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Journal of Strength and Conditioning Research; Aug 2007; 21, 3; ProQuest Nursing & Allied Health Source
pg. 888

Journal of Strength and Conditioning Research, 2007, 21(3), 888–893
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FOOT STRIKE PATTERNS OF RUNNERS AT THE 15-KM POINT DURING AN ELITE-LEVEL HALF MARATHON

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ABSTRACT. Hasegawa, H., T. Yamauchi, and W.J. Kraemer. Foot strike patterns of runners at 15-km point during an elite-level half marathon. *J. Strength Cond. Res. 21(3):888–893. 2007.*—There are various recommendations by many coaches regarding foot landing techniques in distance running that are meant to improve running performance and prevent injuries. Several studies have investigated the kinematic and kinetic differences between rearfoot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS) patterns at foot landing and their effects on running efficiency on a treadmill and over ground conditions. However, little is known about the actual condition of the foot strike pattern during an actual road race at the elite level of competition. The purpose of the present study was to document actual foot strike patterns during a half marathon in which elite international level runners, including Olympians, compete. Four hundred fifteen runners were filmed by 2 120-Hz video cameras in the height of 0.15 m placed at the 15.0-km point and obtained sagittal foot landing and taking off images for 283 runners. Rearfoot strike was observed in 74.9% of all analyzed runners, MFS in 23.7%, and FFS in 1.4%. The percentage of MFS was higher in the faster runners group, when all runners were ranked and divided into 50 runner groups at the 15.0-km point of the competition. In the top 50, which included up to the 69th place runner in actual order who passed the 15-km point at 45 minutes, 53 second (this speed represents $5.45\ \mathrm{m \cdot s^{-1}}$, or 15 minutes, 17 seconds per 5 km), RFS, MFS, and FFS were 62.0, 36.0, and 2.0%, respectively. Contact time (CT) clearly increased for the slower runners, or the placement order increased ($r = 0.71$, $p \leq 0.05$). The CT for RFS + FFS for every 50 runners group significantly increased with increase of the placement order. The CT for RFS was significantly longer than MFS + FFS (200.0 ± 21.3 vs. 183.0 ± 16 millisecond). Apparent inversion (INV) of the foot at the foot strike was observed in 42% of all runners. The percentage of INV for MFS was higher than for RFS and FFS (62.5, 32.0, and 50%, respectively). The CT with INV for MFS + FFS was significantly shorter than the CT with and without INV for RFS. Furthermore, the CT with INV was significantly shorter than push-off time without INV for RFS. The findings of this study indicate that foot strike patterns are related to running speed. The percentage of RFS increases with the decreasing of the running speed; conversely, the percentage of MFS increases as the running speed increases. A shorter contact time and a higher frequency of inversion at the foot contact might contribute to higher running economy.

KEY WORDS. distance running, locomotion, endurance athletes

INTRODUCTION

Performances in distance running have long been thought to be decided mainly by such physiological factors as maximum oxygen consumption, muscle fiber type, anaerobic threshold, and metabolic adaptations within the muscle (16). However, such biomechanical factors as efficient running mechanics or the ability of the muscles and tendons to store and release elastic energy have recently been considered to be more important as limiting factors to achieving higher level performances in distance running (4, 19). Consequently, coaches and runners have now started to appreciate the importance of improving running technique in distance running. Like all athletic movements, running is a product of integrated movement activities of different joints and body segments. Therefore, it is necessary to investigate each joint and segment of motion and their relationships with entire movement of the body to in order to discuss proper running technique. However, understanding how the runner's foot makes contact with the ground during the take-off and stance phases has special importance because the foot is the only body segment to directly supply force to the ground during the running movement and is one of the most susceptible anatomical structures for injury.

Several authoritative instructions or recommendations exist on how the initial foot contact to the ground should be made and take off from the ground. The most prominent foot contact theory is that of a heel-midfoot to forefoot push-off contact sequence. However, contrary to this, we have recently observed using motion analysis of the telecast of the women's marathon at the 2000 Sydney Olympics that the gold medalist did not use this type of foot contact sequence (23). Interestingly, she made a midfoot contact and never fully extended her knees throughout the running cycle. The knee angle was almost the same as the value at foot strike, and the ankle angle at take off was smaller compared with a typical rearfoot landing–type runner (23). Recently several running experts have advocated that to strike the ground first with the heel is an ineffective technique. It was recommended that landing on the midfoot or forefoot may better enhance the running efficiency and mechanics while reducing injury (5–7, 14, 18, 20, 24). Surprisingly, even though these recommendations contradict conventional heel-toe theory and somewhat differ from each other, little is known about actual runners' foot strike patterns during a real road race competition. Only 1 study has reported that nearly 20% of runners made their initial ground contact with their midfoot and forefoot in a 10-km marathon (12). To our knowledge, no study has investigated the foot strike patterns during elite-level racing competition.

In a prior investigation, foot landing kinematics of 14 elite runners and 8 good runners was studied, and ankle angles at foot strike were 90° and 84°, respectively (3). These values are similar to our previous study (23). However, this study was done on a treadmill, not on an over ground during a race. Acquisition of the data for the actual foot landing pattern of elite runners during the competitive race would provide vital information on running technique.

The purpose of the present study was to determine the actual foot strike patterns and characteristics during a competitive half marathon in which international elite-level runners, including Olympians, participated with the intent of recording times needed for qualification.

METHODS

Experimental Approach to the Problem

We studied the 47th Sapporo International Half Marathon combined with the Japanese elimination race for 13th World Championship Half Marathon. The study was approved by the university ethics committee. The race was held on July 4, 2004, in Sapporo, Japan. Starting time was 13:32, and the weather was cloudy with an ambient temperature of 20.6° C and a humidity of 73% at starting time.

Data Collection. Two digital video cameras (JVC GR-VDL9800; Victor Company of Japan, Ltd., Tokyo, Japan) were placed on the edge of the road at a height of 0.15 m with tripods 15.0 m ahead of the 15.0-km time point on the race course. We chose the 15.0-km point because this part of the course was flat and the runners at this time point would be spread out, allowing more effective data collection. The cameras were placed at right angles to the running course and approximately 1.0 m apart from each other so that a sagittal image of the entire stance phase (right before foot strike to taking the toe off) of either foot of a runner could be obtained by at least 1 camera. The shutter speed was $250 \cdot s^{-1}$, and the filming rate was 120 Hz. Another camera (Panasonic NV-GS70K; Matsushita Electric Industrial Co., Ltd., Tokyo, Japan) was placed at a height of 1.5 m diagonally in front of the runners to take the cross-shots of the entire figures of the runners for identification purposes. The shutter speed of this camera was $250 \cdot s^{-1}$, and the filming rate was 60 Hz.

Data Analyses. All video images of foot landing and entire figures of all runners who passed through the filming point were captured on the hard drive of a Macintosh Power Book G4 (Apple Computer) and later analyzed using the digital video analysis system Sorts Code Pro version 5.0 (SportsTech, Sydney, Australia). Individual profiles of all runners' feet were identified after a detailed matching process involving the entire video figure images linked to their number cards and their socks and footwear along with the official race sequence at 15 km.

Foot strikes were classified into 3 patterns: rearfoot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS). Rearfoot strike was defined as a foot strike in which the point of the first contact of the foot with the ground was the heel or rear third part of the sole only and in which the midfoot or forefoot portion did not have any contact at foot strike. Midfoot strike was defined as a foot strike in which the point of the first contact of the foot with the ground was not only the rear third of the sole but the midfoot or entire part of the sole. Forefoot strike was defined as a foot strike in which the point of the first contact of the foot with a ground was the forefoot or front half of the sole and in which the heel did not have any contact at the foot strike (Figure 1).

Contact time (CT) was measured and calculated from the filming rate (1 frame = 120 Hz ≈ 0.0083 sec) and divided into 2 phases for the RFS. Time from the initial heel contact with the ground to any front half part of the foot contact with the ground was defined as flat-foot time (FFT), and the time from the FFT to the take off was defined as push-off time (POT).

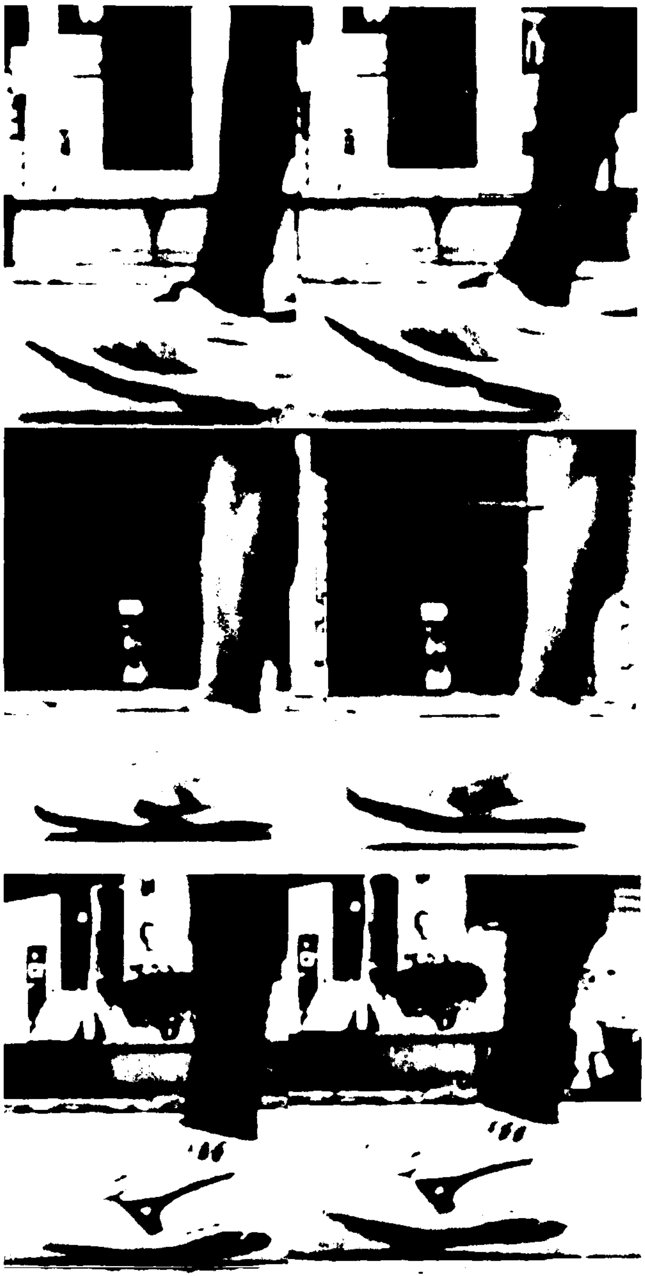

FIGURE 1. Sample picture of foot strike patterns. Rearfoot strike (RFS) (men: third place at 15-km point), midfoot strike (MFS) (women: first place at 15-km point), and forefoot strike (FFS) (21st place at 15-km point) from top to down. Time interval from right to left is 1/120 seconds.

A foot strike pattern in which the area of the first contact of the foot with the ground was the lateral edge of the foot with the inversion angle in the frontal plane was defined as inversion (INV). With or without INV at foot strike was discriminated regardless of foot strike patterns.

Subjects

There were 415 runners (362 men and 53 women) who passed through 15 km time point on the race course.

Statistical Analyses

Because of the lack of a normal distribution in CT value for the 50 runners ranging from fast to slow for every rank order group, the Kruskal-Wallis test was conducted

TABLE 1. Number and percentage of foot strike patterns at the 15-km point during the 2004 Sapporo International Half Marathon.

Foot strike patterns	Men		Women		Total	
RFS	184	74.2%	28	80.0%	212	74.9%
MFS	61	25.6%	6	17.1%	67	23.7%
FFS	3	0.2%	1	2.9%	4	1.4%
Total	248	100.0%	35	100.0%	283	100.0%

RFS = rearfoot strike; MFS = midfoot strike; FFS = forefoot strike.

to analyze the differences between the groups. When a significant *F* value was found, the Bonferroni post hoc test was employed to identify specific differences between the average CT. Because the analysis revealed only 4 FFS, the FFS CT were included into the MFS CT for subsequent analyses. Mann-Whitney's U-test for independent samples was used to detect the difference of average CT between RFS and MFS + FFS for every order group. Unpaired Student's *t*-test was applied to detect the difference of average CT between all RFS and all MFS + FFS. To examine the difference between CT with and without INV for RFS and MFS + FFS and POT with and without INV, 1-way factorial analysis of variance was used. When a significant *F* value was found, a Tukey-Kramer post hoc test was employed make a pair-wise comparison.

Orders at the 15 km-point are on an ordinal scale, but CT is an interval scale. Therefore, Pearson products correlation was used to analyze the relationship between order and CT. All statistical analyses were conducted using SPSS version 10.0 for Windows (SPSS Inc., Chicago, IL), and the significance level was set at $p \leq 0.05$.

RESULTS

Number of Runners Analyzed

The total number of the runners who passed though the 15-km filming point was 415 (362 men and 53 women). Two hundred eight-three runners (68.3%) were able to be distinguished by their foot strike pattern (248 men and 35 women): 145 were right foot and 133 were left foot. It was not possible to distinguish the laterality in 5 feet. We could not differentiate the foot strike pattern for a runner if it was overlapping with another runner's or if the runner passed too close to the cameras. The CT of 261 runners (63% of all runners) was obtained.

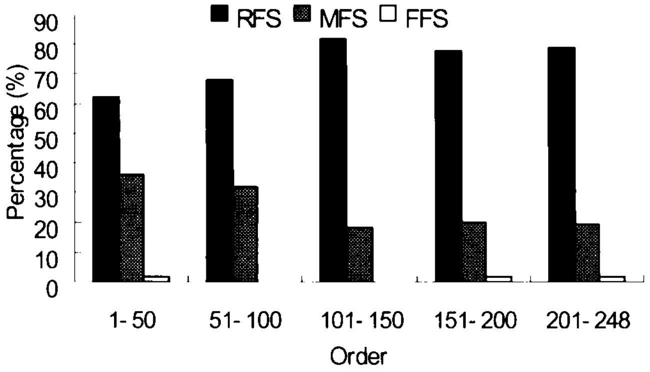

FIGURE 2. Percentages of foot strike patterns of the men runners at the 15-km point during a half marathon.

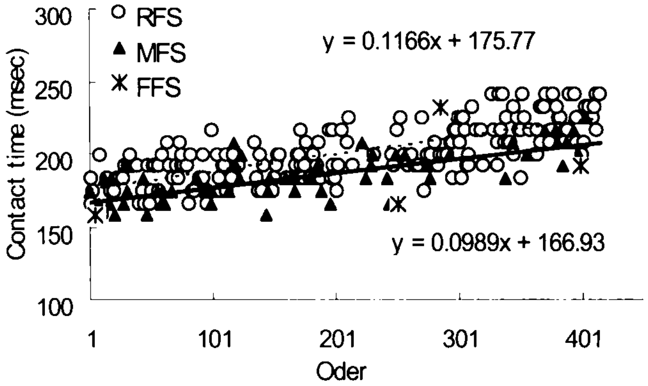

FIGURE 3. Relationship between contact time and race order at the 15-km point. Dashed line shows regression equation for RFS ($n = 197$, $r = 0.80$, $p \leq 0.05$). Solid line shows regression equation for MFS + FFS ($n = 64$, $r = 0.71$, $p \leq 0.05$).

Foot Strike Patterns

The number and percentage of foot strike patterns are presented in Table 1; 74.9% of all analyzed runners were RFS, 23.7% were MFS, and 1.4% were FFS.

The percentages of foot strike pattern for the men (ranked from high to low in 5 groups) at the 15-km point are presented in Figure 2. The RFS, MFS, and FFS were 62.0, 36.0, and 2.0%, respectively, for the top 50 runners; 68.0, 32.0, and 0%, respectively, for the 50 to 100th runners; 82, 18.0, and 0%, respectively, for the 101st to 150th runners; 78.0, 20.0, and 2%, respectively, for the 151st to 200th runners; and 79.0, 19.0, and 2%, respectively, for the last 48 runners. The women were divided into 5 groups in the same manner as the men, and the percentage of RFS, MFS, and FFS were 43.0, 43.0, and 14.0%, respectively, for the first 7 runners; 86.0, 14.0, and 0.0%, respectively, for the second group; 100.0, 0.0, and 0.0%, respectively, for the third group; and 86.0, 14.0, and 0.0%, respectively, for the following 2 groups.

Ground Contact Time

The relationship between CT and the order for all runners is plotted in Figure 3. The CT as a whole clearly tended to increase as the order increased ($r = 0.71$). The correlation coefficient of CT and order for RFS and MFS + FFS were 0.80 and 0.71, respectively. The CT in MFS and FFS tended to be shorter than in RFS except in a

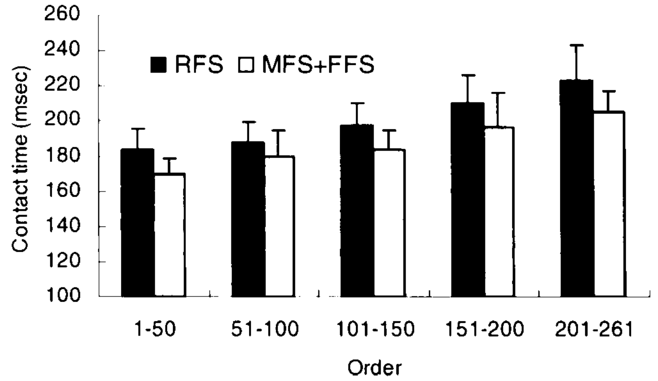

FIGURE 4. Contact time for RFS and for MFS + FFS for every 50 runners from the high order to low order (the last group consists of 61 runners). Significant differences between every order group both in RFS and MFS + FFS and between RFS and MFS + FFS in every order ($p \leq 0.05$).

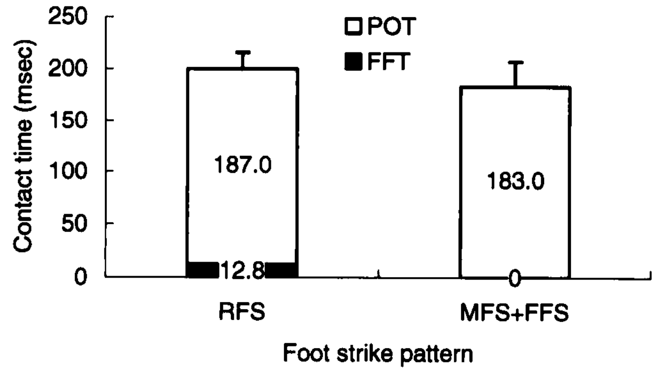

Figure 5. The average contact time for RFS and MFS + FFS. POT: push-off time, FFT: foot flat time. Significant difference between RFS and MFS + FFS ($p \leq 0.05$).

few isolated examples. The CT for RFS and for MFS + FFS in every 50 runners by the order at the 15.0-km point from high to low (the last group consists of 61 runners) are presented in Figure 4. The average CT for each group significantly increased from the high to low order (1–50 < 51–100 < 101–150 < 151–200 < 201–261). The CT for RFS was significantly longer than MFS + FFS in all order groups. The average CT for all RFS was significantly longer than all MFS + FFS (199.8 ± 16.0 vs. 183.0 ± 21.3 millisecond). The average FFT and POT for RFS were 12.8 ± 5.1 and 187.4 ± 20.4 millisecond, respectively (Figure 5).

Inversion of the Foot at Foot Strike

Apparent INV at the foot strike was observed in 42% of all runners. The INV for RFS, MFS, and FFS was 32.0, 62.5, and 50.0%, respectively (Figure 6). The CT and POT with and without INV for RFS and MFS + FFS are presented in Figure 7. All variables with INV were significantly shorter than without INV. The CT without INV for MFS + FFS was significantly shorter than CT without INV for RFS but did not differ from CT with INV for RFS. The CT with INV for MFS + FFS was significantly shorter than the CT with and without INV for RFS and was furthermore significantly shorter than POT without INV for RFS.

DISCUSSION

This is the first study to elucidate the actual foot landing of all runners during the half-marathon race event in which elite level runners competed for an official title.

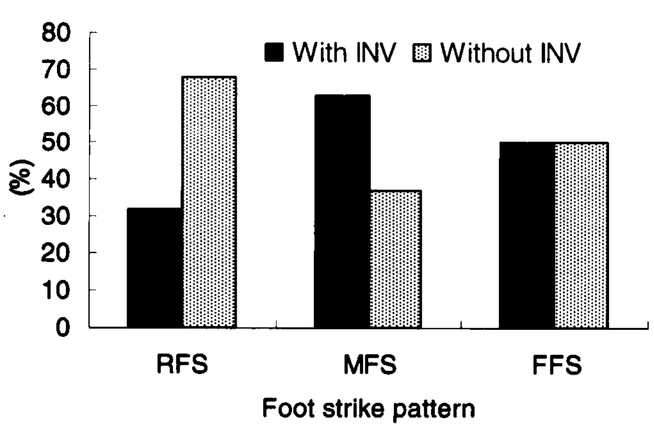

Figure 6. Percentage of with inversion and without inversion (INV) at foot landing for RFS, MFS, and FFS.

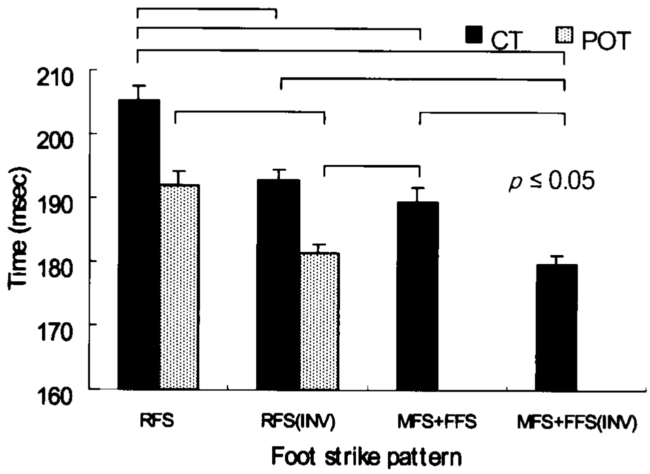

Figure 7. Contact time (CT) for RFS and MFS + FFS and push-off time (POT) for RFS with and without inversion.

The results of the present study showed that not all runners strike their foot to the ground from the heel during the half marathon. In fact, 23.7% were shown to be MFS and 1.4% were classified as FFS. These results support previous research that reported that nearly 20% of runners were MFS and FFS in the 10-km marathon (12) and showed that about 25% runners are MFS in a half marathon. These data clearly demonstrate that not all runners, including elite-level runners, use a heel-first strike pattern that has for so long been the recommended technique. Unfortunately, the heel-first RFS running technique has long been recommended by many coaches, but with the times in long-distance races getting faster and faster, a sprint technique in lower body locomotion is now being adopted, which may be less stressful to the lower limbs and knees.

The foot strike patterns were analyzed for every 50 runners according to the race result order from fast runners to slow runners at the15-km point for men. The analyzed top 50 group included up to the 69th place runner in actual order, who passed the 15-km point at 45 minutes, 53 seconds. This speed represented 5.45 m·s^{-1}, or 15 minutes, 17 seconds per 5 km. The second 50 included the actual 150th-place runner, who passed the 15-km point at 47 minutes, 36 seconds, representing 5.25 m·s^{-1}, or 15 minutes, 52 seconds per 5 km. The third group included up to the actual 242nd place runner, who passed the 15-km point at 50 minutes, 51 seconds, representing 4.91 m·s^{-1}, or 16 minutes, 57 seconds per 5 km. From these records, one could consider the top group as a strictly elite level of competitors and the second group as elite in a broader sense of the term.

Interestingly, the percentage of MFS was the highest at 36.0% for the top 50 runners, but the percentage decreased at 32.0% for the second 50 runners and decreased again at 18.0, 20.0, and 19%, for the third, fourth, and fifth groups, respectively. Our findings indicate that the faster the runners are, the more likely the runners adopt an MFS pattern when they run. This tendency was applicable to women runners as well.

It was not surprising that CT lengthened gradually with increasing order at the 15-km point (Figure 3). In general, running velocities are decided by step length × step frequency. That the step frequency is strongly affected by the CT in the speed range observed in the present study (i.e., about 4.00–5.45 m·s^{-1}) is well established.

Kyröläinen et al. found that CT shortened and step frequency increased with increasing running speed from 3.25 to 6.25 m·s^{-1} in elite middle-distance runners (13). Williams and Cavanagh also reported that CT decreased with increasing running speed at 4.32 to 5.44 m·s^{-1} for a 10-km run (26). Our results clearly support and demonstrate the shortening of CT with increasing running speed in the real half-marathon situation.

More important to note in our results regarding to CT is that the individual CT in MFS + FFS runners tended to be shorter than in RFS all over the rank order except in a few isolated examples, and the average CT of MFS + FFS runners for each 50 runners according to the order at the 15-km point were significantly shorter than that of RFS runners for the every order group (Figure 4). Moreover, average CT for all MFS + FFS runners were also significantly shorter than for RFS (Figure 5). These findings suggest that the faster runners have the shorter CT and that the percentage of MFS + FFS runners who have shorter CT than RFS runners increases in the faster runner groups.

The average CT for MFS was 17.0 milliseconds shorter than for RFS (183.0 vs. 200.0 milliseconds). This value is close to FFT (12.8 milliseconds) in RFS runners but slightly longer. Williams and Cavanagh reported that the RFS runners have longer CT, more extended leg at the foot strike, and a longer time of maximum knee flexion during the support phase than do MFS and FFS runners (25). These results indicate that the longer CT in RFS than MFS + FFS in our data might be due to not only the extra time for FFT but also the time needed for flexion and extension of knee joints. Ardigo et al. (1) examined deceleration time and acceleration time for RFS and FFS and reported that deceleration time was similar for RFS and FFS but CT and acceleration times were longer for RFS. These data indicate that RFS runners landing their foot to the ground from the heel may need a longer time of muscle activation to accelerate their body than MFS or FFS runners running at the same speed as RFS runners in our data.

Running economy (RE), defined as a steady-state oxygen requirement for a given submaximal running velocity, has been shown to be one of the most important factors to improve distance running performance (15, 19). In addition to the previous findings that heavy strength/power training may generally improve RE of distance runners (10, 11), shortening of CT by explosive-type strength training was revealed to be significantly related to improving RE (17). Spurrs et al. (21) did not measure CT but found that musculotendinous stiffness and RE were improved by 6 weeks of plyometric training, a significant correlation. Kyröläinen et al. (13) failed to find a significant correlation between CT and RE but found a shortening of CT and an increase of joint power associated with an increase of stiffness of ankle with increasing running speed. An examination of mechanical work and oxygen uptake for RFS and FFS on a running treadmill revealed that a higher storage and release of energy with a shorter CT took place in the FFS than RFS (1). Because runners with less RE posses a more compliant running style during ground contact (8) and exhibit greater vertical oscillation (26) and greater total vertical impulse (9), this running style may place greater force demands on extensor musculature and as a result may require greater overall aerobic energy demands. One study has examined plantar pressure in the barefoot condition (27) and revealed that flatter foot placement in barefoot running correlates with shorter CT, lower heel pressure, and significantly higher leg stiffness during the stance phase compared with a shod condition.

Although there is no direct evidence indicating that MFS and FFS are related to good RE, putting together these previous findings and our results demonstrating the shorter CT for MFS + FFS than RFS and the higher percentage of MFS in the faster runners, MFS and FFS might be one of the associated factors for good RE to achieve higher performance in distance running. Nevertheless, a study indicated that RFS conversely showed smaller vertical oscillation, longer CT, more extended lower leg at foot strike, and yet higher RE than MFS and FFS (26). The authors suggested that extreme RFS tends to rely on foot wear and skeletal structure to take the load, reducing necessary muscle force, and are more economical. This point seems to contradict our result that a percentage of the runners with shorter CT and MFS were higher ranked in the faster runner group. More studies combined with performance result and biomechanical factors are necessary.

Apparently a higher percentage of runners showed the INV at the foot strike for MFS and FFS than RFS in our data (Figure 6). Our findings obtained from the data during the actual race with a larger number of runners clearly support the previous findings obtained from the experimental research performed in laboratories. In those studies, FFS runners contacted the ground in a greater degree of INV compared with RFS (22, 25). Because greater degrees of plantar flexion at foot landing have also been observed in FFS compared with RFS, a greater degree of INV in FFS appears to be mechanically linked with plantar flexion of the ankle (4, 25). A greater INV at the foot landing to the ground resulted in a greater eversion excursion and a greater eversion velocity in FFS (22, 25). In the present study, the average CT in all MFS + FFT was slightly shorter than the average POT in all RFS, but it was not significant. However, CT with INV was significantly shorter than CT without INV both for RFS and for MFS + FFS. For RFS, POT with INV was also significantly shorter than that without INV. Surprisingly, the CT with INV for MFS + FFS was again significantly shorter than POT without INV for RFS. We defined POT for RFS in this study as the time from any front half part of the foot contact with the ground after the heel contact to take off. The finding that the POT without INV for RFS was longer than the entire CT for MFS + FFS with INV appears to support greater eversion velocity for FFS compared with RFS without INV in previous studies (22, 25). Moreover, INV at foot landing for MFS and FFS could possibly have some mechanism to shorten CT that might be related to improving RE and running performance. According to Stackhouse et al. (22), the INV moment and INV work during the first half of the stance phase are indicative of eccentric control of eversion. The MFS and FFS runners might preliminarily control eccentrically their greater eversion excursions and velocities attained during a push-off phase of the stance. Although the mechanism remains to be elucidated and is beyond the discussion of this study, the stance phase in MFS and FFS with INV has a potentially different kinetic or kinematic advantage from RFS without INV to improve RE and running performance.

Williams et al. (25) reported that peak power absorption and eccentric work at the ankle were greater in FFS compared with the RFS. In another study (2) it was also demonstrated that higher peak power absorption and eccentric work at the ankle in the subjects instructed to contact with midfoot and avoid contact of the heel with the ground. This may overwork the lower leg muscle group and increase the risk for injury, such as Achilles tendonitis. In fact, Williams et al. (25) reported that original RFS subjects felt muscle fatigue as early as they started to convert to FFS in their experiment and had a severe delayed onset of muscle soreness for several days. Conversely, FFS and Pose demonstrated lower power absorption and negative work at the knee (2, 25), which may diminish demands of the leg extensor. It is not clear how RFS, MFS, and FFS defined and discriminated in this study exactly correspond to those including Pose defined in many previous studies, and running speed, runners' experience, running distance, and running frequency are quite different for each runner. However, these findings and our results suggest that there might be a different distribution of concentric and eccentric muscle work between knee and ankle joints and also foot joints with different foot landing techniques. Once a runner tries to change his or her foot landing technique, redistribution of the muscle work between knee, ankle, and foot joints might occur. Preparation to reduce the risk for specific running techniques as it relates to injuries should be taken. Most commercial running shoes have been manufactured on the premise of RFS. Development of running shoes supporting the special needs of certain populations of MFS appears to be necessary.

In conclusion, the percentages of the 3 foot strike patterns during a real elite-level half marathon were elucidated in this study. The percentage of RFS increased with a decreasing of the running speed; conversely, the percentage of MFS increased as the running speed increased. A shorter CT and a higher frequency of inversion tendency at the foot contact, which might contribute to higher running economy, in MFS appeared to be a suggested reason for the high percentage of MFS in the topside group in this investigated elite-level half marathon. Future studies should include the knee and hip joint to elucidate overall leg kinematics during races of high-level distance runners and joggers.

Practical Applications

Foot landing from the heel is not always a good strategy for all runners. About 25% of the runners did not use the technique of landing heel first when they ran a half marathon. In the top 50 runners, including Olympians, at a pace of 15 minutes, 17 seconds per 5 km, 36% were midfoot strikers; in the following 50 runners group running faster than 15 minutes, 52 seconds per 5 km, 32% were midfoot strikers. These results clearly indicate that the percentage of the runners who do not contact heel first increase with running speed. The faster runners use the more midfoot strike and do not land on their heels first. Although a detailed mechanism has not yet been elucidated, the landing technique without heel contact first would appear to have some sort of merit to increase running economy. Shorter contact time with inversion at the foot contact might be one of the examples to use elastic energy and stiffness of the leg muscle to increase running economy. Specific conditioning for improving performance and preventing injuries is needed for the population of runners who use the running technique of not hitting the heel first to the ground. Explosive-type strength training, such as plyometric and tolerance for eccentric loading for the lower leg, is suggested for this purpose.

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Acknowledgments

This study was supported in part by a grant from New Balance Japan Co., Ltd., Tokyo, Japan, through Ryukoku University.

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