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Footstrike pattern at the 10 km and 39 km points of the Singapore marathon in recreational runners

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ABSTRACT

The prevalence of rearfoot striking is ~60% in elite marathoners, but ~90% in North American and European recreational marathoners. Recent data indicate that this prevalence is ~70% in Asian recreational marathoners. How this prevalence changes throughout the course of a marathon remains undocumented. We filmed 350 runners at the 10 km and 39 km marks of the Singapore marathon (~71% Asian field), and classified footstrike patterns in 347 and 327 runners at these locations. The prevalence of rearfoot, midfoot, forefoot, and asymmetric patterns was 65%, 21%, 33%, and 11% at 10 km, which differed significantly from the corresponding 77%, 15%, 1%, and 8% at 39 km ($p < 0.01$). The prevalence of non-rearfoot strikers at both filming locations was greater than reported in the literature for North American recreational marathoners ($p < 0.01$), but lower than reported for non-Asian elite marathoners ($p \leq 0.02$). The 12% increase in rearfoot strikers at the later mark of the marathon in our Asian cohort of recreational runners was greater than the 5% increase reported for the North American-based cohort ($p < 0.01$), but comparable to the one reported for non-Asian elite runners ($p = 0.97$). Our findings confirm previous conclusions that running research should consider and report ethnicity alongside performance standards given that both can (in part) explain biomechanical differences in running gait. Noteworthy is that numerous factors can influence marathon performance and fatigue that here remained unaccounted for, including age, sex, course profile, footwear, and environmental conditions.

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Introduction

The footstrike pattern of runners is typically classified in one of three discrete categories based on which part of the foot makes initial ground contact with the ground as rearfoot (RFS), midfoot (MFS), or forefoot (FFS) strike (Hasegawa et al., 2007). The prevalence of RFS is close to 60% in elite marathoners (Hanley et al., 2019). However, this prevalence approaches 90% in predominantly North American (Kasmer et al., 2013; Larson et al., 2011) and European (Latorre-Román et al., 2015) cohorts of recreational runners participating in long-distance road races. In contrast to such cohorts, we found a lower RFS prevalence (71%) and higher MFS prevalence (17%) at the 10 km mark of the Singapore marathon in a predominantly Asian cohort of recreational runners (Patoz et al., 2019).

Different footstrike patterns involve distinct neuromuscular (Ahn et al., 2014) and biomechanical (Boyer et al., 2014; Ruder et al., 2019; Wei et al., 2019) characteristics. For instance, FFS involves greater ankle eccentric work (Arendse et al., 2004) that can enhance triceps surae muscle fatigue over time (Williams III, McClay, & Manal, 2000). The effect of running-induced fatigue can lead to quantifiable declines in neuromuscular performance (Murray et al., 2019a) and changes in biomechanics, such as preferred footstrike pattern (Larson et al., 2011). Indeed, Hanley et al. (2019) observed an increase in the RFS prevalence of elite marathoners from 60% to 70% between the 8.5 km and 40 km marks of the 2017 International

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Association of Athletics Federations World Championships Marathon (London, UK). Moreover, Larson et al. (2011) observed an increase in the RFS prevalence from 88% to 93% between the 10 km and 32 km marks of the 2009 Manchester City Marathon (New Hampshire, USA) in a mostly North American cohort of runners. Although the medical implications of alterations in footstrike patterns in-race are yet to be fully elucidated; footstrike pattern change suggests neuromuscular fatigue (Jewell et al., 2017), slower running speeds (Breine et al., 2019; Cheung et al., 2017), and overall lower running performance (Bovalino et al., 2020; Latorre-Román et al., 2015). To our knowledge, no study has yet to report alterations in self-selected footstrike patterns in Asian recreational runners during a marathon, which would suggest racing-induced fatigue.

To date, studies in runners and ethnic differences predominantly compare Caucasian (e.g. European and North American) to African (e.g. Ethiopian and Kenyan) runners (Lieberman et al., 2010; Marino et al., 2004; Saltin et al., 1995; Santos-Concejero et al., 2013; Santos-Concejero et al., 2015; Tam et al., 2012; Wishnizer et al., 2013), with limited inclusion of Asian cohorts (Sano et al., 2015; Shu et al., 2015). These studies together highlight differences in physiological (Saltin et al., 1995; Tam et al., 2012), neuromuscular (Sano et al., 2015), anthropometrical (Marino et al., 2004; Shu et al., 2015), footstrike pattern (Lieberman et al., 2010), and running gait (Santos-Concejero et al., 2013; Santos-Concejero et al., 2015) characteristics, and overall indicate that generalisation of research findings from one ethnic group to another is not certain. Road race participation peaked in 2016 worldwide, and continues to grow in Asia despite a global decline in the number of participants since 2016 (Andersen and International Association of Athletics Federations, 2020). It becomes important to include Asian recreational runners in research given their increasing numbers, relative underrepresentation in research, and unique anthropometrics (Hawes et al., 1994; Zarate-Kalfopulos et al., 2012), autonomic responses to exercise (Sun et al., 2016), muscle-tendon unit properties (Sano et al., 2015), and walking gait characteristics (Chen, O'Connor, & Radin, 2003; Ryu et al., 2006; Zhang et al., 2010) compared to other ethnic groups.

Therefore, our aim was to examine self-selected footstrike patterns at two locations of a marathon to examine whether alterations in self-selected footstrike patterns were present in a cohort of predominantly Asian recreational runners. A secondary aim was to compare these data to those reported in two previous investigations (Hanley et al., 2019; Larson et al., 2011). We hypothesised that RFS prevalence would increase from the 10 km to the 39 km mark of the marathon in our cohort. We also expected that this increase in RFS prevalence would be greater than the one sourced from a predominantly North American cohort of recreational marathons (Larson et al., 2011), but smaller than the one sourced from a sample comprised of non-Asian elite marathoners (Hanley et al., 2019) given the corresponding lower and larger prevalence of initial RFS.

Materials and methods

Participants

Three hundred and fifty runners ($N = 350$) were videotaped at the 10 km and 39 km marks (in-race position 51 to 400) of the 2015 Standard Chartered Singapore Marathon on December 6 and classified according to their footstrike pattern. These 350 runners were not necessarily the same at the two locations, as we could not identify individuals from the video recordings.

The nationality of the 51st to 400th finisher was predominantly Asian (71%) according to official race results. The Asian countries most represented included Singapore ($n = 147$, 42%), Japan ($n = 46$, 13%), Malaysia ($n = 14$, 4%), and China ($n = 12$, 3%), but also included Hong Kong, Thailand, Philippines, Nepal, India, Hong Kong, Indonesia, Maldives, Sri Lanka, Vietnam, Taiwan, and Brunei. On this basis, we propose that the runners videotaped at the two locations represented a mostly Asian cohort of recreational runners (finishing time range: 03:12:24 to 04:07:02 and average: 03:47:11 ± 00:14:26). The runners ranked 51st to 400th were predominantly male (87%) and in the 20–29 (17%), 30–39 (39%), 40–49 (34%), or 50–59 (9%) age group categories. The environmental conditions were at 27 °C with 89% humidity at the start time of the race, and 29 °C with 79% humidity 4 h later.

Consistent with our previous research (Patoz et al., 2019), the first 50 runners were not considered because they did not represent a predominantly Asian cohort (62% non-Asian runners) and were considered elite and sub-elite (finishing time range: 02:17:26 to 03:11:30 and average: 02:48:49 ± 00:18:40). The study received approval from our Institutional Review Board (ISNRP: 26/2015).

Procedure

We filmed runners in the sagittal plane using a Sony Handycam (HDR-PJ660, Sony Thai Co., Ltd., Bangkok, Thailand) digital video camera (50 Hz) with an actual focal length of 2.9 to 34.8 mm (35 mm equivalent focal length of 26.8 to 321.6 mm). The camera was mounted atop a 40-cm high tripod, 50 cm from the side of the asphalt road. The two filming locations represented a straight and level portion of the road race to limit the influence of change in elevation on running patterns. The distance between each runner and the camera varied given that the course was about the width of a two-lane road, but was sufficient for footstrike pattern classification. We did not attempt to classify footwear from our video footage.

The three conventional footstrike patterns were defined according to Hasegawa et al. (2007). More explicitly, forefoot strike (FFS) was defined as a footstrike in which the initial contact of the foot with the ground was the forefoot or front half of the sole and with no heel contact. A midfoot strike (MFS) was defined as a footstrike in which the heel and toes contacted the ground simultaneously. A rearfoot strike (RFS) was defined as a footstrike in which the first contact of the foot with the ground was made on the heel or rear third part of the sole and with no midfoot or forefoot contact. For each runner, both right and left footstrikes were classified to enable an additional classification of split strike (SS) representing runners exhibiting left-to-right asymmetries (Larson et al., 2011). For each runner, the most discernible left and right footstrike nearest to the middle of the video image was analysed given that these were closest to the focal point of the camera and less susceptible to camera-related distortional errors. The approach of bilateral classification of footstrike from a single sagittal plane camera was consistent with previous methods (Bertelsen et al., 2013; Larson et al., 2011; Latorre-Román et al., 2015).

From the 350 runners, one right and two left footstrikes at the 10 km mark and eight right and fifteen left footstrikes at the 39 km mark could not be extracted because they were obscured (e.g. behind another runner) or clipped at the edge of the video frame. We removed the data from these runners during our statistical analyses, leading to a final sample size of 347 and 327 runners at the 10 km and 39 km marks, respectively. The footstrike pattern of each runner was determined using a frame-by-frame analysis performed in Apple QuickTime Player. Two researchers with more than five years of experience in footstrike pattern classification completed the analysis independently. In case of uncertainty or disagreement in footstrike pattern classification, a third rater was available for consultation, but not required. The reliability of footstrike pattern classification is almost perfect between raters at higher [agreement >99% at 240 Hz (Kasmer et al., 2013; Murray et al., 2019b)] and lower frame rates [agreement 96% at 30 Hz (Esculier et al., 2018) and 90% at 50 Hz (Latorre-Román et al., 2017)]. These metrics indicate that footstrike data extracted by two independent raters are reliable and generalisable. Visual determination of footstrike pattern from 2D videos has inherent face and content validity, as well as high concurrent validity against 3D motion capture (Esculier et al., 2018; Meyer et al., 2018). Although wearable technologies are now being used to examine changes in biomechanical patterns in race situations (Ruder et al., 2019), the ongoing work to improve their accuracy and validity to determine foostrike pattern (Koska et al., 2018), footstrike angle (Charlton et al., 2019), and foot orientation during running (Falbriard et al., 2020) is laboratory-based. Using wearable technology was not considered given it would have required instrumentation of each runner with a shoe-mounted sensor, which was not practical and economically viable.

Statistical analysis

The prevalence of each footstrike pattern was calculated at both locations from the available population (10 km: $N = 347$ and 39 km: $N = 327$) and compared between locations using a Fisher exact test. The Fisher exact test was selected over the McNemar test because we could not be certain that the runners were the same at the two filming locations. Moreover, we compared the footstrike pattern distributions from our sample to those reported by Larson et al. (2011) and Hanley et al. (2019) using Fisher exact tests given that some of the frequencies were less than five. Expected frequencies were based on those reported by Larson et al. (2011) from the Manchester City Marathon and Hanley et al. (2019) from the World Championships Marathon. As Hanley et al. (2019) did not address asymmetry, we included only symmetrical runners (10 km: $N = 309$ and 39 km: $N = 302$) when contrasting our findings to those from this particular study.

Furthermore, we computed the change in the prevalence (Δ) of each footstrike category (Δ RFS, Δ MFS, Δ FFS, and Δ SS) between the two filming locations as prevalence 39 km minus 10 km. We compared our Δ values to those reported at the 32 km and 10 km marks of the Manchester City Marathon (Larson et al., 2011) using a two-sample test of proportion with corresponding sample sizes set to $N = 327$ and $N = 286$. We also compared our Δ values (excluding Δ SS) to those reported at the 40 km and 8.5 km marks of the World Championships Marathon (Hanley et al., 2019) using a two-sample test of proportion with corresponding sample sizes of $N = 302$ and $N = 148$.

As done previously (Patoz et al., 2019), we investigated differences in the position of individuals in race between the four footstrike patterns at both filming locations using nonparametric Kruskal–Wallis tests to determine whether footstrike was associated with in-race position. Finally, we evaluated Δ RFS, Δ MFS, Δ FFS, and Δ SS as a function of in-race position by grouping runners into groups of 50 consecutive participants, calculating the change in prevalence of each footstrike pattern for each group, and computing Spearman's rank correlation coefficient (r). Statistical analyses were done using customised scripts in R 3.5.0 (The R Foundation for Statistical Computing, Vienna, Austria) and Python 3.6.2 (Python Software Foundation, Beaverton, OR, USA). Level of significance was set at $\alpha \leq 0.05$.

Results

The footstrike pattern of runners at the 10 km and 39 km marks of the Singapore marathon is shown in Table 1. Fisher exact test revealed a significant difference in footstrike pattern distributions between the early and late marks of the marathon ($p < 0.01$). The prevalence of RFS was greater and the prevalence of MFS, FFS, and SS lower at 39 km compared to 10 km (Table 1, Figure 1). Moreover, Fisher exact tests indicated that our observed footstrike pattern distributions at the early and late marks of the Singapore marathon significantly differed from those reported by Larson et al. (2011) (Table 1, $p < 0.01$) and Hanley et al. (2019) (Table 2, early: $p = 0.02$, and late: $p < 0.01$) at both locations. Amongst our 38 runners demonstrating a SS pattern at the 10 km mark, 22 were rearfoot-right and midfoot-left, 14 were rearfoot-left and midfoot-right, 1 was rearfoot-right and forefoot-left, and 1 was rearfoot-left and forefoot-right. Amongst our 25 runners demonstrating a SS pattern at the 39 km mark, 10 were rearfoot-right and midfoot-left, 13 were rearfoot-left and midfoot-right, 1 was rearfoot-left and forefoot-right, and 1 was midfoot-left and forefoot-right.

Figure 1 depicts the change in the prevalence of each footstrike pattern (late minus early) at the

Table 1. Number of footstrike patterns observed in predominantly Asian and non-Asian† recreational runners at the early and late marks of a marathon.

	Early mark		Late mark	
FSP	10 km Singapore $N = 347$	10 km Manchester City† $N = 286$	39 km Singapore $N = 327$	32 km Manchester City† $N = 286$
RFS	226 (65%)	251 (88%)	252 (77%)	266 (93%)
MFS	73 (21%)	9 (3%)	48 (15%)	10 (3%)
FFS	10 (3%)	4 (1%)	2 (1%)	0 (0%)
SS	38 (11%)	22 (8%)	25 (8%)	10 (3%)
	$p < 0.001$*		$p < 0.001$*	

Values are counts and percentages (%). Total percentages do not always add up to 100% because of rounding.
Note. FSP: footstrike pattern, RFS: rearfoot strike, MFS: midfoot strike, FFS: forefoot strike, SS: split strike.
*Significant difference ($\alpha \leq 0.05$) in distribution based on Fisher exact test.
†Reference: Larson et al. (2011).

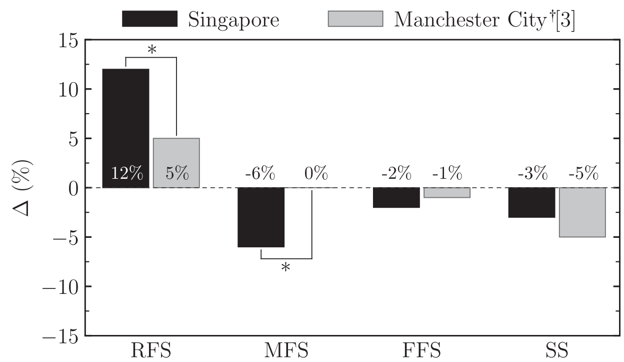

Figure 1. Difference of prevalence of rearfoot strike (RFS), midfoot strike (MFS), forefoot strike (FFS), and split strike (SS) patterns between the late and early marks of a marathon (Δ, Singapore: 39 km and 10 km, and Manchester City: 32 km and 10 km). *Significant difference ($\alpha \leq 0.05$) in prevalence based on two-sample test of proportion. †Reference: Larson et al. (2011).

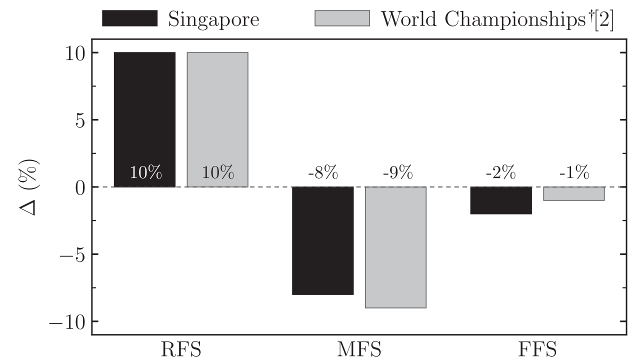

Figure 2. Difference of prevalence of rearfoot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS) patterns between the late and early marks of a marathon (Δ, Singapore: 39 km and 10 km, and World Championships: 40 km and 8.5 km). †Reference: Hanley et al. (2019).

Table 2. Number of footstrike patterns observed in predominantly Asian recreational and non-Asian elite† runners at the early and late marks of a marathon.

	Early mark		Late mark	
FSP	10 km Singapore $N=309$	8.5 km WC† $N=149$	39 km Singapore $N=327$	40 km WC† $N=148$
RFS	226 (73%)	90 (60%)	252 (83%)	104 (70%)
MFS	73 (24%)	53 (36%)	48 (16%)	40 (27%)
FFS	10 (3%)	6 (4%)	2 (1%)	4 (3%)
	$p=0.019$*		$p=0.003$*	

Values are counts and percentages (%).
Note. FSP: footstrike pattern, WC: World Championships, RFS: rearfoot strike, MFS: midfoot strike, FFS: forefoot strike.
*Significant difference ($\alpha \leq 0.05$) in distribution based on Fisher exact test.
†Reference: Hanley et al. (2019).

Singapore marathon alongside those reported for the Manchester City marathon (Larson et al., 2011). Based on the two-sample test of proportion, the Δ RFS ($p<0.01$) and Δ MFS ($p<0.01$) in the Singapore and Manchester City marathons significantly differed, with a larger increase in the prevalence of RFS and decrease in the prevalence of MFS in Singapore. The Δ FFS ($p=0.29$) and Δ SS ($p=0.24$) were similar between marathons. Figure 2 depicts the change in the prevalence of each footstrike pattern from our Singapore marathon data (excluding Δ SS) alongside those reported for the World Championships marathon (Hanley et al., 2019). Two-sample tests of proportion revealed no significant difference for Δ RFS ($p=0.97$), Δ MFS ($p=0.67$), and Δ FFS ($p=0.380$) between marathons.

The Kruskal-Wallis test revealed no significant difference between position of individuals in race and footstrike pattern at both the 10 km ($p=0.60$) and 39 km ($p=0.57$) marks of the Singapore marathon, indicating an equal representation of FFS, MFS, RFS, and SS based on in-race position. Figure 3 depicts the Δ RFS, Δ MFS, Δ FFS, and Δ SS by the in-race position of individuals (groups of 50 runners). There was no significant monotonic evolution in the Δ RFS ($r=0.50$, $p=0.27$), Δ MFS ($r=-0.07$, $p=0.91$), Δ FFS ($r=0.05$, $p=0.91$), and Δ SS ($r=0.00$, $p=1.00$) patterns with the position of individuals in race according to Spearman's rank correlations, indicating an equal change in footstrike patterns based on position.

Discussion

In accordance with our first hypothesis, we observed a greater prevalence of rearfoot strikers at 39 km than 10 km during the Singapore marathon in a cohort of predominantly Asian recreational runners. The 12% increase in the prevalence of RFS in our Asian cohort of recreational runners at the later stage of the marathon was significantly greater than the 5% increase reported to occur in a predominantly North American based cohort, in agreement with our second hypothesis. However, the increase in RFS prevalence was similar between our Asian cohort of recreational runners and a sample comprised of non-Asian elite runners, in contradiction with our expectations. The main reason for the similar increase in RFS prevalence in this latter comparison is likely due to both cohorts demonstrating a lower prevalence of RFS in the earlier marks of the marathons, with a greater proportion of the cohort likely to shift from a

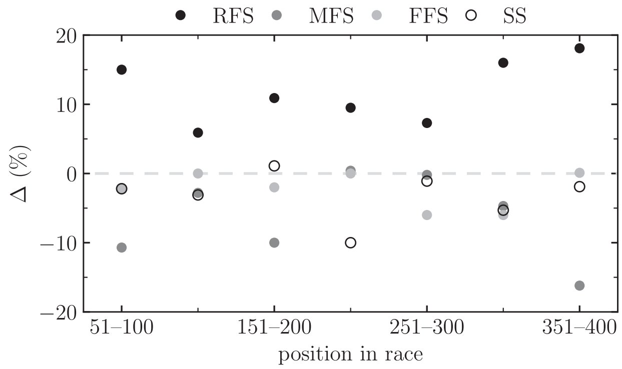

Figure 3. Change in the prevalence (Δ) of rearfoot strike (RFS), midfoot strike (MFS), forefoot strike (FFS), and split strike (SS) patterns between the 39 km and 10 km marks of the Singapore marathon as a function of the in-race position of individuals (groups of 50 runners).

non-RFS to a RFS. Indeed, when runners fatigue, changes from a RFS to non-RFS are seldom, with changes from non-RFS to RFS more prevalent and suggested to reflect an inability to maintain eccentric actions of the plantar flexor muscles (Yong et al., 2014).

In the present study, a significantly greater prevalence of RFS and lower prevalence of MFS, FFS, and SS was observed at the later mark of the marathon compared to the earlier one ($p = 0.003$), which is similar to findings from previous investigations in elite (Hanley et al., 2019) and recreational (Larson et al., 2011) marathon runners, and non-marathoners (Bovalino et al., 2020). Several reasons could explain the alterations in footstrike pattern from non-RFS to RFS. First, non-RFS runners experience a greater eccentric load on the ankle joint and calf muscles (Williams III et al., 2000), with changes in landing technique after a marathon perpetuated as a mechanism compensating neuromuscular fatigue (Peltonen et al., 2012). Indeed, recent electromyographic data (Jewell et al., 2019) support the claims that eccentric actions of the plantar flexor muscles in non-RFS runners are difficult to maintain under race conditions (Yong et al., 2014) and lead to compensatory muscle activation strategies to conserve pace. Switching from a non-RFS to a RFS pattern decreases the activity of the triceps surae muscles and their corresponding plantar flexion torques, delaying the onset of running exhaustion (Jewell et al., 2017; Jewell et al., 2019). Second, runners are more likely to adopt a RFS pattern at slower running speeds (Breine et al., 2014; Cheung et al., 2017). Our runners were probably running slower at 39 km than 10 km given that most recreational runners adopt a positive pacing strategy during a marathon (i.e. decrease in speed as the race progresses) (Nikolaidis & Knechtle, 2018; Santos-Lozano et al., 2014), with the slowest 5-km split being the one from 35 − 40 km (Santos-Lozano et al., 2014). From a metabolic perspective, Gruber et al. (2013) observed a lower relative contribution of carbohydrate oxidation to total energy expenditure when running at moderate speeds (3.5 m/s) with a RFS compared to a FFS pattern, and Miller and Hamill (2015) showed that selecting RFS optimised the metabolic cost. These studies suggested that the RFS pattern might benefit endurance running performance and delay the onset of fatigue compared to non-RFS patterns, explaining the switch towards a RFS pattern.

The proportion of runners exhibiting a RFS pattern in our cohort of mostly Asian recreational runners was 13% greater at both the late and early marks of the marathon compared to the cohort of non-Asian elite runners sampled by Hanley et al. (2019). At the same time, our proportion of RFS was 16 to 23% lower than the one sourced by Larson et al. (2011) from a cohort of North American recreational runners of similar marathon calibre. These observations reinforce that both the elite character of runners and their ethnicity can explain (in part) discrepancies in footstrike pattern distributions and are important characteristics to report in running-related research. The natural running pattern of individuals has been reported to differ between ethnic groups (Hébert-Losier, Lussiana, & Tee, 2016; Pontzer et al., 2014), with some differences likely due to habitual footwear use (Lieberman et al., 2010). The habitual footwear use and shoe preference of Asian runners is unclear, but it has been proposed that many people in Asian countries walk barefooted (Khan & Nataraja Moorthy, 2015; Tharmar et al., 2011), which might predispose them to forefoot running as shown in other habitual unshod populations (Lieberman et al., 2010). Given that footwear use and shoe preference was not examined, it is difficult to speculate further. Nevertheless, worth noting is that the prevalence of the RFS pattern across marathon runners is the greatest across studies regardless of filming location, ethnicity, and performance level.

The ΔRFS (+12%) and ΔMFS (−6%) in our sample of mostly Asian recreational runners significantly differed from the corresponding +5% and 0% changes reported by Larson et al. (2011). The location of our late mark was 7 km later in the race than the one of Larson et al. (2011), which is one plausible explanation other than ethnicity to the differing results. However, a more plausible explanation is the overall lower prevalence of RFS runners in the early mark of the marathon resulting in a greater proportion of MSF and FFS initially that were unable to maintain non-RFS patterns throughout the race. By the same reasoning, one could anticipate a more pronounced shift to the RFS pattern in runners competing at the World Championships (Hanley et al., 2019) than our runners given the 13% lower RFS prevalence in the elite runners at the early mark of the marathon. However, the ΔRFS was similar between the two studies likely due to the elite nature of runners in the former investigation (Hanley et al., 2019), implying a superior training status and affecting their ability to sustain a MFS or FFS pattern throughout the marathon race. These statements align with observations of more pronounced distal to proximal shifts in joint work in recreational than elite runners during a fatiguing run (Sanno et al., 2018), supporting a greater resilience to fatigue in the distal musculature of elite runners.

In contrast to our previous investigation (Patoz et al., 2019), this study observed no significant difference between the in-race position and footstrike pattern prevalence of runners at both the 10 km ($p = 0.60$) and 39 km ($p = 0.57$) marks of the marathon. This result contradicts the observation of Hasegawa et al. (2007) and Kasmer et al. (2013) that faster runners are more likely to MFS, but agree with other studies reporting no significant relationship between footstrike pattern and race performance (Hanley et al., 2019; Larson et al., 2011). The discrepancy in the scientific literature regarding the nature of the relationship between the in-race position and footstrike pattern of individuals might relate to sample size, as pointed out by Kasmer et al. (2013). Indeed, a considerably large cohort of runners might be necessary to define this relationship more clearly, and needs to comprise runners with a wide range of running abilities and varied footstrike patterns. Our previous sample was nearly 3 times greater ($N = 940$ runners), and indicated that FFS tended to be faster, followed by MFS, SS, and RFS when grouped by 100 according to rank (Patoz et al., 2019). It is also possible that the non-significant monotonic evolution in Δ RFS, Δ MFS, Δ FFS, and Δ SS patterns with the in-race position of individuals results from individuals shuffling within groups (i.e. individual race positions were not tracked).

A few limitations to the present study are worth noting. As runners could not be identified based on our sagittal plane video recordings, the intra-individual variation between the early and late marks of the marathon could not be measured. Instead, we reported the prevalence of the different footstrike patterns amongst the 51st to 400th runners passing the early and late marks of the marathon. In addition, our sample size was probably too small to obtain a relation between in-race position and change in footstrike pattern, as highlighted in the above paragraph, and represented various Asian countries, age groups, and genders that present variable anthropometric, physical, and physiological attributes that we did not measure. Furthermore, although a direct comparison with the results reported by Larson et al. (2011) would have been ideal, we could not replicate the 32 km mark due to technical reasons (i.e. access to location and level of the field). Several other factors can influence race results and pacing strategies during a marathon, and therefore footstrike pattern, including course profiles (Hoogkamer et al., 2017; Taboga & Kram, 2019) and environmental conditions (Trubee et al., 2014). It is possible that the hot and humid climate in Singapore led to a greater decline in pace than in London (Hanley et al., 2019) or Manchester (Larson et al., 2011) in our runners, which could have contributed to the increase in RFS in the later part of the Singapore marathon due to slower speeds (Latorre-Román et al., 2015). Finally, we did not consider footwear as a factor in this study. The footwear market and shoe preference of Asian runners could be biased towards more minimal shoes leading to fewer RFS runners compared to more cushioned shoes (Squadrone et al., 2015), as suggests the low prevalence of RFS observed in barefoot (21%) and minimally shod (48%) runners 350 m into the New York City Barefoot Run (Larson, 2014). Finally, we grouped runners into categories based on observable footstrike patterns. Actual foot inclination (Stiffler-

Joachim et al., 2019) or footstrike (Murray et al., 2019b) angles provide a more objective and quantifiable indicator of footstrike pattern, which may be more valid in establishing relationships between footstrike pattern and other biomechanical or performance-related measures.

We observed an increase in RFS runners in the later parts of a marathon potentially resulting from racing-induced fatigue in a predominantly Asian cohort of recreational runners. The increase in the RFS runners was greater in our Asian cohort of recreational runners compared to North American ones, but similar to the increase sourced from non-Asian elite marathoners. The absolute prevalence of RFS remains lower in Asian than North American recreational marathoner at both early and late marks of the race, but greater than non-Asian elite runners. Our findings support our previous conclusions that running research should report ethnicity alongside performance standards given that both can (in part) explain biomechanical differences in running gait. Noteworthy, though, is that numerous factors can influence marathon performance and fatigue that here remained unaccounted for, including age, sex, course profile, footwear, and environmental conditions.

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Disclosure statement

The authors report no conflict of interest.

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