, and frequencies of forefoot, midfoot, and rearfoot striking were compared between the barefoot and minimally shod groups.
Results: A total of 59.2% of barefoot runners were forefoot strikers, 20.1% were midfoot strikers, and 20.7% were rearfoot strikers. For minimally shod runners, 33.3% were forefoot strikers, 19.1% were midfoot strikers, and 47.6% were rearfoot strikers. Foot strike distributions for barefoot and minimally shod runners were significantly different both from one another and from previously reported foot strike distributions of shod road racers.
Conclusion: Foot strike patterns differ between barefoot and minimally shod runners, with forefoot striking being more common, and rearfoot striking less common in the barefoot group.

Keywords: Barefoot; Biomechanics; Foot strike; Gait; Minimal shoes; Running

1. Introduction

Foot strikes during running are typically classified as either (1) rearfoot, in which initial contact is made somewhere on the heel or rear one-third of the foot; (2) midfoot, in which the heel and the region below the fifth metatarsal contact simultaneously; or (3) forefoot, in which initial contact is made on the front half of the foot, after which heel contact typically follows shortly thereafter.[1] Previous research on foot strike patterns in road races indicates that the majority of shod distance runners are rearfoot strikers, with percentages ranging from 74.9% of runners in an elite half-marathon race,[1] to 81% of recreational runners in a 10-km race,[2] to over 90% of recreational runners in marathon distance events[3,4] (Table 1).

Available research suggests that multiple factors influence the type of foot strike exhibited by a given runner under a given set of conditions. For example, several race studies have found that the percentage of non-heel striking runners increased among faster runners,[1,2,4,5] suggesting a speed effect. Running surface has also been shown to influence foot strike. Nigg[6] reports data from an unpublished thesis[7] showing that barefoot runners are more likely to forefoot strike on asphalt (76.7% forefoot, 23.3% rearfoot), and rearfoot strike on grass (45.7% forefoot, 54.3% rearfoot). Gruber et al.[8] found that only 20% of habitually shod runners adopted a midfoot or forefoot strike when running barefoot on a soft surface, versus

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Table 1
Summary of foot strike patterns reported in observational studies of runners in races. To simplify comparisons, data for asymmetrical runners reported by Larson et al.[3] and Kasmer et al.[4] are not included here.

Study	Description of sample	n	Foot strike type (%)		
			Rearfoot	Midfoot	Forefoot
Kerr et al.[2]	9 km mark of 10 km race	628	81.0	19.0	0.0
Kerr et al.[2]	20 km mark of marathon	125	79.0	21.0	0.0
Kerr et al.[2]	35 km mark of marathon	84	82.0	18.0	0.0
Hasegawa et al.[1]	15 km mark of elite half marathon	283	74.9	23.7	1.4
Larson et al.[3]	10 km mark of relay, half, full marathon	881	94.5	3.6	1.9
Larson et al.[3]	Marathoners only at 10 km into race	264	95.1	3.4	1.5
Larson et al.[3]	Marathoners only at 32 km into race	276	96.4	3.6	0.0
Hayes and Caplan[5]	Women's 800 m track	34	32.0	41.0	27.0
Hayes and Caplan[5]	Women's 1500 m track	24	33.0	42.0	25.0
Hayes and Caplan[5]	Men's 800 m track	71	15.0	50.0	35.0
Hayes and Caplan[5]	Men's 1500 m track	52	26.0	37.0	37.0
Kasmer et al.[4]	8.1 km mark of marathon	1151	93.2	6.2	0.6
Larson, this study	Barefoot, 350 m into a 2-mile run on asphalt	169	20.7	20.1	59.2
Larson, this study	Vibram Fivefingers®, 350 m into a 2-mile run on asphalt	42	47.6	19.1	33.3

65% adopting a midfoot or forefoot strike when running barefoot on a hard surface.

Of all potential factors contributing to variation in foot strike type, the role of footwear has perhaps been the subject of most debate and research in recent years. This is in part due to increased interest in barefoot running, as well as marketing of "barefoot-style" minimally-cushioned shoes by running footwear companies.

Results of studies that have examined the effects of footwear on foot strike include:

- Lieberman et al.[9] found that habitually unshod Kenyan and American runners typically land on their midfoot or forefoot while running barefoot, whereas habitually shod Kenyan and American runners tend to contact the ground with the rearfoot/heel first in both shod and unshod conditions.
- Hatala et al.[10] reported that habitually barefoot individuals from the Daasanach tribe of Kenya, a group without a strong running tradition, overwhelmingly tended to land on the rearfoot at a slow jogging pace (2.01−3.00 m/s; 83% rearfoot strikes). Percentage of midfoot strikes increased with running speed among the Daasanach (60% of all foot strikes were classified as midfoot at 6.01−7.00 m/s).
- Squadrone and Gallozzi[11] found that strike index was similar among habitually barefoot runners when running unshod or in minimally cushioned shoes (MCS; Vibram Fivefingers, Vibram USA, Concord, MA, USA) as compared to when they ran in conventional cushioned shoes.
- Hamill et al.[12] found that habitually shod subjects typically switched to a midfoot strike when running barefoot, but landed initially on the heel in all shod conditions (including a minimally cushioned shoe).
- Tenbroek et al.[13] found that habitually shod runners exhibited a flatter foot strike when running barefoot or in minimally cushioned footwear compared to moderate or thickly cushioned shoes, but all contacted first on the heel.
- Bonacci et al.[14] found that habitually shod runners exhibited a less dorsiflexed ankle at contact when running barefoot compared to when they ran in three shod conditions (conventional shoe, racing flat, and moderately cushioned shoe).
- Lieberman[15] found that Tarahumara runners from Mexico who habitually wear minimally cushioned huarache sandals tend to midfoot or forefoot strike when they run, whereas conventionally shod Tarahumara typically land on the rearfoot.
- Pontzer et al.[16] found that the presence of footwear (minimally cushioned sandals *vs.* barefoot) had no effect on strike type among Hadza hunter-gatherers.
- Several additional studies have demonstrated that even if habitually shod runners continue to rearfoot strike when barefoot, they tend to land with reduced dorsiflexion of the ankle at contact than when shod.[17−19]

A limitation of existing studies of foot strike in barefoot and minimally shod runners is that most have been conducted on small sample sizes of subjects in a laboratory setting or along a short outdoor runway. None have examined foot strike patterns of barefoot/minimally shod runners in a race setting on a hard, asphalt surface.

The goals of this study are thus (1) to determine the frequency of forefoot, midfoot, and rearfoot striking in a comparatively large sample of barefoot and minimally shod runners in a recreational road race; (2) to compare foot strike distributions between barefoot and minimally shod runners; and (3) to compare foot strike distributions observed here to those reported in previous studies of recreational distance runners. The null hypotheses tested are: (1) foot strike patterns do not differ between barefoot and minimally shod runners in a recreational road race; (2) foot strike patterns examined here do not differ from those reported previously in the literature for conventionally shod runners in road races.

2. Methods

2.1. Procedure

Runners were videotaped at the New York City Barefoot Run on 25 September, 2011. This event involved loops around Governor's Island in NYC. Runners were videotaped about 350 m from the starting line as they passed by on a flat, asphalt road surface. Only data from the first loop are reported here since many runners only ran one loop around the island (one loop on the course was approximately 3.25 km long).

Video recording was carried out with a Casio Exilim EX-F1 digital camera (Casio America, Inc., Dover, NJ, USA) at a filming rate of 300 Hz. The camera was mounted on a tripod near ground level, and was oriented perpendicular to the passing runners so that they could be videotaped in the sagittal plane. The camera was obscured next to a patch of vegetation so that runners would be unlikely to notice it as they approached. The race course was approximately 10 m in width at the filming location. Thus, distance of runners from the camera was variable, but most runners were sufficiently close to allow clear visualization of the location of initial foot contact. Because there was no formal timing for this event, it was not possible to identify individual runners by their bib numbers or finish times.

2.2. Participants

Foot strike was classified for a total of 241 runners. This sample included 169 barefoot runners, and 42 runners who were wearing Vibram Fivefingers® (VFF) running shoes (remaining runners wore a mixture of sandals, conventionally cushioned running shoes, and other brands of minimally cushioned shoe sample sizes for each were insufficient to allow statistical comparisons). VFF is a minimally cushioned line of footwear characterized by individual pockets for the toes. It was not possible to identify specific shoe models within the brand, but all are minimally cushioned (0–4 mm of midsole cushioning for models available at the time of the race). Pacing for most runners could be subjectively described as an easy jog.

The sample of runners examined in this study was a mixture of habitual barefoot runners, those who had recently begun running barefoot or in minimal running shoes, and those who may have been running barefoot for the first time in this event. Many had traveled from a distance to attend the race, which was part of a weekend-long event that specifically catered to barefoot enthusiasts.

2.3. Data collection

Video for each runner was analyzed frame-by-frame in Apple Quicktime Pro (Apple Inc., Cupertino, CA, USA). Foot strike categorization followed the methods described by Hasegawa et al.[1] and Larson et al.[3] A rearfoot strike was defined as one in which first contact of the foot with the ground was made on the heel or rear one-third of the sole (Fig. 1A). A midfoot strike was defined as one in which the heel and the region below the fifth metatarsal contacted the ground simultaneously (Fig. 1B). A forefoot strike was defined as one in which initial contact of the foot with the ground was on the front half of the sole, with no heel contact at foot strike (Fig. 1C). For each runner, foot strike was classified for the left foot (which was closest to the camera). In most cases, the first foot strike observed for a given runner once they entered the frame of the video was analyzed. Deviations from this procedure occurred only if the initial left foot strike was obscured (e.g., by another runner). A subset analysis that I conducted on a similar sample of video footage in a previous study found that the method of foot strike classification utilized here had a repeatability of 98%.[3]

2.4. Statistical analyses

Foot strike frequency distributions were compared between barefoot and minimally shod runners using chi-square (X^2) analysis. Foot strike distributions obtained here were also compared to those of traditionally shod recreational runners reported by Larson et al.[3] and Kasmer et al.[4] using chi-square analysis (asymmetrical runners in those studies were excluded from the analysis since this study did not attempt to quantify

Fig. 1. Examples of foot strike patterns captured from high-speed video of the 2011 New York City Barefoot Run. (A) Rearfoot strike; (B) midfoot strike; (C) forefoot strike.

frequency of asymmetry). Comparisons are only made to those two studies because they examined a similar recreational sample of runners. A Bonferroni correction was applied to correct for multiple independent comparisons. Thus, frequency distributions compared in chi-square analyses were considered significantly different at $p < 0.01$. All statistical analyses were carried out using NCSS 8 (NCSS, LLC, Kaysville, UT, USA).

3. Results

A total of 59.2% of barefoot runners were forefoot strikers, 20.1% were midfoot strikers, and 20.7% were rearfoot strikers. For the minimally shod runners, 33.3% were forefoot strikers, 19.1% were midfoot strikers, and 47.6% were rearfoot strikers (Table 1).

Results of chi-square analyses indicate that observed foot strike frequency distributions differ significantly between barefoot and minimally shod runners ($X^2 = 13.5$, $df = 2$, $p < 0.01$). The foot strike frequency distribution for barefoot runners in this study differs significantly from those recorded for traditionally shod road racers in Larson et al.[3] ($X^2 = 571.63$, $df = 2$, $p < 0.0001$) and Kasmer et al.[4] ($X^2 = 751.86$, $df = 2$, $p < 0.0001$). The foot strike frequency distribution for minimally shod runners in this study differs significantly from those recorded for traditionally shod road racers in Larson et al.[3] ($X^2 = 149.2$, $df = 2$, $p < 0.0001$) and Kasmer et al.[4] ($X^2 = 265.88$, $df = 2$, $p < 0.0001$) .

4. Discussion

Available published data from road race studies conducted to date indicate that approximately 75%–95% of runners land on their rearfoot when initially contacting the ground[1–4] (Table 1). It is reasonable to presume that the vast majority of the runners in these studies were habitually shod and wore some type of cushioned running shoe during the race, though exact shoe properties might differ among running populations (e.g., racing flats for elite half-marathoners, conventionally cushioned running shoes for recreational marathoners). In support of this presumption, only two of the 936 runners examined by Larson et al.[3] were wearing minimally cushioned running shoes (VFF for both; no runners were barefoot).

In contrast to the above studies, Lieberman et al.[9] observed that initial contact on the midfoot or forefoot is typical for habitually barefoot Kenyan adolescents on a dirt road (88% of foot strikes) and habitually barefoot American adults in the laboratory (75% of foot strikes). Incidence of rearfoot striking in this same population of habitually barefoot American adults increased from 25% to 50% when shod, and habitually shod Kenyans and Americans tended to rearfoot strike regardless of whether they were wearing shoes.[9] These results suggest that footwear may influence foot strike patterns.

Foot strike distributions for barefoot runners observed here were significantly different from those observed previously for shod road racers. Larson et al.[3] and Kasmer et al.[4] observed that less than 10% of runners in their samples were symmetrical forefoot or midfoot strikers. In this study, 79.3% of barefoot runners were forefoot or midfoot strikers. This is fairly close to the percentages observed for habitually barefoot American adults and Kenyan adolescents running without shoes.[9] It is also similar to the pattern observed for adult male Hadza hunter-gatherers running in sandals or barefoot.[16] However, it differs markedly from habitually barefoot Kenyans of the Daasanach tribe,[10] Hadza juveniles, and adult Hadza women.[16]

It is possible that speed, surface properties, and running experience are confounding variables when it comes to comparing foot strike patterns among studies. The habitually barefoot Kenyans in the studies mentioned above were all running on dirt or sand surfaces that are presumably softer than a laboratory runway or an asphalt road. Gruber et al.[8] found that midfoot and forefoot striking was more common in barefoot runners on a hard surface *vs.* a softer surface. Furthermore, the adolescents studied by Lieberman et al.[9] were experienced runners and were running at a fast pace (5.5 m/s). When the Daasanach, who are not considered frequent runners, ran at this speed or faster, frequency of midfoot and forefoot striking increased to the point where they were more common combined than rearfoot striking.[10] In the Hadza tribe, adult women and children typically rearfoot strike, whereas adult men typically midfoot strike.[16] This latter finding suggests that running experience may also influence running form and foot strike type since adult Hadza men tend to run more often while hunting game as compared to Hadza women who primarily gather plant foods. Taken together, results from these studies suggest that determination of foot strike type is multifactorial, with midfoot and forefoot striking being most likely when experienced runners run barefoot on harder surfaces and at faster paces.

Foot strike distribution for minimally shod runners was significantly different from both barefoot runners observed here and from shod runners observed in previous road race studies. A total of 52.4% of minimally shod runners were forefoot or midfoot strikers. Thus, frequency of forefoot and midfoot striking in minimally shod runners on an asphalt road is lower than in barefoot runners, but higher than in traditionally shod runners. It seems that at least in terms of foot strike, running in a minimally cushioned shoe may encourage kinematic patterns that are different than running in a traditionally cushioned shoe, but may not always encourage kinematic patterns similar to that typically observed in barefoot running. The response may be very subject-specific.

Studies have observed significantly higher vertical impact force peaks and loading rates in rearfoot striking barefoot runners.[9,18] Given this, it is somewhat surprising that runners wearing VFF, a shoe that provides minimal impact protection to the foot, would continue to land on the rearfoot on a hard surface like an asphalt road. There are a few possible explanations for this. First, it is possible that runners attending this “barefoot” race who were wearing minimal shoes were less experienced with barefoot running and thus wore shoes for protection (i.e., they were not comfortable running fully barefoot). It has been demonstrated that foot strike patterns in minimal shoes can change with experience, and inexperienced minimally shod runners may exhibit different gait mechanics than those who have had greater acclimation time.[9,20]

Another possible explanation for the difference in foot strike distribution between barefoot and minimally shod runners is that the minimal amount of cushioning present in VFF is enough to moderate impact force such that the body does not respond by making a gait change. Though a recent meta-analysis found that increased vertical impact loading rate is a risk factor for tibial stress fractures,[21] Nigg[22] has questioned whether impact force peaks or loading rates are a significant contributor to running injury. It may be the case that the loading rates experienced by some rearfoot striking minimally shod runners are within a normal range of tolerance for the human body.

A third possibility is that vertical impact force is not the only stimulus for foot strike change, and that some other factor besides a need to reduce impact force contributes to the higher frequency of midfoot and forefoot striking in barefoot runners. For example, Robbins and Gouw[23] proposed that gait modifications in barefoot runners may in part be associated with horizontal loads applied to the plantar surface. In the barefoot condition, gait adaptations may be required to reduce shear forces between the foot and ground surface in order to protect the plantar skin of the foot. It seems reasonable to assume that the presence of even a minimally cushioned shoe sole would both reduce plantar sensation and provide protection from ground shear, and thus stimulus for gait change may not be as strong as when running fully barefoot.

Differences in foot strike patterns observed here between barefoot and minimally shod runners may have implications with regard to running injury. Failure to allow a gradual adaptation to running in minimally cushioned shoes to accommodate gait and tissue adaptation could be potentially injurious. Giuliani et al.[24] reported a case study of two runners who developed 2nd metarsal stress fractures after transitioning to minimally cushioned shoes. Ridge et al.[25] found that approximately 50% of runners who they studied developed marrow edema in at least one foot or ankle bone in concert with a 10-week adaptation to running in minimally cushioned shoes (VFF). Two of their subjects developed stress fractures (2nd metatarsal for one, calcaneus for the other). This suggests increased remodeling of foot bones associated with a change to minimal footwear, which could progress to bone damage in the form of a stress fracture. Unfortunately, Ridge et al.[25] did not report data on running form before or after the transition, and it is uncertain at which point in the gait cycle forces become potentially injurious for individual bones during a transition to minimal shoes (e.g., impact, midstance, toe-off, *etc*.). It is worth noting that Ryan et al.[26] gradually progressed runners into VFF over 12 weeks and found no elevated risk of injury compared to a conventionally cushioned running shoe (increased calf/shin pain was the only significant difference in the minimal shoe). Unfortunately kinematic data were not reported in that study so the role of form could not be addressed.

This study has a few limitations that should be discussed. Because this race was part of a weekend-long barefoot running "festival", many of those attending had participated in form clinics and barefoot running seminars on the day prior to the race. Thus, it is possible that some runners were consciously running according to how they had been taught the previous day. However, since both barefoot and minimally shod runners had the opportunity to attend the same form seminars, the comparisons between barefoot and minimally shod runners in this race should not have been affected.

It is possible that the overall frequency of midfoot and forefoot striking was inflated by subjects forcing their form to meet their perception of how they should run when barefoot or in minimal footwear. It is for this reason that I chose to film in a discrete way 350 m from the starting line. The intent of this protocol was to allow runners time to settle into the run and to minimize the likelihood that they would notice that they were passing a camera. Despite this concern, it should be noted that frequency of forefoot and midfoot striking observed here are not inconsistent with results of other studies that have observed barefoot runners on hard surfaces.[8,9,27]

It is also important to point out that this study only classified the initial contact point of the foot with the ground into three broad categories. It was not possible to examine the forces associated with ground contact or accurately assess kinematic variability within the discrete categories. Wide variation in initial contact position has been recognized for a long time,[28] and such variation may influence patterns of force application. For example, Logan et al.[29] reported a high degree of variability in force measurements among rearfoot-striking runners in a comparison of gait mechanics between cushioned running shoes, racing flats, and distance spikes; they suggested individual differences in initial contact location as a possible explanation for this variation. Altman and Davis[27] found that visually assessed midfoot strikers were often classified as forefoot or heel strikers by the strike index method. Recent research also suggests that runners who contact first on the heel exhibit variation in the location of maximal vertical impact loading, with as many as 25%−33% of runners who contact on the heel experiencing maximal vertical loading rate when the center of pressure is under the midfoot.[30]

Despite the potential for variation in force measurements within visually assessed foot strike categories, a recent laboratory study found that foot strike angle at contact correlates well with kinetic measures of foot strike such as the strike index.[27] It is difficult to obtain accurate measurements of joint angles from video recorded in the field, but the rearfoot strikes observed here for barefoot and minimally shod runners appeared subjectively to be milder (less inclination of the sole relative to the ground at contact) than those observed in the shod runners of Larson et al.[3] This is supported by studies showing that foot positioning at contact in runners wearing minimal footwear is more similar to the barefoot condition than to the conventional shoe condition even if they continue to contact first on the heel.[11,13] It is thus possible that running form varies between footwear conditions in subtle ways that were not measured here, and future studies that attempt to undertake finer scale measurement of kinematic variables in the field are needed.

5. Conclusion

The results of this study provide insight into the role of footwear in determining foot strike pattern. They indicate that the majority of barefoot runners tend to contact the ground on the midfoot or forefoot when running on an asphalt road. This contrasts with the typical rearfoot striking pattern observed in conventionally shod runners on hard surfaces. Results also show that a minimally cushioned running shoe may not perfectly simulate barefoot running, with frequency of midfoot and forefoot striking being approximately equal to rearfoot striking.

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