Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns

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ABSTRACT

It continues to be argued that a forefoot (FF) strike pattern during running is more economical than a rearfoot (RF) pattern; however, previous studies using one habitual footstrike group have found no difference in running economy between footstrike patterns. We aimed to conduct a more extensive study by including both habitual RF and FF runners. The purposes of this study were to determine if there were differences in running economy between these groups and if running economy would change when they ran with the alternative footstrike pattern. Nineteen habitual RF and 18 habitual FF runners performed the RF and FF patterns on a treadmill at 3.0, 3.5, and 4.0 m•s⁻¹. Steady-state rates of oxygen consumption (\(\dot{V}O_2\), ml•kg⁻¹•min⁻¹) and carbohydrate contribution to total energy expenditure (%CHO) were determined by indirect calorimetry for each footstrike pattern and speed condition. A mixed-model ANOVA was used to assess the differences in each variable between groups and footstrike patterns (\(\alpha=0.05\)). No differences in \(\dot{V}O_2\) or %CHO were detected between groups when running with their habitual footstrike pattern. The RF pattern resulted in lower \(\dot{V}O_2\) and %CHO compared to the FF pattern at the slow and medium speeds in the RF group (\(P<0.05\)) but not in the FF group (\(P>0.05\)). At the fast speed, a significant pattern main effect indicated that \(\dot{V}O_2\) was greater with the FF pattern than the RF pattern (\(P<0.05\)) but %CHO was not different (\(P>0.05\)). The results suggest that the FF pattern is not more economical than the RF pattern.

KEY WORDS: running economy, footstrike patterns, sub-maximal oxygen consumption, running performance
INTRODUCTION

Humans are capable of running with different footstrike patterns which are typically defined by the location of the center of pressure relative to the length of the foot at initial ground contact (6) or visually, by the part of the foot that is seen to make initial contact with the ground. These patterns have been described in the literature as 1) rearfoot (RF): strike index of 0–33% and making initial contact with the heel; 2) midfoot (MF): strike index of 34–66% and making initial contact with the whole foot at nearly the same time; and 3) forefoot (FF): strike index of 67–100% and making initial contact with the ball of the foot (1, 6, 11, 17, 21, 32). Although approximately 75% of all runners make initial contact with the heel first (RF pattern), more top finishers of short, middle, and long distance events run by making initial contact with the anterior portion of their foot (FF or MF pattern, described together as FF pattern) (17, 21, 24, 32). The FF pattern has been suggested to enhance running economy compared to the RF pattern in both scientific literature and popular media (17, 20, 25), which has lead to recommendations that RF runners should change to a FF pattern (17, 34). Not only is there no empirical evidence to support these claims, no differences in running economy between RF and FF strike patterns has been detected in three previous studies (2, 11, 34).

Running economy (i.e. sub-maximal, steady state rate of oxygen consumption) is dependent on numerous biomechanical, physiological, and anthropometric factors (12, 29). An improvement in running economy will be accomplished if some physiological or biomechanical change results in a reduction of sub-maximal oxygen consumption over a range of running speeds (42). Several biomechanical features have been identified in more economical runners such as longer ground contact time, lower vertical ground reaction force active and impact peaks, decreased vertical oscillation of the center of mass, greater trunk flexion angle, greater maximum
knee flexion during the stance phase, a more extended leg at touchdown, and reduced plantar flexion joint moments (18, 43). Interestingly, many of these features are characteristic of those runners who use an RF pattern (43).

Running with the FF strike pattern has been endorsed as a way to improve performance despite the mechanics of RF running having been associated with better running economy (18, 43) and there being no difference in rates of oxygen consumption between RF and FF patterns observed in previous studies (2, 11, 34). Additionally, these previous studies comparing running economy between footstrike patterns were limited by small sample sizes, and did not include both habitual RF and habitual FF runners. The small sample sizes may contribute to the difficulty in detecting significant differences in economy across several speeds and between footstrike patterns. While most studies have focused on running economy, examining other metabolic variables, such as rate of carbohydrate oxidation, may be meaningful because carbohydrate availability is one of the limiting factors in endurance exercise (10).

Comparing both habitual RF and habitual FF runners performing their self-selected footstrike pattern could eliminate the potential for artificially high oxygen consumption as a result of performing a novel task. Habitual FF runners, by nature, have already adapted to the mechanical and physiological demands of the task and thus no habituation period is needed. Including both groups of runners also has a number of advantages over training habitual RF runners to use the FF pattern. For example, training studies require adequate adherence to the training protocol, which would be difficult to guarantee without constant monitoring. Therefore, the first purpose of this study was to determine if there were differences in running economy between footstrike patterns in both habitual RF and habitual FF runners performing their preferred footstrike pattern. Given the evidence suggesting that gait mechanics used in RF
running are associated with better economy than the gait mechanics utilized in FF running (18, 43), the first hypothesis was that the running economy would be better in habitual RF runners performing the RF pattern compared to habitual FF runners performing the FF pattern. If the RF strike pattern is indeed more economical than the FF strike pattern, as the biomechanical evidence would suggest, then both habitual RF and habitual FF runners should be more economical when performing the RF strike pattern rather than the FF strike pattern. However, this prediction is contrary both to the empirical evidence suggesting no difference in economy between footstrike patterns, and the suggestions made by advocates of FF running that habitual RF runners should change to the FF pattern to improve running economy. One way to resolve this confusion would be to evaluate habitual RF and habitual FF runners performing both footstrike patterns. Therefore, the second purpose was to determine if there were any changes in running economy when habitual RF and FF runners performed the alternative strike pattern. It was hypothesized that running economy would not improve when habitual RF runners perform the FF running pattern; while running economy would improve when habitual FF runners perform the RF running pattern.

METHODS

Participants. Thirty-seven runners participated in this study after reading and completing the informed consent document and questionnaires approved by the University of Massachusetts Amherst Institutional Review Board. All participants were experienced runners completing an average of 46.2 ± 27.4 km per week with an average preferred running speed of approximately 3.7 ± 0.3 m•s⁻¹ for long running bouts. Participants consisted of healthy individuals, with no history of cardiovascular or neurological disorders and had not sustained an injury to the lower
extremity or back within the past year. Habitual footstrike pattern of each participant was
determined using a combination of the strike index (SI) (6), the characteristics of the vertical
ground reaction force (GRF), and the sagittal plane ankle angle at touch-down (16). Vertical
GRF and center of pressure were recorded at 1200 Hz and three-dimensional ankle angles were
recorded at 240 Hz while each participant performed five over-ground running trials at their
preferred running speed. Participants were classified as RF runners if the strike index was
between 0–33%, the ankle angle at initial contact was above 5 degrees of dorsiflexion, and the
vertical GRF exhibited the presence of a distinctive impact peak. Participants were classified as
MF runners if the strike index was between 34–66%, the ankle angle at initial contact was
between 5 degrees of dorsiflexion to 5 degrees of plantar flexion, and vertical GRF exhibited a
blunted impact peak. Participants were classified as FF runners if the strike index was greater
than 66%, the ankle angle at initial contact was greater than 5 degrees of plantar flexion, and the
vertical impact peak was absent. Given that approximately 2% of recreational and elite runners
are classified as FF runners and 24% as MF runners at long-distance running speeds (17), we
combined MF and FF runners into one group to ensure sufficient statistical power (referred to as
the FF group). The FF group was made up of fourteen participants classified as MF runners and
four participants classified as FF (Table 1). Nineteen participants were classified into the RF
group (Table 1).

*Equipment.* The volume and content of gases expired by each participant while running
on a motorized treadmill was measured by indirect calorimetry using a metabolic cart (TrueOne,
ParvoMedics, Sandy, UT, USA). The volume of gas exchange was used to calculate the gross
rate of oxygen consumption. Motion capture data were used to monitor the footstrike pattern
used by the participants during each condition. Calibration and tracking reflective markers were
placed on the right leg and foot according to previously published standards (28). Three-dimensional motion was recorded by an eight-camera Oqus 3-Series optical motion capture system (Qualisys, Inc., Gothenberg, Sweden) sampling at 240 Hz. A treadmill (Star Trac, Unisen, Inc., Irvine, CA, USA) was placed in the center of the motion capture collection volume. Each participant wore a neutral racing flat running shoe (RC 550, New Balance, Brighton, MA, USA) provided by the laboratory to standardize any effects of cushioning or other footwear properties.

**Experimental Protocol.** Each participant arrived at the laboratory having fasted for at least three hours and had refrained from exercise before the data collection. Each participant was allowed to warm-up on the treadmill for several minutes as needed and to practice each footstrike pattern at running speeds of 3.0, 3.5, and 4.0 m•s\(^{-1}\), which are subsequently referred to as the slow, medium, and fast speeds, respectively. Participants were allowed to adjust their running speeds by no more than 5% if necessary to allow them to run more comfortably. If a participant required an adjustment in the slow, medium, or fast speed, the adjusted speed was used for both footstrike conditions for that participant. None of the participants chose to have the speed adjusted at the slow speed. A small number of participants chose to have the speed adjusted at the medium (n=3) and fast (n=8) speeds. The average medium and fast speeds were the same for both groups and averaged 3.5±0.1 m•s\(^{-1}\) and 3.9±0.1 m•s\(^{-1}\), respectively. The participant was then prepared for data collection by securing the reflective markers onto the right leg and foot. Each participant began the data collection protocol by standing quietly for 10 minutes on the treadmill to record baseline oxygen consumption. The participant then performed each footstrike pattern within one speed condition before continuing to the next speed condition. The order of the footstrike patterns and running speeds was randomized and counterbalanced.
between groups. Each participant ran for a minimum of five minutes during each speed and footstrike pattern condition or until two minutes of steady state oxygen consumption was recorded. Steady state was defined as less than a 10% change in oxygen consumption over a two minute period (40). Each participant rested until the minute-volume of expired air returned to within 0.02 L•min⁻¹ of the baseline value.

In establishing the baseline, the first five minutes of recorded oxygen consumption tended to have high variability as the participants became accustomed to breathing with the mouthpiece. Therefore, the rate of oxygen consumption (\( \dot{V}O_2 \)) averaged over the final five minutes of the baseline period was used as the resting \( \dot{V}O_2 \) value. This value was subtracted from the gross \( \dot{V}O_2 \) measured during the last two minutes of each running condition to determine net mass-specific rate of oxygen consumption (ml•kg⁻¹•min⁻¹).

Absolute rate of carbohydrate (CHO) oxidation in g•min⁻¹ was determined from the rates of carbon dioxide expired (\( \dot{V}CO_2 \)) and oxygen consumed by (27):

\[
CHO = 4.58 \dot{V}CO_2 - 3.23 \dot{V}O_2
\]  (1).

where 4.58 and 3.23 are grams of carbohydrate per liter of carbon dioxide and oxygen, respectively. Because the absolute rate of (CHO) oxidation will vary directly with total energy expended, the relative contribution of carbohydrate to total energy expenditure (%CHO) was calculated by converting CHO in g•min⁻¹ to kcal•min⁻¹ (g * 4 kcal•g⁻¹) and then scaling to the rate of energy expenditure in kcal•min⁻¹.

The three-dimensional positions of the markers placed on the foot and leg were tracked using Qualisys Track Manager software (Qualisys, Inc., Gothenberg, Sweden) then exported to
Visual 3D software (C-Motion, Inc, Rockville, MD, USA). The ankle joint angle at touchdown (AATD) and during the stance phase was calculated using methods published elsewhere (9, 44). Stride frequency (SF) was calculated by first determining the average time in seconds between each initial contact of the right foot on the treadmill for 10 strides during the 15 s capture period. SF was then determined by dividing 60 s•min⁻¹ by this average stride time value. Stride length (SL) was calculated by dividing the treadmill belt speed by SF. Contact time (CT) was calculated as the average time between initial treadmill contact and toe-off of the right foot.

Statistics. The variables that were assessed included the AATD, SL, SF, CT, \( \dot{V}O_2 \), and %CHO. Each variable was subjected to a mixed model ANOVA with footstrike pattern and group as fixed variables and participant nested within group as a random variable. The differences between footstrike patterns (RF and FF) and between groups (habitual RF and habitual FF) and the interaction of footstrike pattern and group were assessed with a significance level of \( \alpha = 0.05 \). A one-way ANOVA was used to determine the differences in running economy variables between groups at baseline and each speed when performing their habitual pattern (\( \alpha = 0.05 \)). Effect sizes were also calculated to determine if the differences between footstrike pattern and groups were biologically meaningful. An effect size (\( d \)) less than 0.4 indicated a small effect, an effect size between 0.5 and 0.7 indicated a moderate effect and an effect size greater than 0.8 indicated a large effect (8).

RESULTS

Running Economy. No significant differences were found for \( \dot{V}O_2 \) or % CHO when comparing the RF and FF groups running with their habitual footstrike pattern at each speed (\( P>0.05, d<0.7 \)) (Fig. 1). At the slow speed, a moderately large effect size (\( d=0.7 \)) was found for
%CHO between groups when running with their habitual pattern, although the difference was not statistically significant. Running economy was expressed as the rate of oxygen consumption (ml•kg\(^{-1}\)•min\(^{-1}\)) to facilitate comparisons with the most directly relevant past research. Although not reported here, statistical significance for all of the oxygen consumption results were the same if we expressed running economy in terms of the energy equivalent of oxygen consumption in either W•kg\(^{-1}\) or J•kg\(^{-1}\)•m\(^{-1}\).

A significant group by footstrike pattern interaction was observed for \(\dot{V}O_2\) and %CHO at the slow speed (\(\dot{V}O_2\): \(P=0.001\); %CHO: \(P=0.007\)) (Fig. 2). In the RF group, the FF pattern resulted in 5.5% greater \(\dot{V}O_2\) and 10.0% greater %CHO compared to the RF pattern (\(\dot{V}O_2\): \(P<0.001, d=0.9\); %CHO: \(P=0.009, d=0.4\)). No significant difference in \(\dot{V}O_2\) or %CHO was observed between footstrike patterns in the FF group (\(\dot{V}O_2\): \(P=0.663, d=0.1\); %CHO: \(P=0.191, d=0.3\)) (Fig. 2). When performing the RF pattern at the slow speed, no difference in \(\dot{V}O_2\) was observed between groups (\(P=0.431, d=0.1\)) although %CHO was 17.5% lower in the RF group compared to the FF group (\(P<0.001, d=0.8\)). When performing the FF pattern at the slow speed, \(\dot{V}O_2\) was 5.8% greater in the RF group compared to the FF group (\(P<0.001, d=0.8\)) (Fig. 2A). There was no significant difference between groups for %CHO when performing the FF pattern at the slow speed (\(P=0.359, d=0.2\)) (Fig. 2B).

At the medium speed, a significant group by footstrike pattern interaction was observed for \(\dot{V}O_2\) (\(P=0.003\)) but not for %CHO (\(P=0.153\)) (Fig. 2). The FF pattern resulted in 3.6% greater \(\dot{V}O_2\) compared to the RF pattern in the RF group (\(P<0.001, d=0.7\)). No significant difference in \(\dot{V}O_2\) was observed between footstrike patterns in the FF group (\(P=0.255, d=0.1\)) (Fig. 2A). The RF group had 3.3% and 6.1% greater \(\dot{V}O_2\) compared to the FF group when performing the RF and FF patterns, respectively, at the medium speed (RF pattern: \(P<0.001, d=0.8\)).
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$d=0.5$; FF pattern: $P<0.001$, $d=1.0$) (Fig. 2A). A significant pattern main effect was observed for %CHO at the medium speed ($P=0.022$, $d=0.2$). The FF pattern resulted in 3.4% greater %CHO compared to the RF pattern at the medium speed (Fig. 2B). No significant group main effect was observed for %CHO at the medium speed ($P=0.326$, $d=0.3$).

No significant group by footstrike interactions or significant group main effects were observed at the fast speed for either $\dot{V}O_2$ or %CHO ($P>0.05$). A significant pattern main effect was observed for $\dot{V}O_2$ but not for %CHO at the fast speed ($\dot{V}O_2$: $P<0.001$; $d=0.4$; %CHO: $P=0.050$, $d=0.2$). The FF pattern resulted in 2.2% greater $\dot{V}O_2$ compared to the RF pattern (Fig. 2A). %CHO was 3.5% greater with the FF pattern compared to the RF pattern, but this difference was not statistically significant (Fig. 2B).

Examining the individual results revealed that 83%, 95%, and 69% of the participants in the RF group had greater $\dot{V}O_2$ with the FF pattern at slow, medium, and fast speeds, respectively (Table 2). In the FF group, 56% of the participants had greater $\dot{V}O_2$ with the FF pattern at the slow speed but this percentage increased to 67% and 75% at the medium and fast speeds respectively (Fig. 2). The individual results also indicated that 78%, 74%, and 75% of the participants in the RF group had greater %CHO when performing the FF pattern at the slow, medium, and fast speeds, respectively (Table 2). In the FF group, 39%, 61%, and 56% of the participants had greater %CHO with the FF pattern at the slow, medium, and fast speeds, respectively (Table 2).

Kinematics. A significant group by footstrike pattern interaction was observed for AATD at each speed ($P<0.05$) (Table 3). Characteristically, the RF pattern resulted in a dorsiflexed position at touch-down whereas the FF pattern resulted in a plantar flexed position at touch-down in both groups ($P<0.001$, $d>1.0$). The RF group had a greater plantar flexion angle at touchdown
compared to the FF group when both performed the FF pattern (slow: $P=0.015$, $d=0.8$; medium: $P=0.030$, $d=0.6$; fast: $P=0.047$, $d=0.6$). No differences in ankle angle were observed between groups when performing the RF pattern (slow: $P=0.455$, $d=0.3$; medium: $P=0.146$, $d=0.6$; fast: $P=0.399$, $d=0.3$). The ankle angle from approximately 15% of stance to toe-off was not different between groups indicating that each group successfully replicated the alternative footstrike pattern.

No significant group by footstrike pattern interactions or group main effects were observed for SF, SL or CT across all speeds ($P>0.05$) (Table 3). However, significant pattern main effects were observed for SF, SL or CT at all three speeds ($P<0.05$) (Table 3). The RF pattern resulted in a less than 2% lower SF, a less than 2% greater SL, and approximately a 10% longer CT compared to the FF pattern at all three speeds.

**DISCUSSION**

The present study compared running economy and the relative contribution of carbohydrate oxidation to total energy expenditure between RF and FF strike patterns in groups that habitually run with either a RF pattern or a FF pattern. We found no difference in rates of oxygen consumption or relative contribution of carbohydrate oxidation to total energy expenditure between habitual RF and FF runners performing their habitual footstrike pattern at a slow, medium, and fast speed. When performing the alternative footstrike pattern, FF running resulted in greater rates of oxygen consumption than RF running in the RF group at the slow and medium speeds and across groups at the fast speed. FF running also resulted in greater carbohydrate oxidation than RF running in the RF group at the slow speed and across groups at the medium speed but no difference was observed at the fast speed.
The major finding of this study was that, among habitual RF and habitual FF runners, there does not appear to be any particular advantage to one group over another in running economy. However, there may be an advantage to being habituated to the RF strike pattern with respect to carbohydrate oxidation relative to total energy expenditure. Previous studies did not find differences in running economy between footstrike patterns, but only included one group of runners habituated to either the RF or FF patterns (2, 11, 34). The first hypothesis of the present study was that running economy would be better in habitual RF runners performing the RF pattern compared to habitual FF runners performing the FF pattern. This hypothesis was rejected. Small effect sizes and no statistically significant differences in the rates of oxygen consumption or carbohydrate oxidation were found between groups when performing their habitual pattern at each speed. However, moderate effect sizes indicated that the contribution of carbohydrate to total energy expenditure was lower in the RF group when both groups performed their habitual footstrike pattern at the slow and medium speeds. This result suggests that the RF group running with the RF pattern might conserve the limited intramuscular glycogen stores and potentially be able to sustain an endurance run longer (35) than the FF group performing the FF pattern. Thus, among runners fully habituated to a specific footstrike pattern, the RF pattern may have a particular advantage to the FF pattern in the primary physiologic factors that affect endurance running performance. These findings support earlier experimental evidence indicating that the mechanics of the RF strike pattern were characteristic of more economical runners.

Another major finding of this study was that the RF strike pattern was more economical than the FF strike pattern in habitual RF runners across a range of sub-maximal running speeds. Additionally, in the FF group, there was a trend for the RF strike pattern to be more economical
than the FF strike pattern, although statistical significance was only detected when the data were collapsed across groups at the fast speed. Therefore, the second hypothesis, that running economy would not improve when habitual RF runners perform the FF running pattern; and running economy would improve when habitual FF runners perform the RF running pattern, was supported in the RF group for all speeds, and in the FF group at the fast speed. The rate of oxygen consumption increased by 2.3–5.5% and carbohydrate oxidation by 5.1–10.0% in the RF group when running with the FF pattern compared to the RF pattern at each speed. In the FF group, the rate of oxygen consumption and carbohydrate oxidation were similar between footstrike patterns at the slow and medium speeds. However, at the fast speed, the FF pattern resulted in a 2.2% greater rate of oxygen consumption and 3.5% greater relative carbohydrate oxidation compared to the RF pattern when the data were collapsed across group. These results indicate that the RF pattern was more economical than the FF pattern in both groups at the fast speed, but only in the RF group at the slow and medium speeds. Thus, contrary to suggestions that habitual RF runners should switch to a FF pattern to improve running economy (17, 25), there does not appear to be any benefit to running economy by performing the FF pattern, regardless of prior experience with each footstrike pattern.

Previous studies investigating running economy between footstrike patterns used participants habituated to either the RF or FF patterns (1, 10, 32). It may be argued that performing the non-habitual pattern resulted in artificially high rates of oxygen consumption given that performing a novel task typically causes an increase in the rate of oxygen consumption and requires habituation to observe any improvement in economy (7, 37). However, a movement pattern that results in an immediate reduction in rates of oxygen consumption is considered more economical than the original movement pattern (42). In the
present study, the FF group was more economical than the RF group when performing the RF pattern at the slow and medium speeds. Additionally, the RF pattern was more economical at the fast speed in both groups, indicating that the RF pattern resulted in an immediate improvement in running economy compared to the FF pattern. Together, these findings suggest that training was not necessary for the FF group to have a lower rate of oxygen consumption when performing the RF pattern compared to habitual RF runners or compared to the FF pattern at the fast speed. However, training with the RF pattern may be required to elicit an improvement in carbohydrate oxidation given that the RF group had lower rates of carbohydrate oxidation compared to the FF group.

A strength of the present study was that both habitual RF and habitual FF runners were included. Thus, the potential for spuriously high oxygen consumption as a result of performing a novel footstrike pattern was eliminated in our main comparison. This previously unused research design may eliminate the need for long habituation periods when examining metabolic or mechanical differences between footstrike patterns. The present study and others (39, 41) have demonstrated that a long accommodation period is not required in order for RF runners to successfully replicate the lower extremity joint angles of the alternative footstrike pattern. However, differences in running economy variables between groups performing the same footstrike pattern in the present study may be a result of different muscle activation patterns, co-contraction, and muscle forces that take longer to accommodate to a new gait pattern than kinematic adjustments (3, 14). Consequently, a long-term training study would be beneficial, to confirm the results of the present study by comparing running economy before and after neuromuscular and physiological adaptations have accommodated to the alternative footstrike pattern.
The results from the present study may provide a rationale for testable hypotheses of a long-term training study. It is possible that if the RF group sufficiently trained with the FF pattern, running economy when performing the FF pattern could improve. However, the results from the FF group in the present study suggest that habituation to the FF pattern would not result in it becoming more economical than the RF pattern. Conversely, the results from the RF group in the present study suggest that if the FF group had sufficient training with the RF pattern, then this pattern would become more economical than the FF pattern.

Altered stride characteristics have previously been observed between footstrike patterns (2, 11, 13, 38). Deviations from preferred stride length and stride frequency have been shown to increase the rate of oxygen consumption and cost of transport (7, 19, 30, 31). However, the measure of running economy may not be sufficiently sensitive to be affected by small deviations in stride parameters (i.e. below ±5%) (19, 26). The present study found less than a 2% difference in stride parameters between RF and FF strike patterns. Thus, stride characteristics likely do not explain the increased rates of oxygen consumption observed with the FF pattern compared to the RF pattern in the present study and another study examining walking (11). In a recent study in which stride characteristics were controlled, no difference was found in running economy between shod RF and shod FF running in a group of habitual FF runners (34). In addition to a small sample size and using runners of only one habitual footstrike pattern, the lack of statistically significant differences might have been the result of participants performing a novel task and performing that task using prescribed (i.e. not self-selected) stride parameters with the alternative footstrike pattern.

Contact time has previously been found to be inversely related to the metabolic cost of running (22, 23, 42, 43). This cost of generating force hypothesis (23) was supported in the RF
group at the slow and medium speeds and across groups at the fast speed. During these conditions, FF running resulted in a shorter contact time and greater rates of oxygen consumption than RF running. Conversely, contact time differed between footstrike patterns in the FF group at the slow and medium speeds although no differences in the rates of oxygen consumption were observed in this group at these speeds. These findings from the FF group during the slow and medium speeds do not support the cost of generating force hypothesis. Therefore, depending on running speed and habitual footstrike pattern, the FF running pattern may represent a condition, additional to surface hardness and surface gradient, in which the metabolic cost of force generation hypothesis does not hold (2, 22).

Although the present study found that FF running resulted in greater rates of oxygen consumption in the RF group at all speeds and across groups at the fast speed, group mean percent differences in rates of oxygen consumption between footstrike patterns at each speed ranged from approximately 2–5%. Variation in the rate of oxygen consumption above 5% may be needed to detect biologically meaningful differences in running economy between conditions or individuals (4, 29, 33, 36). However, individual results showed percent differences in rates of oxygen consumption up to 13% between footstrike pattern conditions. At the slow speed, 61% of the RF group participants but only 28% of the FF group participants had a 5% difference or greater in the rate of oxygen consumption between footstrike patterns (Table 2). Additionally, the RF pattern reduced the rates of oxygen consumption in more participants, regardless of habitual footstrike pattern, compared to the FF pattern. These findings suggest that the acute response to switching footstrike patterns with respect to running economy is highly individualized but the RF pattern may be more beneficial to most runners. Recreational runners may find a benefit in maintaining or switching to the RF pattern only if it results in a 5% or...
greater difference in rates of oxygen consumption compared to the FF pattern. In elite athletes, however, any enhancement in running economy may improve his or her placement in an endurance race (5).

Improvements in the relative contribution of carbohydrate oxidation to total energy expenditure may also be beneficial to both elite and recreational runners. The rate of carbohydrate oxidation is especially important during long endurance events that have the potential to deplete muscle glycogen stores and is thus the limiting factor in performance of endurance events (10). Compared to RF running in the present study, FF running resulted in greater carbohydrate oxidation at the slow speed in the RF group and across groups at the medium speed. Therefore, at these running speeds, the RF pattern may confer benefits in endurance events because carbohydrate oxidation was reduced compared to the FF pattern. In a recent study on recreational, sub-elite runners, it was found that FF runners switched to a RF pattern between the 10 km and 32 km locations of a marathon (24). The participants ran at speeds within the range included in this study. Taken together, this previous and the present study suggest that a change to a RF pattern within a race may be a mechanism to conserve muscle glycogen stores, allowing runners to run longer before muscle glycogen depletion occurs. Although this finding may also be highly individualized and dependent on relative running intensity, the present study found that approximately 75% of the RF group participants and 61% of the FF group participants had greater rates of carbohydrate oxidation with the FF pattern compared to the RF pattern at each speed (Table 2).

The present study was the first to detect significant differences in running economy between RF and FF strike patterns to our knowledge. The discrepancy between findings of the present compared to previous studies may be a result of the differences in the speeds tested or the
number of participants, but is also likely due to the inclusion of both habitual RF and habitual FF runners in the present investigation (1, 10, 33). The present study found that the FF pattern was less economical than the RF pattern in habitual RF runners at all speeds and in both RF and FF runners at the fast speed. These findings support previous studies that identified features characteristic of the RF strike pattern to be associated with more economical runners (16, 41). Despite these previous findings, it has been suggested that the FF pattern may be more economical as a result of greater elastic energy utilization in the longitudinal arch of the foot and in the Achilles tendon (17, 25, 34). Although a previous study suggested greater elastic energy return with FF running estimated from external mechanical work ratios (2), the difference in elastic energy utilization between footstrike patterns in these anatomical structures has yet to be investigated directly. The results from the present study suggest that if the FF pattern results in greater elastic energy utilization in these structures, then it may not result in a reduction to total body metabolic cost. It is possible that any metabolic benefit of an increase in elastic energy utilization may be negated by the substantial forces required by the plantar flexors during FF running compared to RF running (34). FF running may also be less economical because of the smaller amount of shoe cushioning in this area compared to the heel (15). By not utilizing shoe cushioning in FF running, additional muscular contractions may be needed to attenuate impacts thus increasing metabolic energy consumption (43).

In conclusion, the results from the present study indicated that there was no difference in running economy between habitual RF and FF runners performing their habitual footstrike pattern. However, performing the alternative footstrike pattern resulted in significantly greater rates of oxygen consumption in the RF group at the slow and medium speeds and in both groups at the fast speed. Additionally, FF running resulted in greater relative contribution of
carbohydrate oxidation to total energy expenditure in the RF group at the slow speed and across groups at the medium speed. These results suggest that running with a RF pattern might confer benefits in endurance events in both habitual RF and FF runners. Moreover, our findings do not support previous recommendations that habitual RF runners should switch to a FF pattern to gain a performance advantage. Rather, it may be beneficial for some habitual FF runners to adopt the RF pattern, though long-term training with the RF pattern may be required to improve carbohydrate oxidation and confer benefits in endurance running events.

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DISCLOSURES

No conflicts of interest are declared by the authors.

AUTHOR CONTRIBUTIONS

All authors were responsible for the conceptual and experimental design of the research and for interpretation, manuscript editing and revisions, and approved the final version of the manuscript. A.H.G. performed data collection, analysis, prepared figures, and drafted the manuscript.
REFERENCES


FIGURE CAPTIONS

Fig 1: Group mean A) net mass-specific rate of oxygen consumption (\(\dot{V}O_2\)) and B) relative rate of carbohydrate oxidation to total energy expenditure (%CHO) for the rearfoot (RF) and forefoot (FF) groups performing their habitual footstrike pattern at each speed. Error bars indicate ±1SD.

Fig 2: Group mean A) net mass-specific rate of oxygen consumption (\(\dot{V}O_2\)) and B) relative rate of carbohydrate oxidation to total energy expenditure (%CHO) of the rearfoot (RF) and forefoot (FF) groups performing the RF and FF strike patterns at each speed. Error bars indicate ±1SD. * indicates a significant difference between footstrike patterns within the indicated group (\(P<0.05\)). † indicates a significant difference between groups when performing the FF strike pattern (\(P<0.05\)). ‡ indicates a significant difference between groups when performing the RF strike pattern (\(P<0.05\)). § indicates a significant difference between footstrike patterns when the data were collapsed across group (\(P<0.05\)).
Table 1: Mean ± SD participant characteristics of the rearfoot group (RF) and the forefoot group (FF). Strike index and sagittal plane ankle angle at touchdown were determined from over-ground running at the participant’s preferred running speed and footstrike pattern. Positive ankle angles represent dorsiflexion, negative angles represent plantar flexion. * indicates a significant difference between groups determined by student’s t-test ($P<0.05$).

<table>
<thead>
<tr>
<th></th>
<th>RF group</th>
<th>FF group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/Females</td>
<td>12/7</td>
<td>14/4</td>
</tr>
<tr>
<td>Age, yr</td>
<td>26.7 ± 6.1</td>
<td>25.6 ± 6.4</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.8 ± 0.1</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>70.1 ± 10.0</td>
<td>68.7 ± 9.8</td>
</tr>
<tr>
<td>Preferred speed, m·s⁻¹</td>
<td>3.5 ± 0.9</td>
<td>3.7 ± 0.3</td>
</tr>
<tr>
<td>Weekly distance, km</td>
<td>42.9 ± 29.0</td>
<td>49.8 ± 25.9</td>
</tr>
<tr>
<td>Strike Index, % *</td>
<td>12.4 ± 7.8</td>
<td>57.0 ± 12.1</td>
</tr>
<tr>
<td>Ankle angle at touchdown, deg *</td>
<td>13.6 ± 4.6</td>
<td>-5.4 ± 6.7</td>
</tr>
</tbody>
</table>
Table 2: Summary of individual participant results for rate of oxygen consumption ($\dot{V}O_2$) and relative rate of carbohydrate oxidation to total energy expenditure (%CHO). Values indicate the number of participants within the rearfoot (RF) and forefoot (FF) groups that had lower $\dot{V}O_2$ or %CHO with the indicated footstrike pattern condition. Values in parentheses indicate the number of participants who had a greater than ±5% difference between conditions.

<table>
<thead>
<tr>
<th></th>
<th>Slow Speed</th>
<th>Medium Speed</th>
<th>Fast Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF group</td>
<td>FF group</td>
<td>RF group</td>
</tr>
<tr>
<td></td>
<td>n = 18</td>
<td>n = 18</td>
<td>n = 19</td>
</tr>
<tr>
<td>$\dot{V}O_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF pattern</td>
<td>15 (11)</td>
<td>10 (1)</td>
<td>18 (4)</td>
</tr>
<tr>
<td>FF pattern</td>
<td>3 (0)</td>
<td>8 (1)</td>
<td>1 (0)</td>
</tr>
<tr>
<td>%CHO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF pattern</td>
<td>14 (13)</td>
<td>7 (5)</td>
<td>14 (12)</td>
</tr>
<tr>
<td>FF pattern</td>
<td>4 (3)</td>
<td>11 (9)</td>
<td>5 (1)</td>
</tr>
</tbody>
</table>

At the fast speed, one participant from each group had a zero magnitude change between conditions for %CHO.
Table 3: Mean ± SD for the stride characteristics when performing the rearfoot (RF) and forefoot (FF) patterns. Variables include the ankle angle at touchdown (AATD), stride length (SL), stride frequency (SF) and contact time (CT). Positive ankle angles represent dorsiflexion, negative represent plantar flexion. Listed statistics include the effect sizes for the group main effect (“group”) and the pattern main effect (“pattern”).

<table>
<thead>
<tr>
<th>Speed</th>
<th>AATD, deg</th>
<th>SF, strides·min⁻¹</th>
<th>CT, s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF Group</td>
<td>FF Group</td>
<td>Effect Size</td>
</tr>
<tr>
<td></td>
<td>M/FF</td>
<td>M/FF</td>
<td>group</td>
</tr>
<tr>
<td>slow*</td>
<td>8.3 ± 2.4</td>
<td>7.5 ± 2.7</td>
<td>0.3</td>
</tr>
<tr>
<td>medium*</td>
<td>7.6 ± 2.5</td>
<td>6.1 ± 2.7</td>
<td>0.1</td>
</tr>
<tr>
<td>fast*</td>
<td>7.6 ± 3.2</td>
<td>6.6 ± 2.8</td>
<td>0.2</td>
</tr>
<tr>
<td>slow†</td>
<td>2.17 ± 0.14</td>
<td>2.17 ± 0.17</td>
<td>0.0</td>
</tr>
<tr>
<td>medium†</td>
<td>2.47 ± 0.20</td>
<td>2.45 ± 0.17</td>
<td>0.1</td>
</tr>
<tr>
<td>fast†</td>
<td>2.76 ± 0.16</td>
<td>2.75 ± 0.19</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*A significant group by pattern interaction (*P*<0.05), † significant pattern main effect (*P*<0.01).