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# Foot-strike pattern and performance in a marathon

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## Abstract

**Purpose—**To: 1) determine prevalence of heel-strike in a mid-size city marathon, 2) determine if there is an association between foot-strike classification and race performance, and 3) determine if there is an association between foot-strike classification and gender.

**Methods—**Foot-strike classification (fore-foot strike, mid-foot strike, heel strike, or split-strike), gender, and rank (position in race) were recorded at the 8.1 kilometer (km) mark for 2,112 runners at the 2011 Milwaukee Lakefront Marathon.

**Results—**1,991 runners were classified by foot-strike pattern, revealing a heel-strike prevalence of 93.67% (n=1,865). A significant difference between foot-strike classification and performance was found using a Kruskal-Wallis test ($p < 0.0001$), with more elite performers being less likely to heel-strike. No significant difference between foot-strike classification and gender was found using a Fisher's exact test. Additionally, 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 the majority of mid- to long-distance runners and more importantly, may predict their injury profile based on the biomechanics of a heel strike running pattern. This knowledge can aid the clinician in the appropriate diagnosis, management, and training modifications of the injured runner.

### Keywords

running; gait biomechanics; endurance; physical performance; injury

## Introduction

The effect of foot-strike type on running economy and injury rates has been highly prevalent in recent literature.[1,2,3,4,5,6,7,8,9,10,11,12] However, no conclusive results have been

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published. The following foot-strike type classification is common: fore-foot strike as the ball of the foot landing before the heel (toe-heel-toe run), mid-foot 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.[13,14,15,16] Only one has included the “average” runner.[16]

A thorough review of literature to date found that four studies have documented foot-strike prevalence of runners in mid- to long-distance races.[13,14,15,16] In 1964, Nett[13] became the first researcher to study “in-race” foot-strike prevalence, prior to the advent of the modern running shoe. Nett collected high-speed (64 frames/second) video of elite German runners from competitive races varying in distance between 100 meters and 26.2 miles, and concluded that the majority of long-distance runners (1,500 meters to marathon) were mid-foot striking or fore-foot 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 remaining 3 studies, which having been conducted since 1983, after the advent of the modern running shoe, concluded that the majority of runners were heel-striking.[14,15,16] In 1983, Kerr[14] studied foot-strike patterns in 753 recreational runners that competed in either a 10km race or a marathon (at 20km and 35km), concluding that 1) approximately 80% of runners were rear-foot striking and 2) mid-foot striking was more common among the faster runners. However, this study reported results from 3 separate data points in 2 distinct races and despite the relatively large sample size, only reported 2 fore-foot strikers. Hasewaga[15] examined foot-strike prevalence of 283 elite runners at the 2004 Sapporo International Half Marathon in Japan concluding that 1) 74.9% of the runners were rear-foot striking and 2) mid-foot striking was more common in the faster runners. This sample, however, was limited to a relatively small number of elite runners. In 2009, Larson[16] 87 evaluated 286 sub-elite runners at the 10km and 32km marks of a marathon, concluding that 1) between 87.8% and 93.0% of the runners were rear-foot striking and 2) there was no statistical relationship between marathon finish time and foot-strike at the 32km mark. However, this 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 mid-foot strikers, 10 asymmetrical strikers, and no fore-foot strikers.

This study was designed to evaluate the foot-strike patterns of a large number of “average” runners in a single race through the use of a high speed digital video camera. The primary objectives of this study include: 1) determining prevalence of heel-strike in a mid-size city marathon, 2) determining if there is an association between foot-strike classification and performance, and 3) determining if there is an association between foot-strike classification and gender. A secondary objective in this research was determining if an association exists between shoe wear and performance. By obtaining a larger sample size, this study aims to provide stronger statistical power for the observed heel-strike prevalence in Larson’s study of sub elite 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 2,112 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 kilometers (km) of the marathon were screened for study inclusion. Runners were excluded from further analysis if either a) the runner was walking (n=104) or b) foot-strike classification was unable to be determined for at least one foot-strike (n=17). The remaining 1,991 runners were included for foot strike classification. The study was granted an exemption from IRB 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, Wisconsin, USA (2 October 2011).

## Methodology

A Casio EX-ZR100 digital video camera was set-up 30cm from the side of the road, securely mounted atop a tri-pod at a height of 61cm, and angled at 30 degrees 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 per second. The filming location was 8.1 kilometers into the race. The 8.1km mark was chosen for several reasons. It represented a straight and level portion of the course, as confirmed by our tripod level, and was a 2-lane road, not within 1 km of an aid station, minimizing walking. In addition, the 8.1km distance allowed ample time for the separation of runners, allowing 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 1hour, or at a distance of 15 kilometers 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 8.1km mark. For runners, running “side-by-side”, the runners were ranked left to right such that the runner furthest left was given the lowest rank (e.g. fastest) and the runner furthest right was given the highest rank (e.g. slowest).

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

For each runner, approximately three to four adequate foot-strikes were captured on film. Foot-strike classification was then completed for each foot-strike, simultaneously, but independently by a three member panel, utilizing frame-by-frame analysis provided by Apple QuickTime Version 7.6.9. Foot-strike classifications were defined as fore-foot strike, mid-foot 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 foot. The runners classified as split-strike were further reviewed in similar fashion, with additional classification completed for each foot.

Following 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 fore-foot, mid-foot, 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 1,991 runners. Shoe wear was classified either as minimalist or traditional. Minimalist shoe wear was defined as shoes known to have a heel-lift of less than or equal to 4mm and included (but was not limited to) Vibram® Five Fingers, Newton®, Merrell® Glove, and New Balance® Minimus. This is compared to a heel-lift of traditional shoes commonly greater than 12mm.

### Statistical Analysis

Overall prevalence of each foot-strike classification was calculated. Additionally, 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 non-parametric Kruskal-Wallis test was used for all runners (n=1,991) to compare rank among each foot-strike classification (fore-foot strike, mid-foot strike, heel strike, 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 (fore-foot strike, mid-foot strike, and split strike) using foot-strike classification as the grouping variable.

A Fisher's exact test was used for all runners (n=1,991) to evaluate the relationship between each foot-strike classification and gender. A second Fisher's 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

2,112 runners were recorded at the 8.1km mark. 1,991 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 mid-foot/heel strike, 1 fore-foot/heel strike, and 1 mid-foot/fore-foot strike. A total of 1,986 out of these 1,991 were unanimously classified, making the inter-rater reliability of foot-strike classification among the three panel members 99.7%. In the five cases that panel members differed in opinion, classification of foot-strike was based on the opinion of the two-thirds majority. In no case were all three 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 1,991 runners among foot-strike classifications (forefoot strike, mid-foot strike, heel strike, and splitstrike) at the 8.1km mark ($\chi^2 216 = 32.85$, d.f.=3, $p < 0.0001$): ranking first were fore-foot strikers, followed by split-strikers, then mid-foot strikers, and lastly heel-strikers (Figure 3). However, among the 126 non-heel strikers (inclusive of fore-foot strikers, mid-foot strikers, and split strikers), there was no significant difference between foot-strike classification and rank demonstrated through the use of a Kruskal-Wallis test at the 8.1km mark ($\chi^2 221 = 1.31$, d.f.=2, $p = 0.52$).

A Fisher's exact test between foot-strike classification and gender for all 1,991 runners revealed a non-significant trend of males being more likely than females to fore-foot strike, mid-foot strike, and split-strike, while being less likely than females to heel strike as shown in Table 1 ($p=0.0727$). Among the 126 non-heel strikers, a Fisher's exact test revealed no significant relationship between foot-strike and gender in this subgroup ($p = 0.8227$).

Among the 126 non-heel strikers, 27 (21.43%) were observed to be wearing minimalist shoes: 1 of 11 fore-foot strikers (9.09%), 23 of 101 mid-foot 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 8.1km mark ($\chi^2 236 = 2.01$, d.f. =1, $p = 0.16$) in this subgroup.

## Discussion

In order to place this sample population in context, the 2011 Milwaukee Lakefront Marathon's official website reported 3,050 registered runners. There were 2,077 finishers (1,201 male; 876 female). The top overall finish time was 2:22:17. The top female 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; sub-elite runners, as evidenced by the mean finish time of 4:18:01; as well as non-competitive marathon runners, as evidenced by the 104 walkers at the 8.1km mark.

Of the previous "in-race" foot-strike studies cited, this sample is most reflective of a similar mid-size city marathon - the 2009 Manchester City Marathon researched by Larson.[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 75$^{th}$ percentile relative to the elite runners analyzed by Kerr[14] and Hasewaga[15]. Thus, this study population is most representative of the current average mid- 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]

This study attempted to further support the foot-strike classification prevalence of the current "average" runner, as observed by Larson[16] and opposed to the more elite runner observed by Hasewaga[15], Kerr[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 above, a 30 degree 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 1,991 of 2,008 runners (runners not walking) with an inter-rater reliability of 99.7%. Second, this data was collected from one race at one location with one camera, reducing variables such as race conditions. Third, this 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 in order to differentiate among them. For instance, a fore-foot strike with 1 degree of plantarflexion is only 1 degree more plantarflexed than a mid-foot strike and 2 degrees more plantarflexed than a heel strike. The transition between initial contact and the mid-foot stance of loading response is near instantaneous. Thus, the importance of capturing the exact moment of initial contact is of extreme importance 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[16], who also studied a group of mostly sub-elite runners at the 10km and 32km 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 this study may have been even higher if data was 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 Hasewaga's and Kerr's population of more elite level runners heel-strike prevalence between 74.9% and 80%.[14,15]

As discussed by Larson[16], possible etiologies to explain the increased heel-strike prevalence that was further supported by this study in relation to Kerr's[14] and Hasewaga's[15] are two-fold. First, in the relative sub-elite population of runners it is believed that compared to the elite runner, the sub-elite runner tends to run with a decreased cadence (step rate), which favors a more 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 preclude accurate foot-strike classification.

The relationship of foot-strike and performance was examined for each of the previous studies cited. Both Kerr[14] and Hasewaga[15] reported that a non-heel strike pattern was more common among faster runners, without proving statistical significance. Larson[16], however reported no significant relationship between marathon finish time and foot-strike after analysis ($p = 0.44$). This study of 1,991 runners demonstrated a significant difference between foot-strike classification and rank at the 8.1km mark ($p < 0.0001$). Ranking first were fore-foot strikers, followed by split-strikers, then mid-foot strikers, and lastly heel-strikers. These findings reflect the non-significant trends noted by Hasewaga[15] and Kerr[14], but are in contrast to the results reported by Larson.[16]

While the findings of Larson[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 a total of 461 total finishers), including 266 heel-strikers, 10 mid-foot strikers, 10 asymmetrical strikers, and no fore-foot strikers. This study's sample size was 1,991 runners, including 1,865 heel-strikers, 101 mid-foot strikers, 11 fore-foot strikers, and 14 split strikers. The winner, or most "elite" runner, in Larson's study finished in 2:55:16 and would have ranked 33$^{rd}$ in this study. The increased number of runners, including elite runners that have been previously demonstrated to favor mid-foot 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 females being more likely to heel-strike than males, this was not found to be significant. Further "in-race" studies, with a larger sample size, would be necessary to test for statistical significance.

Despite not having completed a formal shoe wear analysis for all 1,991 runners, it was the author's observation that less than 21.43% of all runners appeared to be wearing minimalist shoes. This observation may suggest that those runners wearing minimal shoes were more likely to fore-foot or mid-foot strike than those runners 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 previously suggested.[10,19]

## Practical Applications

The significant difference between foot-strike classification and rank that is suggested by this 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 fore-foot or mid-foot striking is responsible for more elite runners. The former, or avoidance of heel-striking, may be supported by two relatively new concepts. First, there is a societal movement of minimalist running. Minimalist running (e.g. barefoot running, chi running, pose running technique) promotes a non-heel strike gait pattern. Second, there is an increased awareness of the optimal cadence and of lowering vertical bounce. Recently, more average runners are being "coached" on the optimal cadence of ~ 170–195 steps / minute,[20,21] compared to the average cadence of 150–160 steps / minute.[22] The latter, or improved running economy of a non-heel strike gait pattern, is in debate and without definitive conclusion.[1,2,5,6,7,9,11] 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.[1,3,4,5,7,8,9,10,12] 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 (i.e. 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. Additionally, 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- to long-distance runners and more importantly, may predict their injury profile based on the biomechanics of a heel-strike running pattern. This knowledge can aid the clinician in the appropriate diagnosis, management, and training modifications of the injured runner.

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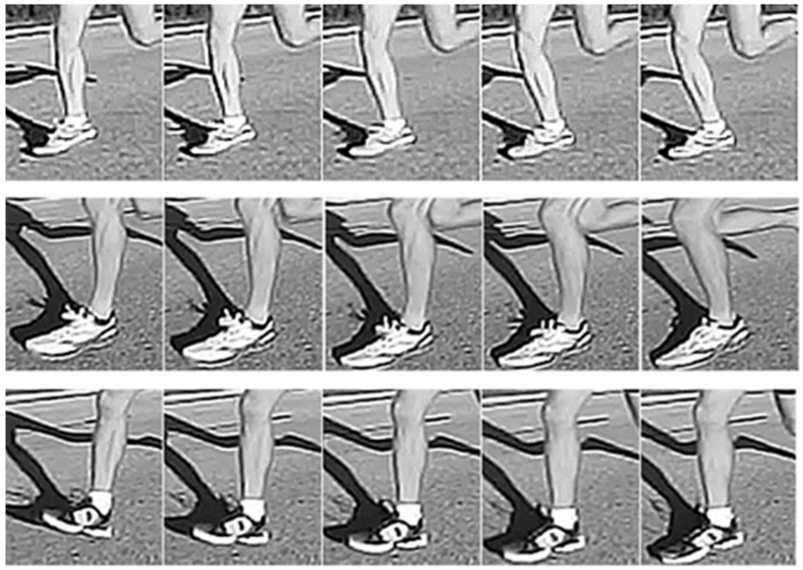

**Figure 1.**

Examples of foot-strike pattern at the 8.1km mark of the 2011 Milwaukee Lakefront Marathon. Five frames (left-to-right, non-consecutive, every other frame). From top to bottom: fore-foot strike, mid-foot strike, and heel strike.

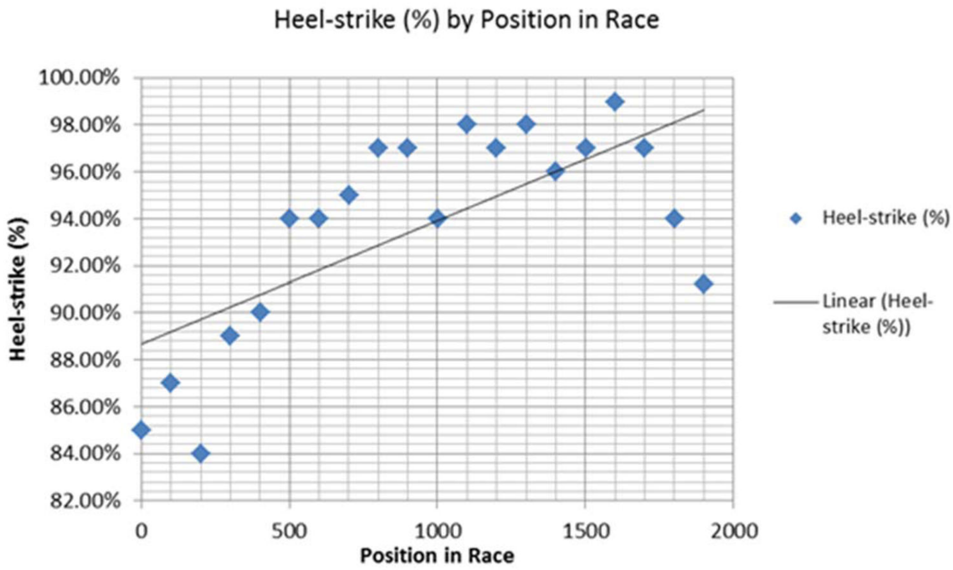


**Figure 2.**
Heel strike (%) by rank (position in race) at the 8.1km mark.

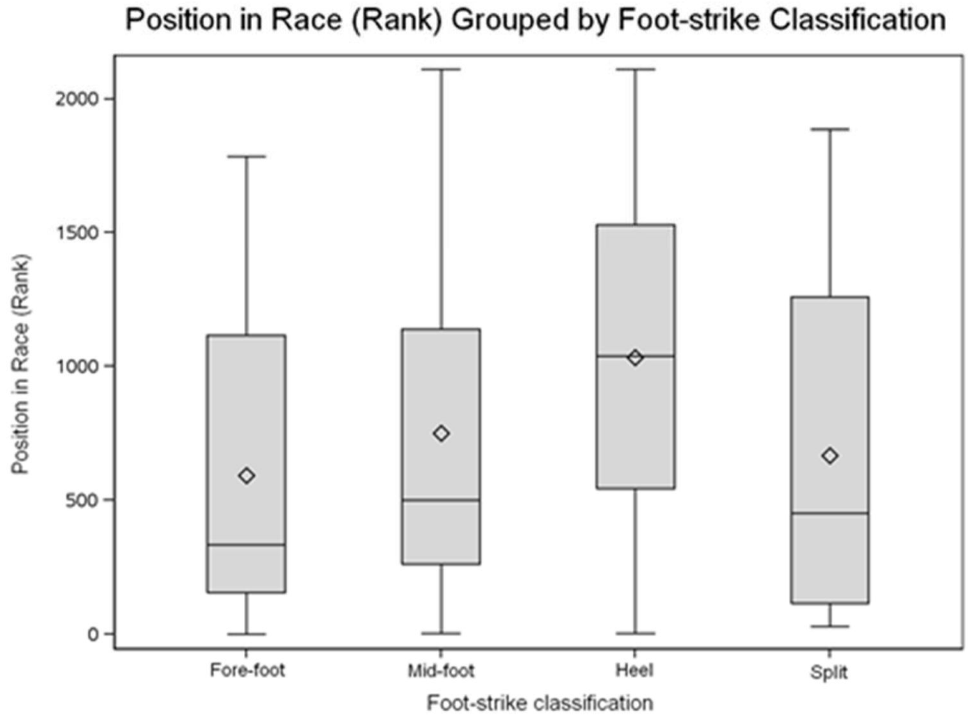


**Figure 3.**

Kruskal-Wallis box-plot for rank (position in race) grouped by foot-strike classification ($p < 0.0001$).

**Table 1**

Foot-strike evaluation of 1,991 runners, divided by foot-strike classification and gender (% of Gender = % of gender with specific foot-strike pattern, % of Total = % of total foot-strike pattern observed in particular gender, OR=Odds Ratio, CI=Confidence Interval).

| | | N | % of Gender | % of Total |
|---|---|---|---|---|
| | Fore-foot | 7 | 0.60% (OR=1.25, CI=0.36–4.28) | 63.64% |
| | Mid-foot | 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% |
| Male n=1160 | Split | 9 | 0.78% (OR=1.28, CI=0.49–0.93) | 64.29% |
| | Fore-foot | 4 | 0.48% | 36.36% |
| | Mid-foot | 30 | 3.61% | 29.70% |
| | Heel | 792 | 95.31% | 42.47% |
| Female n=831 | Split | 5 | 0.60% | 35.71% |
| | Fore-foot | 11 | | 0.55% |
| | Mid-foot | 101 | | 5.07% |
| | Heel | 1865 | | 93.67% |
| Total N=1991 | Split | 14 | | 0.70% |