J Appl Physiol 115: 194–201, 2013.
First published May 16, 2013; doi:10.1152/japplphysiol.01437.2012.

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

Allison H. Gruber, Brian R. Umberger, Barry Braun, and Joseph Hamill

Department of Kinesiology, University of Massachusetts, Amherst, Massachusetts

Submitted 30 November 2012; accepted in final form 9 May 2013

Gruber AH, Umberger BR, Braun B, Hamill J. Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns. *J Appl Physiol* 115: 194–201, 2013. First published May 16, 2013; doi:10.1152/japplphysiol.01437.2012.—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 whether there were differences in running economy between these groups and whether 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. 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 with 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 footstrike pattern main effect indicated that $\dot{V}O_2$ was greater with the FF pattern than with 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.

running economy; footstrike patterns; submaximal oxygen consumption; running performance

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), with a strike index of 0–33% and where initial contact is made with the heel; *2*) midfoot (MF), with a strike index of 34–66% and where initial contact is made with the whole foot at nearly the same time; and *3*) forefoot (FF), with a strike index of 67–100% and where initial contact is made with the ball of the foot (1, 6, 11, 17, 21, 32). Although ~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 with the RF pattern in both scientific literature and popular media (17, 20, 25), which has led to recommendations that RF runners should change to a FF pattern (17, 34). Not only is there no empirical evidence to support these claims, but 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., submaximal, steady-state rate of oxygen consumption ($\dot{V}O_2$)] 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 submaximal $\dot{V}O_2$ 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 $\dot{V}O_2$ 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. Although 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 $\dot{V}O_2$ 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 whether 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

Address for reprint requests and other correspondence: A. H. Gruber, Biomechanics Laboratory, Dept. of Kinesiology, 23A Totman Bldg., 30 Eastman Ln., Univ. of Massachusetts, Amherst, MA 01003 (e-mail: agruber @kin.umass.edu).

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 with 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 to 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 whether 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 strike pattern, whereas running economy would improve when habitual FF runners perform the RF strike 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/wk with an average preferred running speed of ~3.7 ± 0.3 m/s 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 touchdown (16). Vertical GRF and center of pressure were recorded at 1,200 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 and 33%, the ankle angle at initial contact was above 5° 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 and 66%, the ankle angle at initial contact was between 5° of dorsiflexion and 5° of plantar flexion, and vertical GRF exhibited a blunted impact peak. Participants were classified as FF runners if the strike index was >66%, the ankle angle at initial contact was >5° of plantar flexion, and the vertical impact peak was absent. Given that ~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 14 participants classified as MF runners and 4 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). The volume of gas exchange was used to calculate the gross rate of $\dot{V}O_2$. 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, Gothenberg, Sweden) sampling at 240 Hz. A treadmill (Star Trac, Unisen, Irivine, CA) 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) provided by the laboratory to standardize any effects of cushioning or other footwear properties.

Table 1. *Participant characteristics of the RF and FF groups*

	RF Group	FF Group
Men/women	12/7	14/4
Age, yr	26.7 ± 6.1	25.6 ± 6.4
Height, m	1.8 ± 0.1	1.8 ± 0.1
Body mass, kg	70.1 ± 10.0	68.7 ± 9.8
Preferred speed, m/s	3.5 ± 0.9	3.7 ± 0.3
Weekly distance, km	42.9 ± 29.0	49.8 ± 25.9
Strike index*, %	12.4 ± 7.8	57.0 ± 12.1
Ankle angle at touchdown*, degrees	13.6 ± 4.6	−5.4 ± 6.7

Values are means ± SD. 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. RF, rearfoot; FF, forefoot. *Significant difference between groups determined by Student's *t*-test ($P < 0.05$).

Experimental protocol. Each participant arrived at the laboratory having fasted for at least 3 h 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, 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 and 3.9 ± 0.1 m/s, respectively. The participant was 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 min on the treadmill to record baseline $\dot{V}O_2$. 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 5 min during each speed and footstrike pattern condition or until 2 min of steady-state $\dot{V}O_2$ was recorded. Steady state was defined as a <10% change in $\dot{V}O_2$ over a 2-min period (40). Each participant rested until the minute volume of expired air returned to within 0.02 l/min of the baseline value.

In establishing the baseline, the first 5 min of recorded $\dot{V}O_2$ tended to have high variability as the participants became accustomed to breathing with the mouthpiece. Therefore, the rate of $\dot{V}O_2$ averaged over the final 5 min 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 2 min of each running condition to determine net mass-specific rate of $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$).

Absolute rate of carbohydrate oxidation ($\dot{V}CHO$) in grams per minute was determined from the rates of carbon dioxide expired ($\dot{V}CO_2$) and $\dot{V}O_2$ by (27):

$$\dot{V}CHO = 4.58\dot{V}CO_2 - 3.23\dot{V}O_2 \quad (1)$$

where 4.58 and 3.23 are grams of carbohydrate per liter of carbon dioxide and oxygen, respectively. Because $\dot{V}CHO$ will vary directly with total energy expended, the relative contribution of carbohydrate to total energy expenditure (%CHO) was calculated by converting $\dot{V}_{CHO}$ in grams per minute to kilocalories per minute (g * 4 kcal/g) and then scaling to the rate of energy expenditure in kilocalories per minute.

The three-dimensional (3D) positions of the markers placed on the foot and leg were tracked using Qualisys Track Manager software (Qualisys, Gothenberg, Sweden) then exported to Visual 3D software (C-Motion, Rockville, MD). 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 strides/min 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 whether the differences between footstrike pattern and groups were biologically meaningful. An effect size (*d*) of <0.4 indicated a small effect, an effect size between 0.5 and 0.7 indicated a moderate effect, and an effect size of >0.8 indicated a large effect (8).

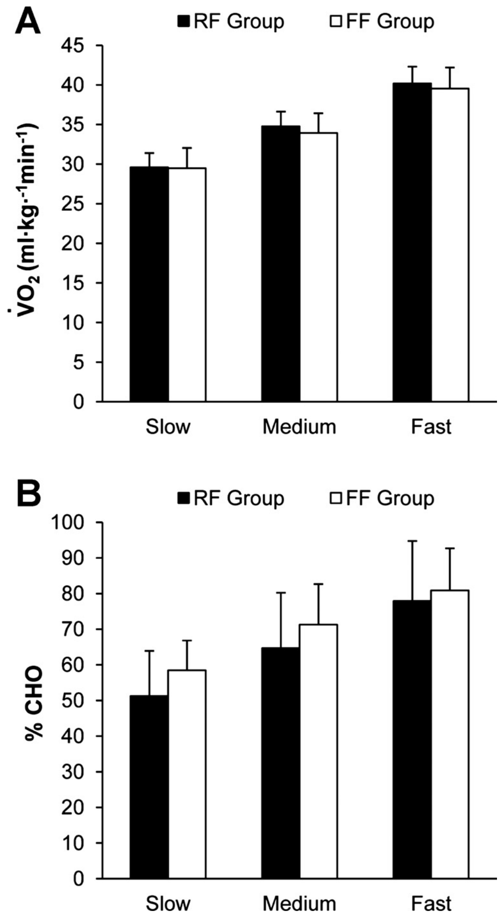

Fig. 1. Group mean net mass-specific rate of oxygen consumption ($\dot{V}O_2$; *A*) and relative rate of carbohydrate oxidation to total energy expenditure (%CHO; *B*) for the rearfoot (RF) and forefoot (FF) groups performing their habitual footstrike pattern at each speed. Error bars indicate +1 SD.

RESULTS

Running economy. No significant differences were found for $\dot{V}O_2$ or %CHO when the RF and FF groups running with their habitual footstrike pattern at each speed were compared ($P > 0.05$; $d < 0.7$) (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 $\dot{V}O_2$ (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 $\dot{V}O_2$ results were the same if we expressed running economy in terms of the energy equivalent of $\dot{V}O_2$ in either Watts per kilogram or Joules per kilogram per minute.

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 with 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 the RF pattern was performed 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 with the FF group ($P < 0.001$, $d = 0.8$). When the FF pattern was performed at the slow speed, $\dot{V}O_2$ was 5.8% greater in the RF group compared with the FF group ($P < 0.001$, $d = 0.8$) (Fig. 2*A*). There was no significant difference between groups for %CHO when the FF pattern was performed at the slow speed ($P = 0.359$, $d = 0.2$) (Fig. 2*B*).

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 with 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. 2*A*). The RF group had 3.3% and 6.1% greater $\dot{V}O_2$ compared with the FF group when the RF and FF patterns, respectively, were performed at the medium speed (RF pattern: $P < 0.001$, $d = 0.5$; FF pattern: $P < 0.001$, $d = 1.0$) (Fig. 2*A*). 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 with the RF pattern at the medium speed (Fig. 2*B*). 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 with the RF

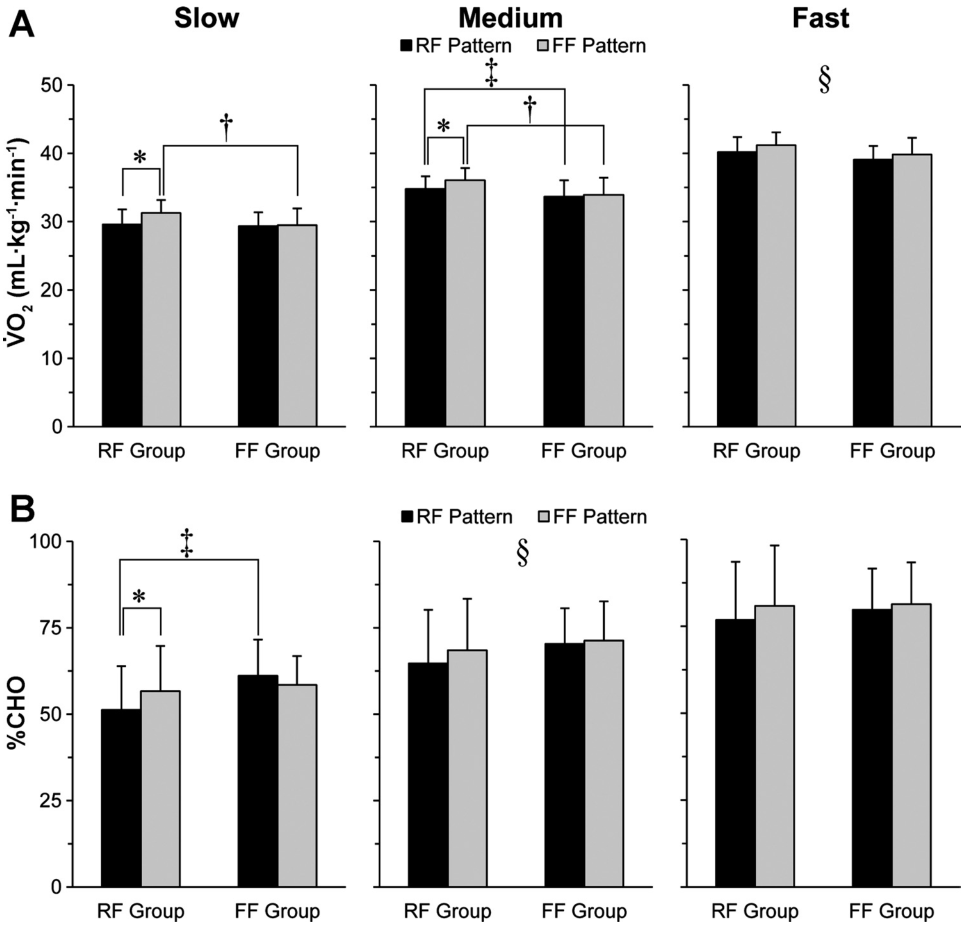

Fig. 2. Group mean net mass-specific rate of $\dot{V}O_2$ (*A*) and relative %CHO (*B*) of the RF and FF groups performing the RF and FF strike patterns at each speed. Error bars indicate +1 SD. *Significant difference between footstrike patterns within the indicated group ($P < 0.05$). †Significant difference between groups when performing the FF strike pattern ($P < 0.05$). ‡Significant difference between groups when performing the RF strike pattern ($P < 0.05$). §Significant difference between footstrike patterns when the data were collapsed across group ($P < 0.05$).

pattern (Fig. 2*A*). %CHO was 3.5% greater with the FF pattern compared with the RF pattern, but this difference was not statistically significant (Fig. 2*B*).

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 the FF pattern was performed 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 touchdown, whereas the FF pattern resulted in a plantar-flexed position at touchdown in both groups ($P < 0.001$, $d > 1.0$). The RF group had a greater plantar flexion angle at touchdown compared with 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 the RF pattern was performed (slow: $P =$

Table 2. *Summary of individual participant results for rate of $\dot{V}O_2$ and %CHO*

	Slow Speed		Medium Speed		Fast Speed	
	RF group (n = 18)	FF group (n = 18)	RF group (n = 19)	FF group (n = 18)	RF group (n = 16)	FF group (n = 16)
$\dot{V}O_2$						
RF pattern	15 (11)	10 (1)	18 (4)	12 (1)	11 (3)	12 (2)
FF pattern	3 (0)	8 (1)	1 (0)	6 (1)	5 (0)	4 (0)
%CHO						
RF pattern	14 (13)	7 (5)	14 (12)	11 (5)	11 (8)	8 (4)
FF pattern	4 (3)	11 (9)	5 (1)	7 (5)	4 (3)	7 (3)

Values indicate the number of participants within the RF and FF groups that had lower rate of oxygen consumption ($\dot{V}O_2$) or relative rate of carbohydrate oxidation to total energy expenditure (%CHO) with the indicated footstrike pattern condition. Values in parentheses indicate the number of participants who had a greater than ±5% difference between conditions. At the fast speed, one participant from each group had a zero magnitude change between conditions for %CHO.

Table 3. *The stride characteristics when the RF and FF patterns were performed*

	RF Group		FF Group		Effect Size	
Speed	RF	M/FF	RF	M/FF	Group	Pattern
AATD, degrees						
Slow*	8.3 ± 2.4	−8.4 ± 3.4	7.5 ± 2.7	−5.7 ± 3.6	0.3	5.0
Medium*	7.6 ± 2.5	−8.4 ± 3.5	6.1 ± 2.7	−6.1 ± 3.7	0.1	4.6
Fast*	7.6 ± 3.2	−9.0 ± 3.1	6.6 ± 2.8	−6.7 ± 4.0	0.2	4.6
SL, m						
Slow†	2.17 ± 0.14	2.14 ± 0.14	2.17 ± 0.17	2.14 ± 0.14	0.0	0.2
Medium†	2.47 ± 0.20	2.44 ± 0.19	2.45 ± 0.17	2.43 ± 0.19	0.1	0.1
Fast†	2.76 ± 0.16	2.74 ± 0.19	2.75 ± 0.19	2.70 ± 0.23	0.1	0.2
SF, strides/min						
Slow†	83.1 ± 5.2	84.5 ± 5.3	83.6 ± 6.2	84.5 ± 5.5	0.0	0.2
Medium†	84.8 ± 5.7	85.9 ± 5.8	85.9 ± 5.5	86.7 ± 6.3	0.2	0.2
Fast†	86.2 ± 4.4	87.2 ± 5.1	86.9 ± 5.3	88.3 ± 6.3	0.2	0.2
CT, s						
Slow†	0.268 ± 0.015	0.243 ± 0.012	0.261 ± 0.021	0.235 ± 0.016	0.5	1.6
Medium†	0.247 ± 0.016	0.225 ± 0.013	0.238 ± 0.018	0.214 ± 0.014	0.7	1.5
Fast†	0.230 ± 0.014	0.208 ± 0.013	0.221 ± 0.017	0.198 ± 0.014	0.7	1.6

Values are means ± SD. Variables include the ankle angle at touchdown (AATD), stride length (SL), stride frequency (SF), and contact time (CT). Positive ankle angles represent dorsiflexion; negative ankle angles represent plantar flexion. Listed statistics include the effect sizes for the group main effect (group) and the pattern main effect (pattern). *Significant group by pattern interaction ($P < 0.05$). †Significant pattern main effect ($P < 0.01$).

0.455, $d = 0.3$; medium: $P = 0.146$, $d = 0.6$; fast: $P = 0.399$, $d = 0.3$). The ankle angle from ~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 <2% lower SF, a <2% greater SL, and an ~10% longer CT compared with 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 $\dot{V}O_2$ 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 the alternative footstrike pattern was performed, FF running resulted in greater rates of $\dot{V}O_2$ 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 with habitual FF runners performing the FF pattern. This hypothesis was rejected. Small effect sizes and no statistically significant differences in the rates of $\dot{V}O_2$ or carbohydrate oxidation were found between groups when their habitual pattern was performed 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 physiological 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 submaximal 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 $\dot{V}O_2$ 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 with the RF pattern at each speed. In the FF group, the rate of $\dot{V}O_2$ 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 $\dot{V}O_2$ and 3.5% greater relative carbohydrate oxidation compared with the RF pattern when the data were collapsed across groups. 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 nonhabitual pattern resulted in artificially high rates of $\dot{V}O_2$ given that performing a novel task typically causes an increase in the rate of $\dot{V}O_2$ and requires habituation to observe any improvement in economy (7, 37). However, a movement pattern that results in an immediate reduction in rates of $\dot{V}O_2$ 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 the RF pattern was performed 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 with the FF pattern. Together, these findings suggest that training was not necessary for the FF group to have a lower rate of $\dot{V}O_2$ when performing the RF pattern compared with habitual RF runners or compared with 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 with 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 $\dot{V}O_2$ 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 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 $\dot{V}O_2$ 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 $\pm 5\%$) (19, 26). The present study found a $<2\%$ difference in stride parameters between RF and FF strike patterns. Thus stride characteristics likely do not explain the increased rates of $\dot{V}O_2$ observed with the FF pattern compared with 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 $\dot{V}O_2$ 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 $\dot{V}O_2$ 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, in 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 $\dot{V}O_2$ in the RF group at all speeds and across groups at the fast speed, group mean percent differences in rates of $\dot{V}O_2$ between footstrike patterns at each speed ranged from ~2 to 5%. Variation in the rate of $\dot{V}O_2$ 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 $\dot{V}O_2$ 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 $\geq 5\%$ difference in the rate of $\dot{V}O_2$ between footstrike patterns (Table 2). Additionally, the RF pattern reduced the rates of $\dot{V}O_2$ in more participants, regardless of habitual footstrike pattern, compared with 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 $\geq 5\%$ difference in rates of $\dot{V}O_2$ compared with 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 with 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 with the FF pattern. In a recent study on recreational, subelite runners, it was found that FF runners switched to a RF pattern between the 10- 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 ~75% of the RF group participants and 61% of the FF group participants had greater rates of carbohydrate oxidation with the FF pattern compared with 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 with 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 with RF running (34). FF running may also be less economical because of the smaller amount of shoe cushioning in this area compared with 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 $\dot{V}O_2$ 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, although long-term training with the RF pattern may be required to improve carbohydrate oxidation and confer benefits in endurance running events.

ACKNOWLEDGMENTS

We thank Carl Jewell, Samuel del Pilar II, and Richard Viskochil for assistance with this project.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: A.H.G., B.R.U., B.B., and J.H. conception and design of research; A.H.G. performed experiments; A.H.G. analyzed data; A.H.G., B.R.U., B.B., and J.H. interpreted results of experiments; A.H.G. prepared figures; A.H.G. drafted manuscript; A.H.G., B.R.U., B.B., and J.H. edited and revised manuscript; A.H.G., B.R.U., B.B., and J.H. approved final version of manuscript.

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