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Foot-Strike Pattern and Performance in a Marathon

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Purpose: To determine prevalence of heel strike in a midsize city marathon, if there is an association between foot-strike classification and race performance, and if there is an association between foot-strike classification and gender. ***Methods:*** Foot-strike classification (forefoot, midfoot, heel, or split strike), gender, and rank (position in race) were recorded at the 8.1-km mark for 2112 runners at the 2011 Milwaukee Lakefront Marathon. ***Results:*** 1991 runners were classified by foot-strike pattern, revealing a heel-strike prevalence of 93.67% (n = 1865). A significant difference between foot-strike classification and performance was found using a Kruskal-Wallis test ($P < .0001$), with more elite performers being less likely to heel strike. No significant difference between foot-strike classification and gender was found using a Fisher exact test. In addition, subgroup analysis of the 126 non-heel strikers found no significant difference between shoe wear and performance using a Kruskal-Wallis test. ***Conclusions:*** The high prevalence of heel striking observed in this study reflects the foot-strike pattern of most mid-distance to long-distance runners and, more important, may predict their injury profile based on the biomechanics of a heel-strike running pattern. This knowledge can help clinicians appropriately diagnose, manage, and train modifications of injured runners.

Keywords: running, gait biomechanics, endurance, physical performance, injury

The effect of foot-strike type on running economy and injury rates has been highly prevalent in recent literature.[1–12] However, no conclusive results have been published. The following foot-strike-type classification is common: forefoot strike as the ball of the foot landing before the heel (toe-heel-toe run), midfoot strike as simultaneous landing of the heel and ball of the foot, and heel strike (rear-foot strike) as the heel landing before the ball of the foot (heel-to-toe run).[10] Despite the numerous studies attempting to define the advantages and disadvantages of certain foot-striking patterns and shoe wear, there remains a relatively small number of in-race studies in which actual foot-strike prevalence, as well as the subsequent effect on performance, has been documented.[13–16] Only 1 has included "average" runners.[16]

A thorough review of literature to date found that 4 studies have documented foot-strike prevalence of runners in mid-distance to long-distance races.[13–16] In 1964, Nett[13] became the first researcher to study in-race foot-strike prevalence, before the advent of the modern running shoe. Nett collected high-speed (64 frames/s) video of elite German runners from competitive races varying in distance between 100 m and 26.2 miles and concluded that most long-distance runners (1500 m to marathon) were midfoot striking or forefoot striking. However, this conclusion was derived from a small number of elite runners competing in races of varying distances and running conditions, with a frame rate comparably slower than current high-speed video cameras. The other 3 studies, which were conducted since 1983, after the advent of the modern running shoe, concluded that most runners were heel striking.[14–16] In 1983, Kerr et al[14] studied foot-strike patterns in 753 recreational runners who competed in either a 10-km race or a marathon (at 20 km and 35 km), concluding that approximately 80% of runners were rear-foot striking, and midfoot striking was more common among the faster runners. However, that study reported results from 3 separate data points in 2 distinct races and, despite the relatively large sample size, only reported 2 forefoot strikers. Hasegawa et al[15] examined foot-strike prevalence of 283 elite runners at the 2004 Sapporo International Half Marathon in Japan, concluding that 74.9% of the runners were rear-foot striking, and midfoot striking was more common in the faster runners. That sample, however, was limited to a relatively small number of elite runners. In 2009, Larson et al[16] evaluated 286 subelite runners at the 10-km and 32-km marks of a marathon, concluding that between 87.8% and 93.0% of the runners were rear-foot striking and there was no statistical relationship between marathon finish time and foot strike at the 32-km mark. However, that was based on a small subset of the marathon runners. Only 286 of 461 finishers were included for analysis of foot-strike classification and performance, including 266 heel-strikers, 10 midfoot strikers, 10 asymmetrical strikers, and no forefoot strikers.

The current study was designed to evaluate the foot-strike patterns of a large number of "average" runners in

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a single race using a high-speed digital video camera. The primary objectives of this study included determining prevalence of heel-strike in a midsize city marathon, determining if there is an association between foot-strike classification and performance, and determining if there is an association between foot-strike classification and gender. A secondary objective in this research was determining if there is an association between shoe wear and performance. By obtaining a larger sample size, this study aimed to provide stronger statistical power for the observed heel-strike prevalence in Larson's study of subelite runners and to observe a statistically significant association between foot strike and gender, foot strike and performance, and shoe wear and performance.

Methods

Subjects

All 2112 runners, including pacers (specifically marked individuals trained to run the marathon at a certain pace to guide other runners, but not competing in the race), completing the first 8.1 km of the marathon were screened for study inclusion. Runners were excluded from further analysis if either they were walking (n = 104) or foot-strike classification could not be determined for at least 1 foot strike (n = 17). The remaining 1991 runners were included for foot-strike classification. The study was granted an exemption from oversight by the Medical College of Wisconsin Institutional Review Board in accordance with 45CFR46.101(b)(4).

Design

This study was an observational cohort study, completed at the 2011 Milwaukee Lakefront Marathon, Milwaukee, WI (October 2, 2011).

Methodology

A Casio EX-ZR100 digital video camera was set up 30 cm from the side of the road, securely mounted atop a tripod at a height of 61 cm, and angled at 30° from perpendicular to the marathon course. This angle was selected as opposed to a direct perpendicular angle as it was found to obtain sufficient video for accurate foot-strike classification of a larger proportion of runners, specifically, runners running side by side. The frame rate was set to 240 frames/s. The filming location was 8.1 km into the race. The 8.1-km mark was chosen for several reasons. It represented a straight and level portion of the course, as confirmed by our tripod level, and was on a 2-lane road, not within 1 km of an aid station, minimizing walking. In addition, the 8.1-km distance allowed ample time for the separation of runners, enabling more effective data collection. Finally, the relatively short distance from the starting line reduced the possibility of altered foot-strike pattern as a consequence of muscle fatigue, which has been demonstrated to occur as early as 1 hour, or at a distance of 15 km into a run in well-trained runners.[17,18] Camera time (not equivalent to gun time), rank (position in the race), gender, and a detailed runner description were determined by observation at the 8.1-km mark. When running side by side, the runners were ranked left to right such that the runner farthest left was given the lowest rank (eg, fastest) and the runner farthest right was given the highest rank (eg, slowest).

Video data collected from the race were then transferred to a Compaq 6710b laptop with an Intel Core 2 CPU, processor speed of 2.40 GHz, and 2 GB RAM. The video was analyzed using QuickTime Version 7.6.9 software and projected on a projector screen with a ViewSonic PJ458D DLP projector.

For each runner, approximately 3 to 4 adequate foot strikes were captured on film. Foot-strike classification was then completed for each foot strike, simultaneously but independently by a 3-member panel, using frame-by-frame analysis provided by Apple QuickTime Version 7.6.9. Foot-strike classifications were defined as forefoot strike, midfoot strike, and heel strike based on the proposed classification as defined by Lieberman[10] (Figure 1). An additional classification of split strike was used for runners with asymmetry between foot strike of the left and the right feet. The runners classified as split strike were further reviewed in similar fashion, with additional classification completed for each foot.

After foot-strike classification of all runners, there was a subjective observation that a larger proportion of the non-heel strikers appeared to be wearing minimalist shoe wear. Thus, researchers evaluated the shoe wear of the 126 non-heel strikers (inclusive of forefoot, midfoot, and split strikers) to determine if there was an association between shoe wear and performance. Shoe-wear analysis was limited to this subset as there was insufficient video clarity to determine shoe wear for all 1991 runners. Shoe wear was classified as either minimalist or traditional. Minimalist shoe wear was defined as shoes known to have a heel lift of less than or equal to 4 mm and included (but was not limited to) Vibram Five Fingers, Newton, Merrell Glove, and New Balance Minimus. This is compared with a heel lift of traditional shoes commonly greater than 12 mm.

Statistical Analysis

Overall prevalence of each foot-strike classification was calculated. In addition, prevalence of heel strike by rank was graphically evaluated by grouping runners into rank groups of 100 consecutive runners.

Due to largely unequal sample sizes, a nonparametric Kruskal-Wallis test was used for all runners (N = 1991) to compare rank among each foot-strike classification (forefoot, midfoot, heel, and split strike) using foot-strike classification as the grouping variable. A second Kruskal-Wallis test was used for all non-heel strikers (n = 126) to compare rank among each foot-strike classification in this subgroup (forefoot, midfoot, and split strike) using foot-strike classification as the grouping variable.

A Fisher exact test was used for all runners (N = 1991) to evaluate the relationship between each foot-

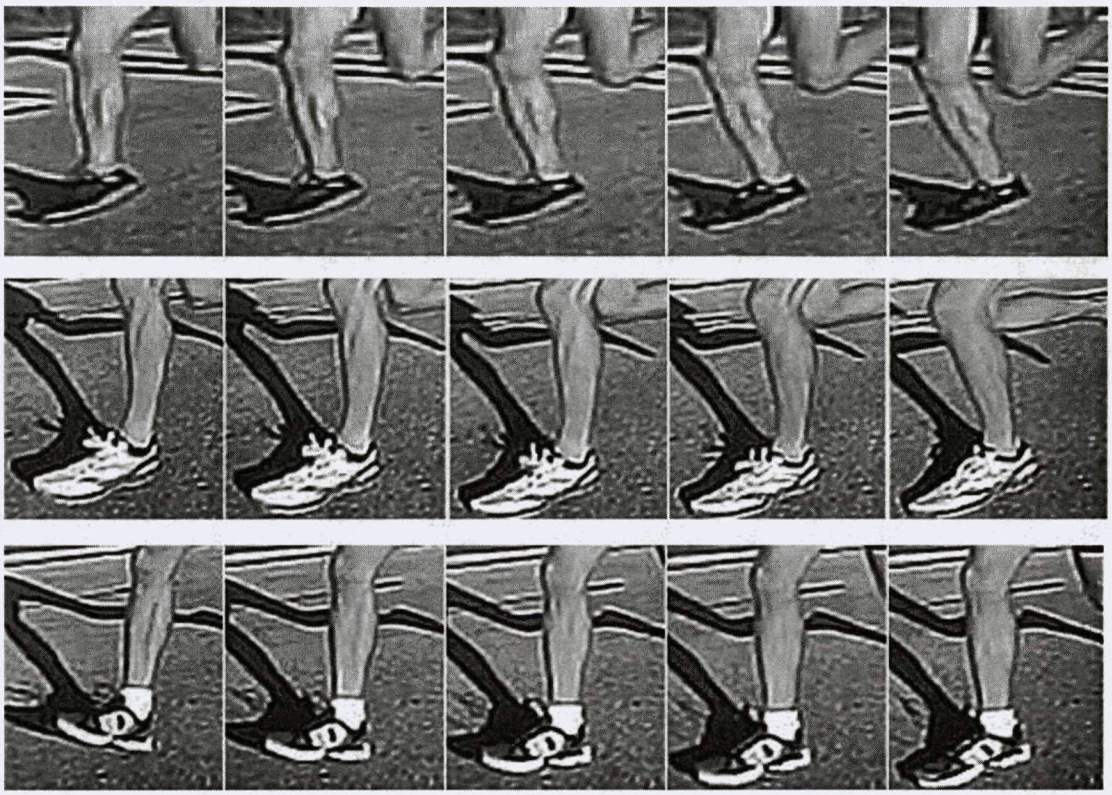

Figure 1 — Examples of foot-strike pattern at the 8.1-km mark of the 2011 Milwaukee Lakefront Marathon, 5 frames (left to right, nonconsecutive, every other frame). From top to bottom: forefoot strike, midfoot strike, and heel strike.

strike classification and gender. A second Fisher exact test was used for all non-heel strikers (n = 126) to evaluate the relationship between each foot-strike classification and gender in this subgroup.

Prevalence of minimalist shoes for all non-heel strikers (n = 126) was calculated. A Kruskal-Wallis test was used to compare rank by shoe wear using shoe wear as the grouping variable.

Results

Of the 2112 runners who were recorded at the 8.1-km mark, 1991 runners met inclusion/exclusion criteria and were classified by foot-strike type as shown in Table 1. The split strikers were further classified as 12 midfoot/heel strike, 1 forefoot/heel strike, and 1 midfoot/forefoot strike. A total of 1986 out of these 1991 were unanimously classified, making the interrater reliability of foot-strike classification among the 3 panel members 99.7%. In the 5 cases in which panel members differed in opinion, classification of foot strike was based on the opinion of the two-thirds majority. In no case were all 3 panel members in disagreement.

Heel-strike prevalence by rank, grouped by 100 runners, is included in Figure 2. A significant difference between foot-strike classification and race rank was demonstrated by a Kruskal-Wallis test comparing rank for all 1991 runners among foot-strike classifications (forefoot, midfoot, heel, and split strike) at the 8.1-km mark ($\chi^2 = 32.85$, $df = 3$, $P < .0001$): Ranking first were forefoot strikers, followed by split strikers, then midfoot strikers, and, finally, heel strikers (Figure 3). However, among the 126 non-heel strikers (inclusive of forefoot strikers, midfoot strikers, and split strikers), there was no significant difference between foot-strike classification and rank demonstrated by a Kruskal-Wallis test at the 8.1-km mark ($\chi^2 = 1.31$, $df = 2$, $P = .52$).

A Fisher exact test between foot-strike classification and gender for all 1991 runners revealed a nonsignificant trend of men being more likely than women to forefoot strike, midfoot strike, and split strike while being less likely than women to heel strike, as shown in Table 1 ($P = .0727$). Among the 126 non-heel strikers, a Fisher exact test revealed no significant relationship between foot strike and gender in this subgroup ($P = .8227$).

Among the 126 non-heel strikers, 27 (21.43%) were observed to be wearing minimalist shoes: 1 of 11 forefoot strikers (9.09%), 23 of 101 midfoot strikers (22.77%), and 3 of 14 split strikers (21.43%). No significant difference between shoe wear and rank was demonstrated using a Kruskal-Wallis test comparing rank among shoe wear (minimalist or traditional) at the 8.1-km mark ($\chi^2 = 2.01$, $df = 1$, $P = .16$) in this subgroup.

Table 1 Foot-Strike Evaluation of 1991 Runners, Divided by Foot-Strike Classification and Gender

	Strike	n	% of gender[a]	% of total[b]
Male n = 1160	Forefoot	7	0.60% (OR = 1.25, CI = 0.36–4.28)	63.64%
	Midfoot	71	6.12% (OR = 1.73, CI = 1.12–2.68)	70.30%
	Heel	1073	92.50% (OR = 0.68, CI = 0.43–3.85)	57.53%
	Split	9	0.78% (OR = 1.28, CI = 0.49–0.93)	64.29%
Female n = 831	Forefoot	4	0.48%	36.36%
	Midfoot	30	3.61%	29.70%
	Heel	792	95.31%	42.47%
	Split	5	0.60%	35.71%
Total N = 1991	Forefoot	11		0.55%
	Midfoot	101		5.07%
	Heel	1865		93.67%
	Split	14		0.70%

Abbreviations: OR indicates odds ratio; CI, confidence interval.

[a] % of gender with specific foot-strike pattern. [b] % of total foot-strike pattern observed in particular gender.

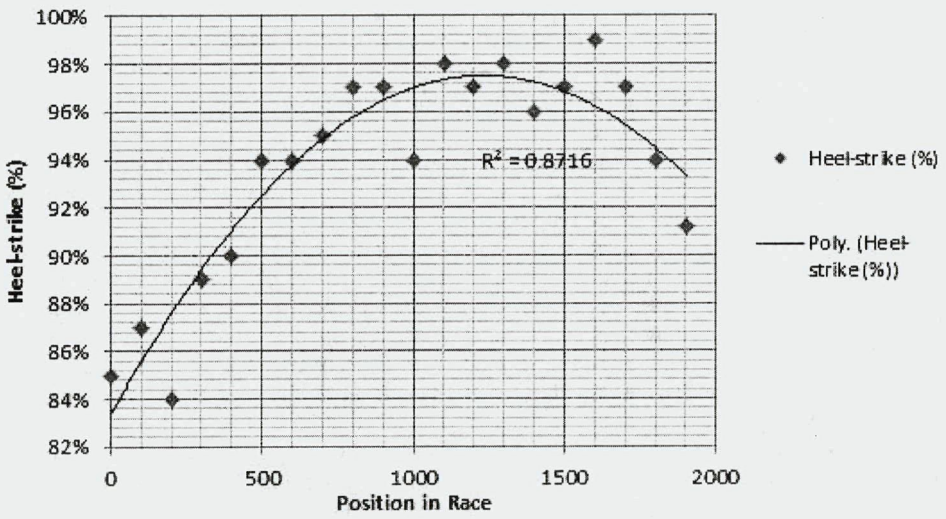

Figure 2 — Heel strike (%) by rank (position in race) at the 8.1-km mark.

Discussion

To place this sample population in context, the 2011 Milwaukee Lakefront Marathon's official Web site reported 3050 registered runners. There were 2077 finishers (1201 men, 876 women). The top overall finish time was 2:22:17. The top women's finish time was 2:54:15. Mean finish time was 4:18:01, with a standard deviation of 48:01. This marathon draws elite runners, as evidenced by the 375 Boston Marathon qualifiers; and subelite runners, as evidenced by the mean finish time of 4:18:01; as well as noncompetitive marathon runners, as evidenced by the 104 walkers at the 8.1-km mark.

Of the previous in-race foot-strike studies cited, this sample is most reflective of a similar midsize city marathon—the 2009 Manchester City Marathon researched by Larson et al.[16] While the top finishing time of 2:55:16 was significantly slower than the Milwaukee Lakefront Marathon top finishing time, the mean finishing time of 4:12:36 was slightly faster. For both races, the majority of runners would not have finished better than the 75th percentile relative to the elite runners analyzed by Kerr et al[14] and Hasegawa et al.[15] Thus, this study population is most representative of the current average mid-distance to long-distance runner, who on average is comparatively slower than his or her counterpart from the recent past, as noted by the rise of mean finishing times in marathons.[16]

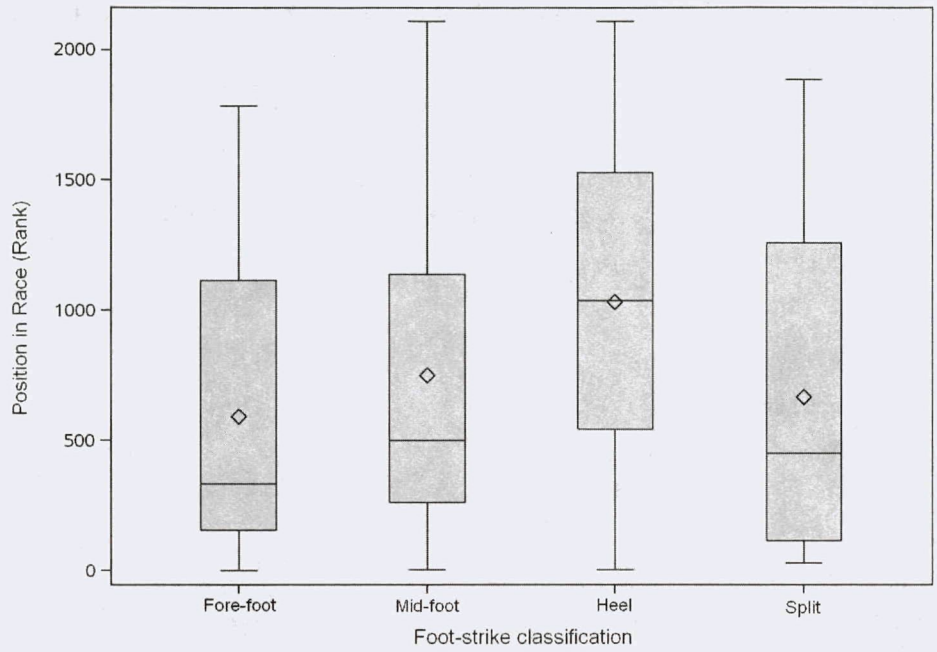

Figure 3 — Kruskal-Wallis box plot for rank (position in race) grouped by foot-strike classification ($P < .0001$).

This study attempted to further support the foot-strike classification prevalence of the current "average" runner, as observed by Larson et al,[16] and opposed to the more elite runner observed by Hasegawa et al,[15] Kerr et al,[14] and Nett.[13] It also attempted to determine statistical significance of additional relationships, some of which have been previously investigated, such as foot-strike classification and gender, foot-strike classification and performance, and shoe wear and performance. This study was designed to accomplish these objectives as follows: First, it represented the largest sample size of any observational foot-strike study to date. This larger sample size spans all foot-strike classifications, produces stronger statistically powered data, and allows an improved ability to determine significance in statistical relationships. As stated previously, a 30° angle from perpendicular was selected, as it represented the optimal angle to collect adequate video on the largest number of runners while not compromising the ability to classify each individual runner's foot strike, as demonstrated by the classification of 1991 of 2008 runners (runners not walking) with an interrater reliability of 99.7%. Second, these data were collected from 1 race at 1 location with 1 camera, reducing variables such as race conditions. Third, the study employed a camera with a high frame rate, which can be attributed to recent advances in digital-video technology. As foot-strike classifications represent a continuum of angles between the foot and the ground at initial contact, it is important to capture the exact moment of initial contact to differentiate among them. For instance, a forefoot strike with 1° of plantar flexion is only 1° more plantar flexed than a midfoot strike and 2° more plantar flexed than a heel strike. The transition between initial contact and the midfoot stance of loading response is near instantaneous. Thus, the importance of capturing the exact moment of initial contact is extremely important for accurate foot-strike classification and relies on high frame-rate capabilities.

Overall, this study observed a 93.67% heel-strike prevalence, which is similar to the findings of Larson et al,[16] who also studied a group of mostly subelite runners at the 10-km and 32-km marks of a marathon and cited a heel-strike prevalence of 87.8% and 93.0%, respectively. This suggests that the heel-strike prevalence observed in the current study may have been even higher if data had been collected later in the race. However, as shown in Figure 2, the more elite runners, as denoted by a lower rank, demonstrated lower heel-strike prevalence. In fact, the heel-strike prevalence of the top 300 runners was 85.3%, which appears more consistent with the populations of Hasegawa et al[15] and Kerr et al[14] of more elite-level runners' heel-strike prevalence between 74.9% and 80%.

As discussed by Larson et al,[16] possible etiologies to explain the increased heel-strike prevalence that was further supported by this study in relation to those of Kerr et al[14] and Hasegawa et al[15] are 2-fold. First, in the relative subelite population of runners it is believed that, compared with elite runner, subelite runners tend to run with a decreased cadence (step rate), which favors a heel-strike pattern.[11] Second, the improved frame rate of current high-speed digital video cameras allows for increased precision in determining the exact moment of initial contact when viewing foot strike. As previously discussed, a low frame rate may not be able to differentiate the exact moment of initial contact and thus precludes accurate foot-strike classification.

The relationship of foot strike and performance was examined for each of the previous studies cited. Both Kerr et al[14] and Hasegawa et al[15] reported that a non-heel-strike pattern was more common among faster runners, without proving statistical significance. Larson et al,[16] however, reported no significant relationship between marathon finish time and foot strike after analysis ($P = .44$). The current study of 1991 runners demonstrated a significant difference between foot-strike classification and rank at the 8.1-km mark ($P < .0001$). Ranking first were forefoot strikers, followed by split strikers, then midfoot strikers, and, finally, heel strikers. These findings reflect the nonsignificant trends noted by Hasegawa et al[15] and Kerr et al[14] but are in contrast to the results reported by Larson et al.[16]

While the findings of Larson et al[16] suggest there is no significant relationship between marathon finish time and foot-strike classification, this may be due to a small sample size combined with a relative lack of elite runners. Larson's sample size was 286 runners (of 461 total finishers), including 266 heel strikers, 10 midfoot strikers, 10 asymmetrical strikers, and no forefoot strikers. The current study's sample size was 1991 runners, including 1865 heel strikers, 101 midfoot strikers, 11 forefoot strikers, and 14 split strikers. The winner, or most "elite" runner, in Larson's study finished in 2:55:16 and would have ranked 33rd in the current study. The increased number of runners, including elite runners who have been previously demonstrated to favor midfoot strike,[2] may have increased this study's ability to document statistical significance between foot-strike classification and performance.

While analysis by gender revealed a trend of women being more likely to heel strike than men, this was not found to be significant. Further in-race studies, with larger sample sizes, would be necessary to test for statistical significance.

Despite not having completed a formal shoe-wear analysis for all 1991 runners, we observed that fewer than 21.43% of all runners appeared to be wearing minimalist shoes. This observation may suggest that runners wearing minimal shoes were more likely to forefoot or midfoot strike than those wearing traditional running shoes. However, subgroup analysis of the 126 non-heel strikers did not reveal a significant difference between shoe wear and performance. A significant difference was demonstrated only between foot-strike classification and rank, suggesting that a runner's foot strike may be more important to his or her overall performance than his or her shoe wear, as has previously been suggested.[10,19]

Practical Applications

The significant difference between foot-strike classification and rank that is suggested by the current study is of unknown origin and consequence. This study cannot determine if more experienced well-trained runners have been advised to avoid heel striking or if a possible improved running economy of forefoot or midfoot striking is responsible for more elite runners. The former, the avoidance of heel striking, may be supported by 2 relatively new concepts. First, there is a societal movement of minimalist running. Minimalist running (eg, barefoot running, chi running, pose running technique) promotes a non-heel-strike gait pattern. Second, there is an increased awareness of optimal cadence and of lowering vertical bounce. Recently, more average runners are being "coached" on the optimal cadence of ~170 to 195 steps/min,[20,21] compared with the average cadence of 150 to 160 steps/min.[22] The latter, improved running economy of a non-heel-strike gait pattern, is in debate and without definitive conclusion.[1,2,5–7,9,11] Despite the suggested statistical significance between foot-strike classification and performance, this study does not conclude that all runners should adopt a forefoot-strike technique. This is, in part, due to the unknown clinical consequences between foot-strike classification and injury rate, which is likewise in debate and without definitive conclusion.[1,3–5,7–10,12] Unless a more definitive conclusion regarding foot-strike pattern, running economy, and injury rate is reached, a preferred foot-strike pattern cannot be universally recommended.

However, biomechanically, certain injuries may be more prevalent for each foot-strike classification,[8,10,12,23] and knowing the foot-strike classification of the runner may assist in proper diagnosis and treatment recommendations, including specific training modifications.

Further in-race research is necessary to validate these findings among various runner populations, race conditions, and distances, if it is generalizable. Further studies (both in-race and laboratory) may help differentiate not only the cause but also the consequences (ie, running economy and injury rates) of the suggested findings.

Conclusion

This study suggests that heel-strike prevalence in a mid-size city marathon is approximately 94%. A statistically significant difference was found between foot-strike classification and performance, with more elite performers being less likely to heel strike. No significant difference between foot-strike classification and gender was found. In addition, subgroup analysis of the 126 non-heel strikers found no significant difference between shoe wear and performance, perhaps emphasizing the importance of foot-strike pattern over shoe wear. Clinically, the high prevalence of heel striking observed in this study reflects the foot-strike pattern of the majority of mid-distance to long-distance runners and, more important, may predict their injury profile based on the biomechanics of a heel-strike running pattern. This knowledge can help clinicians appropriately diagnose, manage, and train modifications of injured runners.

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References

1. Cavanagh PR, Lafortune MA. Ground reaction forces in distance running. *J Biomech.* 1980;13:397–406. PubMed doi:10.1016/0021-9290(80)90033-0
2. Williams KR, Cavanagh PR, Ziff JL. Biomechanical studies of elite female distance runners. *Int J Sports Med.* 1987;8:S107–S118. PubMed doi:10.1055/s-2008-1025715
3. Robbins SE, Hanna AM. Running-related injury prevention through barefoot adaptations. *Med Sci Sports Exerc.* 1987;19:148–156. PubMed
4. Robbins SE, Gouw GJ, Hanna AM. Running-related injury prevention through innate impact-moderating behavior. *Med Sci Sports Exerc.* 1989;21:130–139. PubMed
5. Willson JD, Kernozek TW. Plantar loading and cadence alterations with fatigue. *Med Sci Sports Exerc.* 1999;31:1828–1833. PubMed doi:10.1097/00005768-199912000-00020
6. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med.* 2004;34:465–485. PubMed doi:10.2165/00007256-200434070-00005
7. Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *J Sports Med Phys Fitness.* 2009;49:6–13. PubMed
8. Davis IS, Bowser B, Mullineaux D. Do impacts cause running injuries? a prospective investigation. Paper presented at: 2010 ASB Annual Meeting; August 18–21, 2010; Providence, RI. Abstract 472.
9. Lieberman DE, Vedkadesan M, Werbel WA, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature.* 2010;463:531–535. PubMed doi:10.1038/nature08723
10. Lieberman DE. What can we learn about running from barefoot running: an evolutionary medical perspective. *Exerc Sport Sci Rev.* 2012;40:63–72. PubMed doi:10.1097/JES.0b013e31824ab210
11. Perl DP, Daoud AI, Lieberman DE. Effects of footwear and strike type on running economy. *Med Sci Sports Exerc.* 2012;44(7):1335–1343. PubMed doi:10.1249/MSS.0b013e318247989e
12. Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE. Foot strike and injury rates in endurance runners: a retrospective study. [published online ahead of print January 3, 2012] *Med Sci Sports Exerc.*2012;44(7):1325–1334. PubMed doi:10.1249/MSS.0b013e3182465115
13. Nett T. Foot plant in running. *Track Technique.* 1964;15:462–463.
14. Kerr BA, Beauchamp L, Fisher V, Neil R. Footstrike patterns in distance running. In Kerr BA, ed. *Biomechanical Aspects of Sports Shoes and Playing Surfaces: Proceedings of the International Symposium on Biomechanical Aspects of Sport Shoes and Playing Surfaces.* Calgary: Alberta University Press; 1983:135–142.
15. Hasegawa H, Yamauchi T, Kraemer WJ. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *J Strength Cond Res.* 2007;21:888–893. PubMed
16. Larson P, Higgins E, Kaminski J, et al. Foot strike patterns of recreational and sub-elite runners in a long-distance road race. *J Sports Sci.* 2011;29:1665–1673. PubMed doi:10.1080/02640414.2011.610347
17. Place N, Lepers R, Deley G, Millet GY. Time course of neuromuscular alterations during a prolonged running exercise. *Med Sci Sports Exerc.* 2004;36:1347–1356. PubMed doi:10.1249/01.MSS.0000135786.22996.77
18. Ross EZ, Goodall S, Stevens A, Harris I. Time course of neuromuscular changes during running in well-trained subjects. *Med Sci Sports Exerc.* 2010;42:1184–1190. PubMed
19. Krabak BJ, Hoffman MD, Millet GY, Chimes GP. Barefoot running. *PM R.* 2011;3:1142–1149. PubMed
20. Daniels JT. *Daniel's Running Formula.* Champaign, IL: Human Kinetics; 2005.
21. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation of joint mechanics during running. *Med Sci Sports Exerc.* 2011;43:296–302. PubMed
22. Elliott BC, Blanksby BA. Optimal stride length considerations for male and female recreational runners. *Br J Sports Med.* 1979;13:15–18. PubMed doi:10.1136/bjsm.13.1.15
23. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc.* 2006;38:323–328. PubMed doi:10.1249/01.mss.0000183477.75808.92

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