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Abstract

Although the biomechanical properties of the various types of running foot strike (rearfoot, midfoot, and forefoot) have been studied extensively in the laboratory, only a few studies have attempted to quantify the frequency of running foot strike variants among runners in competitive road races. We classified the left and right foot strike patterns of 936 distance runners, most of whom would be considered of recreational or sub-elite ability, at the 10 km point of a half-marathon/marathon road race. We classified 88.9% of runners at the 10 km point as rearfoot strikers, 3.4% as midfoot strikers, 1.8% as forefoot strikers, and 5.9% of runners exhibited discrete foot strike asymmetry. Rearfoot striking was more common among our sample of mostly recreational distance runners than has been previously reported for samples of faster runners. We also compared foot strike patterns of 286 individual marathon runners between the 10 km and 32 km race locations and observed increased frequency of rearfoot striking at 32 km. A large percentage of runners switched from midfoot and forefoot foot strikes at 10 km to rearfoot strikes at 32 km. The frequency of discrete foot strike asymmetry declined from the 10 km to the 32 km location. Among marathon runners, we found no significant relationship between foot strike patterns and race times.

Keywords: *Running, foot strike, biomechanics, fatigue, asymmetry, gait*

Introduction

Although the exact point of initial contact of the foot with the ground during running is highly variable among runners, foot strikes during running are typically classified discretely as: (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 ball of the foot contact nearly simultaneously (usually along the lateral margin); and (3) forefoot, in which initial contact is made on the front half of the foot, after which heel contact typically follows shortly thereafter (Hasegawa, Yamauchi, & Kraemer, 2007). A number of studies have compared the kinetic and kinematic properties, as well as the relative metabolic efficiency, of these various foot strike patterns during running (Ardigo, Lafortuna, Minetti, Mongnoni, & Saibene, 1995; Arendse et al., 2004; Cavanagh & Lafortune, 1980; Laughton, McClay-Davis, & Hamill, 2003; Lieberman et al., 2010; Munro, Miller, & Fuglevand, 1987; Nilsson & Thorstensson, 1989; Stackhouse, Davis, & Hamill, 2004; Williams, Cavanagh, & Ziff, 1987; Williams, McClay, & Manal, 2000), and recent research has begun to elucidate the relationship between footwear (or lack thereof) and the foot strike (De Wit, De Clercq, & Aerts, 2000; Divert, Mornieux, Baur, Mayer, & Belli, 2005; Lieberman et al., 2010; Squadrone & Gallozi, 2009).

Somewhat surprisingly, limited data exist regarding foot strike patterns in large samples of distance runners in non-laboratory settings. In fact, to our knowledge, only two studies have analysed foot strike patterns of large numbers of runners in a competitive distance race (Hasegawa et al., 2007; Kerr, Beauchamp, Fisher, & Neil, 1983). Kerr et al. (1983) examined foot strike patterns among recreational runners in a 10 km race and at two points in a marathon (at 20 km and 35 km). They reported approximately 80% rearfoot strikers in all three of their samples, with most remaining runners being midfoot strikers (they only reported two forefoot strikers in total). Kerr and colleagues (1983) also

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reported that midfoot striking was more common among the faster runners in their sample. Hasegawa et al. (2007) examined foot strike patterns among elite runners at the 15 km point of the 2004 Sapporo International Half Marathon in Japan. Similar to Kerr et al. (1983), Hasegawa et al. (2007) reported that 74.9% of the runners in their sample were rearfoot strikers, 23.7% were midfoot strikers, and just 1.4% were forefoot strikers. They also observed that midfoot striking was more common in the faster runners in their sample, and provided data separately for both male and female runners (Hasegawa et al., 2007). Kerr et al. (1983) did not break their data down by gender.

Running shoe design and technology, runner demographics (Noakes, 2002, 2003), and portable high-speed video recording technology have changed a great deal since Kerr et al. (1983) conducted their study in the early 1980s. For example, Kerr et al. (1983) recorded their video at only 60 Hz, which may not be fast enough to accurately capture the exact moment of foot contact with the ground. This, combined with the fact that Hasegawa et al. (2007) were looking specifically at elite runners, and the overall paucity of foot strike data from any distance race, raises the question of how predominantly recreational runners wearing modern running shoes typically strike the ground while running. Furthermore, data are limited regarding the frequency of foot strike asymmetry in a large population of distance runners. Taken together, such data could have implications for future running shoe design, as well as provide a basis for interpreting studies that show a relationship between a particular foot strike pattern and injury risk in runners.

One additional factor that was not addressed by either Kerr et al. (1983) or Hasegawa et al. (2007) is the potential effect of fatigue on foot strike in a long-distance race. Unfortunately, although Kerr et al. (1983) did record foot strike at two points in a marathon, they did not compare intra-individual variation between the two points, and thus the potential effect of fatigue on running form and foot strike was not addressed. This question is of interest as researchers have suggested that increased eccentric contraction of the triceps surae in forefoot running can increase fatigue in these muscles over time (e.g. Williams et al., 2000). In support of this observation, Arendse et al. (2004) reported increased ankle eccentric work in forefoot strikers. Furthermore, anecdotal reports of delayed onset muscle soreness in the triceps surae are commonplace from new barefoot runners as well as those attempting to consciously alter stride to a midfoot or forefoot landing, particularly in a shoe with a reduced offset between midsole height in the heel versus forefoot. Thus, one could hypothesize that runners might alter their gait to mitigate fatigue in these muscles late in a race of marathon length (e.g. exhibited by an increase in frequency of rearfoot striking).

Our goals in this study were: (1) to determine the frequency of forefoot, midfoot, and rearfoot striking in a large sample of mostly recreational runners during a long-distance road race; (2) to compare foot strike distributions observed here to those reported in previous studies; (3) to quantify the frequency and types of left/right foot strike asymmetry in this population of runners; (4) to compare foot strike between marathon runners at the 10 km and 32 km points to assess the potential effects of late-race fatigue; and (5) to determine whether foot strike pattern is related to race time among marathon runners.

The null hypotheses that we specifically tested were: (1) foot strike patterns examined here do not differ from those reported previously in the literature; (2) foot strike distributions for the right and left legs of asymmetrical runners will be similar (i.e. no left/right bias for any particular strike type); (3) rearfoot striking frequency will remain constant between the 10 km and 32 km points of a marathon (i.e. midfoot and forefoot runners do not alter their gait to a heel striking pattern to manage fatigue of the triceps surae); and (4) there is no relationship between foot strike pattern and race time.

Methods

Procedure

We filmed participants in the Manchester City Marathon in Manchester, New Hampshire, USA on 1 November 2009. Runners were filmed at two separate locations: near the 10 km mark of the marathon and half-marathon, and near the 32 km mark of the marathon. At the first location, we filmed half-marathon runners, marathon relay runners, and full-marathon runners. At the second location, only full-marathon runners were filmed.

We filmed runners at both locations with a Casio Exilim EX-F1 digital camera 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 filmed in the sagittal plane. Filming locations were characterized by relatively flat ground surfaces so that running gaits would not be influenced by an incline or decline in elevation. The race course was fairly open at each location – about the width of a one-lane road at the 10 km location, and about the width of a two-lane road at the 32 km location. Thus, distance of runners from the camera was variable, but the vast majority of runners were sufficiently close to allow for clear visualization of the location of foot contact. We did not classify runners if distance from the camera precluded clear visualization of foot strike location (this was rare). To assist with identification of individual full-marathon runners, digital still photographs were taken as they approached the filming site, and bib numbers were recorded in sequence as they passed. Where necessary, runner identifications were confirmed by comparing video images to official race photographs published on-line by Brightroom Event Photography (www.brightroom.com).

Gender of individual marathon runners was determined via reference to published race results. Due to practical limitations (i.e. large sample size combined with the considerable challenge of positively identifying runners from film), we did not attempt to identify relay or half-marathon runners, and thus gender data were not collected for these runners.

Participants

We recorded video from a total of 936 runners at the 10 km mark for whom both right and left foot strike could be classified. This sample included marathon relay runners, half-marathon runners, and full-marathon runners. The latter were identified via methods described above so that they could be separated out for further comparative analyses. The purpose of analysing this sample was to provide descriptive statistics on foot strike pattern for a large number of mostly recreational runners and to allow for an assessment of the frequency and types of foot strike asymmetry found among runners in a road race.

We were able to positively identify and synchronize video from a total of 286 individual full-marathon runners at the 10 km the 32 km locations. Walkers at both locations and those for whom both foot strikes could not be classified were not included in this sample. The purpose of this second dataset was to allow for comparisons to be made between marathon runners at two points in the race – one early, prior to the onset of significant fatigue, and one late, after the point where fatigue typically becomes an issue for marathon runners. This sample was also used to investigate the relationship between foot strike pattern and runner speed (obtained from published race results).

For reference purposes, this was a mostly recreational population of runners, with only 20 of the 461 full-marathon finishers completing the race in under 3 h, and well over half finishing in over 4 h. The mean finish time for the 286 marathon runners we analysed was $3:57:31 \pm 00:34:17$. The winning marathon time was 2:23:46.

The study received approval from the Institutional Review Board of our institution.

Data collection

Video for each runner was analysed frame-by-frame in Apple Quicktime Pro. The high filming speed (300 Hz) allowed for clear visualization of the point of initial contact between the foot and the ground.

We followed Hasegawa et al. (2007) by defining a forefoot strike (FFS) as one in which initial contact of the foot with the ground is on the front half of the sole, with no heel contact at foot strike (Figure 1a). A midfoot strike was defined as one in which the sole of the shoe from heel to ball (i.e. roughly near the base of the fifth metatarsal head) contacted the ground simultaneously (typically along the lateral margin; Figure 1b). A rearfoot strike (RFS) is one in which

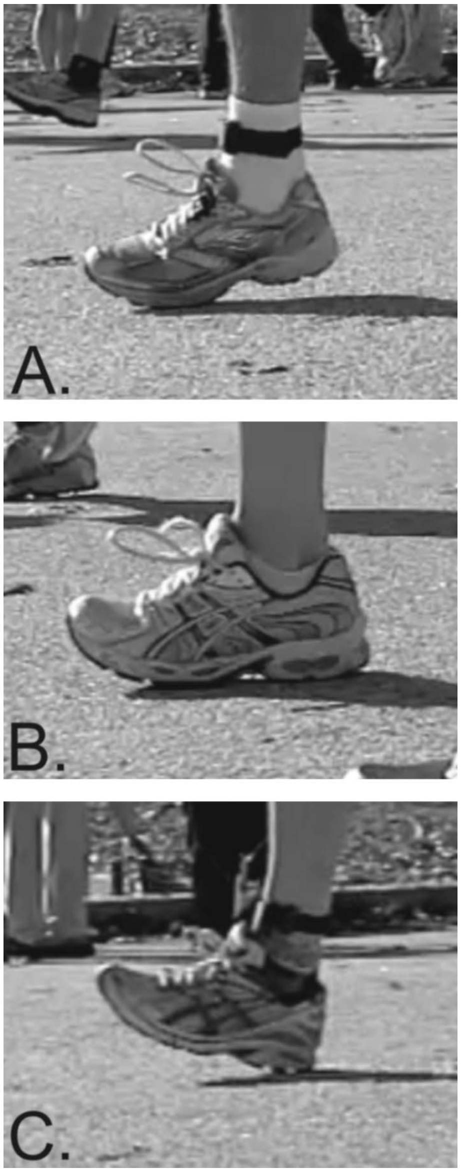

Figure 1. Examples of foot strike patterns taken from video at the 10 km mark of the Manchester City Marathon. (A) Forefoot strike. (B) Midfoot strike. (C) Rearfoot strike.

first contact of the foot with the ground was made on the heel or rear one-third of the sole (Figure 1c). For each runner, we classified foot strike for both the right and left foot. In most cases, we analysed the first two foot strikes observed for a given runner once they entered the frame of the video, regardless of which foot entered first. Deviations from this procedure occurred if one foot strike was obscured (e.g. by another runner) or clipped off at the edge of the video frame.

To maintain consistency, the foot strike of each runner was classified by the primary author, with independent classification done by at least one co-author so that a second opinion could be obtained in cases of uncertainty. To determine repeatability of classifications, we used a random number generator to produce 50 numbers between 1 and 286 that corresponded to the order in which individual runners passed the camera at the 32 km location of the marathon. Without referring to original classifications, the primary author then reclassified foot strikes for both feet of each individual in this random subsample and subsequently compared them with the original classifications (total of 100 foot strikes reclassified). Only 2 of the 100 reclassified foot strikes differed from the original classification (98% congruence).

Statistical analyses

Analysis of 10 km sample. We compared foot strike frequency distributions for our sample of relay, half-marathon, and full-marathon runners at the 10 km race location to those reported by Hasegawa et al. (2007) and Kerr et al. (1983) using chi-square (χ^2) analysis. Since neither previous study reported data on foot strike asymmetry, and Hasegawa et al. (2007) reported that their totals include data from a mixture of sides depending on what was available in their video sequences, we opted to include only symmetrical runners ($n = 881$) for our comparative dataset in this analysis.

Chi-square analysis was also used to test for differences in foot strike frequency distributions between the left and right legs of asymmetrical runners ($n = 55$) in the 10 km sample, as well as to compare foot strike patterns between male and female full-marathon runners at the 10 km location. Since the small sample sizes of non rearfoot-striking marathon runners would have led to 50% of the cells having a value less than 5 in a complete analysis of foot strike differences between males and females, we opted to pool midfoot and forefoot strikers for this analysis and instead compare frequencies of rearfoot striking and non-rearfoot striking. Yates' correction was employed for this analysis since there were only two non-rearfoot striking females in this sample.

Comparisons between 10 km and 32 km samples. Due to non-independence of samples, we used McNemar's test to determine if rearfoot striking was more common at 32 km than at 10 km. We classified individual foot strikes (two per runner) as rearfoot or non-rearfoot (i.e. forefoot or midfoot) for this analysis. McNemar's test was also used to compare frequency of asymmetrical runners between the 10 km and 32 km locations.

Since we do not have instantaneous pace/speed data for runners at each location, we chose to examine the relationship between foot strike pattern and time taken to reach the half-marathon and full-marathon timing mats as a way to determine if there was a relationship between foot strike and speed of individual marathon runners. Due to dramatically unequal samples sizes among foot strike types, we used the non-parametric Kruskal-Wallis test to compare half-marathon time in seconds among rearfoot symmetrical, midfoot symmetrical, forefoot symmetrical, and asymmetrical runners using foot strike pattern exhibited at the 10 km mark as our grouping variable. The same analysis was performed to compare full-marathon time in seconds among foot strike groupings at the 32 km location. Symmetrical forefoot strikers were omitted from the latter analysis (none were observed at 32 km).

Results

Numbers and percentages of foot strikes for all relay, half-marathon, and full-marathon runners recorded at the 10 km location (936 runners total) are presented in Table I. Excluding asymmetrical runners, 94.4% of symmetrical runners were rearfoot strikers, 3.6% were midfoot strikers, and 1.9% were forefoot strikers. Results of chi-square analyses indicate that our observed foot strike frequency distribution (excluding asymmetrical runners) differs significantly from those reported by Hasegawa et al. (2007; $\chi^2 = 110.59$, d.f. $= 2$, $P < 0.001$) and Kerr et al. (1983; $\chi^2 = 106.52$, d.f. $= 2$, $P < 0.001$).

Among the 55 asymmetrical relay, half-marathon, and full-marathon runners in the 10 km sample, 31 were rearfoot-left, midfoot-right, 10 were midfoot-left, rearfoot right, 7 were midfoot-left,

Table I. Foot strike patterns for relay, half-marathon and marathon runners ($n = 936$) at approximately 10 km of the Manchester City Marathon/Half-marathon.

Foot strike pattern	Count	Percentage
Rearfoot	832	88.9
Midfoot	32	3.4
Forefoot	17	1.8
Asymmetrical	55	5.9

forefoot-right, 6 were rearfoot-left, forefoot-right, and 1 was forefoot-left, midfoot-right. Chi-square analysis indicates that foot strike distributions differ significantly between the right and left legs of asymmetrical runners ($\chi^2 = 30.4$, d.f. = 2, $P < 0.001$). This suggests that heel striking is more common on the left side, and midfoot and forefoot striking are more common on the right side in asymmetrical runners.

Numbers and percentages of foot strikes for marathon runners at the 10 km and 32 km locations (286 runners) are presented in Table II. Results of McNemar's test comparing foot strike patterns for individual feet at 10 km and 32 km indicates that rearfoot striking was more common at 32 km ($P < 0.01$). Altogether, 92.3% of individual forefoot strikes at the 10 km location changed pattern to either a midfoot or rearfoot strike at 32 km (5 out of 5 on the left foot, 7 out of 8 on the right foot), and 59.5% of midfoot strikes at the 10 km point were reclassified as rearfoot strikes at 32 km (7 out of 12 on the left foot, 15 out of 25 on the right foot). Although one runner who was rearfoot striking with the left foot at 10 km was observed forefoot striking on the same foot at 32 km, and 8 individual strikes switched from rearfoot to midfoot, the vast majority (98.2%) of rearfoot striking feet at 10 km remained rearfoot striking feet at 32 km.

Results of McNemar's test comparing frequency of asymmetry between individual runners at 10 km and 32 km indicates that asymmetry was less common at 32 km ($P < 0.01$). Foot strike patterns for marathon runners are further broken down by gender in Table III. There was no significant difference in the frequency of rearfoot versus non-reafoot striking between males and females at the 10 km location ($P = 0.42$).

Mean half-marathon times for foot strike categories at the 10 km location are as follows: rearfoot ($n = 251$) = 1:50:47 ± 00:14:48, midfoot ($n = 9$) = 1:45:52 ± 00:16:35, forefoot ($n = 4$) = 1:51:09 ± 00:06:06, asymmetrical ($n = 20$) = 1:47:54 ± 00:13:31. Results of a Kruskal-Wallis test comparing half-marathon time among foot strike classifications at the 10 km location indicated no significant difference ($\chi^2 = 1.39$, d.f. = 3, $P = 0.71$). Mean full-marathon times for footstrike categories at the 32 km location are as follows: rearfoot ($n = 266$) = 3:57:27 ± 00:34:33, midfoot ($n = 10$) = 4:06:20 ± 00:24:39, forefoot (none observed), asymmetrical ($n = 10$) = 3:50:13 ± 00:36:05. Results of a Kruskal-Wallis test comparing full-marathon time among foot strike classifications at the 32 km location indicated no significant difference ($\chi^2 = 1.65$, d.f. = 2, $P = 0.44$).

Table II. Foot strike patterns for marathon runners ($n = 286$) at approximately 10 km and 32 km of the Manchester City Marathon.

	10 km data		32 km data	
Foot strike pattern	Count	Percentage	Count	Percentage
Rearfoot	251	87.8	266	93.0
Midfoot	9	3.1	10	3.5
Forefoot	4	1.4	0	0.0
Asymmetrical	22	7.7	10	3.5

Discussion

Available published data from in-race studies conducted to date indicate that approximately 75–80% of runners land on their rearfoot when initially contacting the ground (Hasegawa et al., 2007; Kerr et al., 1983). Foot strike distributions from the 10 km point of the Manchester City Marathon differ significantly from those reported in previous studies, likely reflecting the greater number of rearfoot strikers (94.4% when excluding asymmetrical runners) and smaller number of midfoot strikers (3.6% when excluding asymmetrical runners) that we observed (Table I). Thus, in our sample of mostly recreational runners wearing mostly typical modern running shoes (it was impossible to specifically identify each shoe by type from the video, but all runners observed were shod, and only a few runners were observed wearing so-called "minimalist" shoes like the Vibram Fivefingers), rearfoot striking was more common and midfoot striking was less common than has been previously reported.

We suspect that the recreational profile and slower speed of runners observed in this study in part explain the discrepancies between rearfoot strike frequency reported here versus in-race foot strike pattern distributions reported previously. For example, Hasegawa et al. (2007) observed that 74.9% of runners in their sample from the Sapporo International Half-Marathon were rearfoot strikers. However, the runners observed in that study were elite

Table III. Foot strike patterns of male and female marathon runners at approximately 10 km and 32 km of the Manchester City Marathon.

	Females ($n = 80$)		Males ($n = 206$)	
Foot strike pattern	Count	Percentage	Count	Percentage
Rearfoot (10 km)	75	92.5	176	85.9
Midfoot (10 km)	1	1.3	8	3.9
Forefoot (10 km)	1	1.3	3	1.5
Asymmetrical (10 km)	4	5.0	18	8.7
Rearfoot (32 km)	76	93.8	190	92.7
Midfoot (32 km)	1	1.3	9	4.4
Forefoot (32 km)	0	0.0	0	0.0
Asymmetrical (32 km)	4	5.0	6	2.9

half-marathoners, and even the Manchester City Half-Marathon winner (winning time = 1:09:45) would not have ranked among the top 100 runners examined by Hasegawa et al. (2007). Kerr et al. (1983) observed approximately 80% rearfoot strikers among a more "recreational" population of runners, but even there the low-end speed for which they reported mean foot strike percentages (12.42 km $\cdot$ h^{-1}) was still faster than 85% of the marathon runners in our sample based upon average race pace.

In addition to the overall faster profile of runners in their studies, both Hasegawa et al. (2007) and Kerr et al. (1983) observed more midfoot strikes among the faster runners in their samples. Although midfoot strikers had the fastest mean time to the half-marathon point of the Manchester City Marathon, statistical analysis indicated that speed differences observed here among foot strike groups were not significant for either the 10 km or 32 km samples. Our small sample sizes for non-heel striking runners suggest that considerable caution should be taken when interpreting these results. The relationship between foot strike and speed demonstrated by previous studies could provide some explanation for the observation that rearfoot striking was overall more common among the slower population of runners examined here. It is possible that there is a threshold speed at which rearfoot striking becomes extremely common. For example, rearfoot strike frequencies reported for slower runners in Hasegawa and colleagues' (2007) study are more comparable to those observed here.

A second factor that could have contributed to the larger percentage of rearfoot strikers and lower percentage of midfoot strikers that we observed is the fact that our filming speed was over twice that employed by Hasegawa et al. (2007), and five times that used by Kerr et al. (1983). When filming speed is insufficient, it is possible that the exact moment of initial foot contact might be missed in marginal rearfoot or forefoot strikes. Depending on the angle between the foot and ground in the sagittal plane on contact, there are many ways that a runner can land on the rearfoot or forefoot, but only one in which the runner can land on the midfoot (simultaneous contact at heel and ball of foot). Given that all foot strike types will ultimately end with the foot being flat on the ground, film in which the exact moment of initial contact on the rearfoot or forefoot is missed could result in overestimation of midfoot strikes, and underestimation of rearfoot and forefoot strikes.

Regardless of potential explanations for our observed foot strike frequencies, as the numbers of participants in marathons have grown, average finish times have also risen substantially, suggesting that the population of runners that we observed is very different from those observed in previous studies (Noakes, 2002, 2003). Thus, we would suggest that data reported here might be a more accurate reflection of foot strike patterns among modern recreational runners than those reported by Hasegawa et al. (2007) or Kerr et al. (1983).

Although the vast majority of runners observed in our samples were rearfoot strikers, it should be noted that the discrete category that we refer to as a rearfoot strike encompasses wide variation in the exact location of foot contact with the ground (as long as it was on the rear one-third of the shoe). For example, Cavanagh and LaFortune (1980) observed a continuum of initial foot–ground contact points along nearly the entire posterior 60% of shoe length in runners that they examined. Similarly, while some rearfoot striking runners in our sample landed at the very back of the heel with a highly dorsiflexed foot, others landed only slightly towards the back one-third of a more plantarflexed foot (and others could be found at just about every point in between). Had we measured centre-of-pressure tracings, peak vertical impact forces, or loading rates, we suspect that considerable variation would have been found among our sample of rearfoot strikers. Indeed, Logan and colleagues (Logan, Hunter, Hopkins, Feland, & Parcell, 2010) reported a high degree of variability in kinetic measurements such as loading rate and peak vertical impact force among heel-striking runners, and suggested individual differences in initial contact location as a possible explanation.

It is tempting to conclude that the high percentage of rearfoot strikers observed in this sample indicates that this is the way that most humans prefer to run. However, a potentially confounding variable is that nearly all runners observed here (with only a few exceptions) were wearing highly cushioned running shoes with a raised heel. Lieberman et al. (2010) recently demonstrated that habitually unshod runners typically land on their forefoot while running, whereas habitually shod runners tend to strike the ground with the rearfoot/heel as observed in most runners in this study. Furthermore, Nett (1964) filmed runners with high-speed video in the 1950s, before the advent of modern, cushioned shoes with a pronounced heel lift, and concluded that nearly all contacted the ground with the midfoot or forefoot, with the exact location related to the length of the race they competed in (i.e. a proxy for running speed). These studies suggest that the more typical heel-striking pattern exhibited by most traditionally shod modern runners might in some cases be related to the construction of the shoes that they have been training and racing in.

Owing to the factors mentioned above, it is difficult to determine whether the patterns observed here or in previous studies reflect preferred gait on the part of the runners, whether the shoes being worn condition or predispose runners to this gait, or whether it might represent a combination of these factors. Considering that faster runners tend to wear racing flats or lightweight shoes that typically have a smaller heel lift and less cushion, the potential for footwear to be a confounding variable when relating speed to foot strike pattern from in-race data should also be considered. In any case, given the continuing high incidence of overuse injuries in runners (Hreljac, 2004; van Gent et al., 2007; Walter, Hart, McIntosh, & Sutton, 1989), the potential influence of footwear (or lack thereof) on the kinematics and kinetics of running gait (De Wit et al., 2000; Divert et al., 2005; Hamill, Russell, Gruber, & Miller, 2011; Lieberman et al., 2010; Logan et al., 2010; Nigg, Bahlsen, Luethi, & Stokes, 1987; Reinschmidt & Nigg, 1995; Squadrone & Gallozi, 2009; Stacoff, Denoth, Kälin, & Stüssi, 1988; Stacoff et al., 2001), and the potential relationship between kinematic and/or kinetic variables and injury in runners (Hreljac, 2004; Hreljac, Marshall, & Hume, 2000; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Oakley & Pratt, 1988; Pohl, Hamill, & Davis, 2009; Williams et al., 2000; Zadpoor & Nikooyan, 2011), it would seem that additional research on this topic is warranted.

Foot strike asymmetry

Numerous studies have documented gait asymmetry in runners, particularly as it relates to injury risk (Karamanidis, Aeampatzis, & Brüggemann, 2003; Vagenas & Hoshizaki, 1988, 1992; Williams et al., 1987; Zifchock, Davis, & Hamill, 2006; Zifchock, Davis, Higginson, McCaw, & Royer, 2008). However, to our knowledge discrete patterns of foot strike asymmetry have not been quantified in a large sample of runners in a competitive distance race. We provide data showing that 55 of 936 runners (5.9%) at the 10 km location exhibited an asymmetrical foot strike pattern. Furthermore, asymmetrical runners tended to heel strike more often on the left side, forefoot or midfoot strike on the right side, and asymmetry in marathon runners declined in frequency at the 32 km marathon location.

In most cases asymmetries were relatively minor, with one foot landing on the midfoot and the other landing slightly more towards the heel. We suspect that the decline in asymmetry at 32 km is mostly due to these minor asymmetries collapsing down to rearfoot strikes on both sides. In addition to subtle asymmetries, we observed a few cases where runners exhibited a rearfoot strike on one foot and a forefoot strike on the other. It is unclear whether these asymmetrical landing patterns were simply chance observations of a single unusual foot strike sequence or genuine gait asymmetries, but at least one individual with a heel–forefoot asymmetry repeated the pattern at both the 10 km and 32 km filming locations. While we hesitate to speculate on the cause of any of these gross asymmetries, Williams et al. (1987) observed an individual with a rearfoot-left, forefoot-right asymmetry in their study of the biomechanical characteristics of elite female distance runners and indicated that the participant was recovering from a groin injury. To our knowledge, ours is the first study to report on foot strike asymmetry in a large population of runners in a race setting, and it thus provides baseline observational data on the phenomenon.

Foot strike and fatigue

By recording foot strikes for the same individual at both the 10 km and 32 km locations of a marathon, we were able to address whether foot strike early in a race of marathon length differs from that observed later in the same race, at a point when runners often begin to feel the effects of late-race fatigue. Our results indicate that rearfoot striking was significantly more common at 32 km than it was at 10 km. Furthermore, all symmetrical forefoot strikers and most asymmetrical runners who exhibited a forefoot strike on one foot at the 10 km point shifted to a midfoot or rearfoot strike at the 32 km point. Similarly, a large number of midfoot strikers at 10 km became rearfoot strikers at 32 km. A number of researchers have investigated the effects of fatigue on the kinematics of the running gait (Bates, Osternig, & James, 1977; Christina, White, & Gilchrist, 2001; Elliot & Roberts, 1980; Mizrahi, Verbitsky, & Isakov, 2000; Mizrahi, Verbitsky, Isakov, & Daily 2000; Williams, Snow, & Agruss, 1991), but we were unable to find any that commented specifically on the effects of fatigue on foot strike pattern in a marathon-length distance race.

Relating to the topic of fatigue, Willson and Kernozek (1999) reported decreased loading of the heel in fatigued treadmill runners and suggested that adoption of a midfoot landing strategy might explain this, although they did not report kinematic data. In contrast, our observations indicate that marathon runners who changed landing pattern in our sample generally switched from midfoot and forefoot landing styles to a rearfoot landing at the 32 km mark of the marathon. Williams et al. (2000) suggested that forefoot striking places a heavier eccentric load on the ankle joint and calf muscles during running, and we would thus speculate that fatigue in the triceps surae complex in the lower leg might have caused these runners to shift their gait late in the race. Our results, combined with the fact that both Kerr et al. (1983) and Hasegawa et al. (2007) also observed only a very small number of forefoot strikers in their analyses, and Nett's (1964) observation that longer distance racers in the 1950s tended to land on the midfoot, indicate that a forefoot striking running gait may not be ideal for most habitually shod runners in a race of the length and intensity of a marathon.

Conclusions

Analysis of foot strike patterns among mostly recreational distance runners indicates that the vast majority contact the ground initially on the rearfoot, with frequency of rearfoot striking exceeding previous reports from in-race studies. Discrete foot strike asymmetry was observed in approximately 6% of runners, and comparison of foot strike patterns at the 10 km and 32 km race locations indicates that a high percentage of runners switched from a midfoot or forefoot strike to a rearfoot strike late in the race, presumably due to fatigue.

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