Running Stride Peak Forces Inversely Determine Running Economy in Elite Runners

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ABSTRACT

Støren, Ø, Helgerud, J, and Hoff, J. Running stride peak forces inversely determines running economy in elite runners. J Strength Cond Res 25(1): 117–123, 2011—The present study investigated the relationship between running economy (RE) at 15 km/h, 3,000-m race time, maximal strength, and a number of physiological, anthropometrical, and mechanical variables. The variables measured included RE, maximal oxygen consumption, heart rate, step length and frequency, contact time, and the peak horizontal and vertical forces of each step. Maximal strength was measured as the 1 repetition maximum (1RM) half-squat using a leg press machine. Eleven male elite endurance athletes with a VO2max of 75.8 ± 6.2 mL/kg·min−1 participated in this study. After the anthropometric data were collected, they were tested for RE, running characteristics, and force measures on a level treadmill at 15 km/h. The athletes wore contact soles, and the treadmill was placed on a force platform. Maximal oxygen consumption and 1RM were tested after the RE measurements. The sum of horizontal and vertical peak forces revealed a significant inverse correlation (p < 0.05) both with 3,000-m performance (R = 0.71) and RE (R = 0.66). Inverse correlations were also found (p < 0.05) between RE and body height (R = 0.61) and between RE and body fat percentage (R = 0.62). In conclusion, the sum of horizontal and vertical peak forces was found to be negatively correlated to running economy and 3,000-m running performance, indicating that avoiding vertical movements and high horizontal braking force is crucial for a positive development of RE.

KEY WORDS oxygen cost of running, horizontal and vertical forces, long distance running

INTRODUCTION

Running economy (RE) has been identified as 1 of 3 major physiological determinants for distance running performance (23). RE has been shown to be independent of running speed while exercising between 60 and 90% of maximal oxygen consumption (VO2max) (11). Interindividual variations in RE have been demonstrated by Conley and Krahenbuhl (5), di Prampero et al. (6) and Helgerud (11). The causes of this variability are not well understood, but it seems likely that anatomical traits, mechanical and neuromuscular skills, and storage of elastic energy are important factors (23). Therefore, it is important to investigate further the factors affecting RE because such knowledge may improve training methods and distance running performance.

Williams and Cavanagh (28) have demonstrated that 54% of the interindividual variations in RE can be explained by kinematic variables. According to Heglund and Taylor (10), the cost of moving (measured as the energy cost per kilogram bodyweight per stride) is approximately the same for all animals, independent of body size, but it increases with increasing speed. They found that, among different-sized animals, RE was determined primarily by the cost of activating the muscles and of generating a unit of force per unit of time (10). It is hypothesised by Taylor (27) that it is the time course of force development during locomotion, rather than the mechanical work that the muscles perform, that determines RE. Farley and McMahon (7) and Kram and Taylor (18) have found RE to be proportional to the weight supported (i.e., directly dependent on the vertical forces). However, by increasing and decreasing horizontal resistance during treadmill running, Chang and Kram (4) have found horizontal forces to constitute more than 33% of the total metabolic cost of horizontal running. For track running, Kyrolainen et al. (19) found that the average horizontal forces in the braking phase of the step could explain more than 80% of RE.

Nummela et al. (21) have shown a strong negative correlation between contact time and RE among young runners. Furthermore, in a study by Paavolainen et al. (22), it is indicated that better performance in a 10-km time trial is related to higher preactivation of the working muscles,
accompanies with shorter contact times (CT), during the run. However, Williams and Cavanagh (28) and Kyrolainen et al. (19) did not find a significant correlation between CT and RE when comparing distance running mechanics, RE, and performance. Kyrolainen et al. (19) also did not find significant correlations between stride frequency and CT. It seems appropriate to investigate further running mechanics because the previously published results regarding the role of horizontal and vertical forces, the role of CT, and the stride frequency in RE are not all in agreement with each other.

In addition to running mechanics, both physiological and anthropometric variables have previously been reported to have an influence on RE. These include ventilation (9), calf circumference (20), pelvis width (28), leg length (25), and percentage of body fat (2).

In intervention studies, maximal strength training performed as a supplement to endurance training has improved RE by approximately 5% in cross country skiing, soccer, and long distance running (14–16,26,30) without any concurrent changes in VO2max or body weight (BW). The mechanisms behind these improvements are not yet fully understood, but it is suggested that neuromuscular rather than hypertrophic responses are the main source of the reported improvements (16). Osterás et al. (30) partly explain the improved work economy through a specific change in the force-velocity relationship and the mechanical power output. Wisløff et al. (29) have shown a strong correlation between maximal strength, maximal rate of force development in lower-limb extensors, and the peak running velocity among elite soccer players. Theoretically, at submaximal running velocities, a lesser percentage of the maximal strength in the lower-limb extensors would then be activated for each stride, reducing the actual demand of the number of motor units recruited. It is also possible that with an improved rate of force development, the time spent in the contraction phase would be reduced. This would result in a shorter CT between the foot and the ground during each stride. If fewer motor units are recruited at the same time, or if the time spent in contracting muscles is shorter, there could be an increase in the circulatory flow through the working muscles, thus improving the availability of O2 and other substrates. If the lower threshold motor units are recruited at the same time, a longer time to exhaustion at a standard submaximal running velocity could be expected, as shown by Støren et al. (26).

Thus, the aim of this study was to detect possible relationships among running mechanics, physiological and anthropometrical measures, maximal strength in the lower extremities, and running economy among elite endurance athletes.

METHODS

Experimental Approach to the Problem

The main objective of the present study was to investigate the relationships between physiological, anthropometrical, and mechanical variables and oxygen cost of running. To do this, 11 elite endurance athletes registered their seasonal best 3,000-m performance time and performed a set of anthropometrical tests, a 1 repetition maximum (1RM) half-squat test in a leg press machine, a submaximal running test with force measurements and ergospirometrical measurements on a level treadmill, and a VO2max test on a treadmill with 5.2% inclination. The submaximal running speed was set to 15 km/h, assumed to be above 70% of maximal aerobic speed (MAS) and below the lactate threshold (approximately 85% of VO2max) for all subjects. This intensity range is within the zone (60–90% of VO2max) where RE has been shown to be independent of running speed (11).

Subjects

Eleven well-trained male elite endurance athletes, competing in orienteering, cross-country skiing, biathlon, and long distance running participated in this study. All athletes were informed of the experimental risks and signed an informed consent document prior to the investigation. The investigation was approved by the regional Human Research Ethics committee for mid-Norway. Subject characteristics are presented in Table 1.

Procedures

The subjects performed all the tests on 1 day, always between 11 AM and 6 PM. They were instructed to prepare for the test in the same manner as for a competition. This includes only easy training the last 24 hours and no eating the last 2 hours before testing. The subjects were only allowed to drink water the last hour prior to the tests and between tests. All subjects were familiar with running on the treadmill.

First, the subjects were measured for body weight, height, body fat (Lange skin caliper), Beta Technology, Santa Cruz, California, U.S.A.) at the chest, the suprailiac, the abdomen, the thigh, and the triceps. Pelvis width and calf circumference (measured just above the ankles) were also measured. They were then asked for their seasonal best 3,000-m track time. After a 5-minute warm-up, the subjects ran for 1 minute at 15 km/h on a level treadmill (Technogym RunRace, Gambettola, Italy). The submaximal running speed was set to 15 km/h, assumed to be above 70% of maximal aerobic speed (MAS) and below the lactate threshold (approximately 85% of VO2max) for all subjects. The subjects were wearing contact soles to measure the vertical forces (Pedar-X contact soles, Novel, Munich, Germany). The front of the treadmill was placed on a force platform (Kistler, Switzerland), with the rear end of the mill hanging freely in a special device designed for this purpose at the Department of Circulation and Medical Imaging, Faculty of Medicine (Norwegian University of Science and Technology, Trondheim, Norway). The force platform could thus measure the horizontal forces. An example of force characteristics for 1 of the subjects in 1 step is presented in Figure 1.

Average peak force (APF) for both vertical and horizontal forces was calculated as the average of the peaks over a 10-second period. CT and step frequency (SF) were also measured. The subjects then ran for 5 minutes at the same...
horizontal treadmill at 15 km/h⁻¹. VO₂ (Cortex Metamax II, Cortex, Leipzig, Germany) and heart rate (Polar S410, Kempele, Finland) were continuously measured. The test-retest reliability, represented by the coefficient of variation for running economy, was measured in our laboratory to be 2.5% (n = 10). After the 5 minutes, a VO₂max test was performed, using an incremental protocol at 5.2% inclination. The coefficient of variation has previously been shown to be less than 1% for these types of measurements at our laboratory.

After the VO₂max test, the subjects were allowed 15 minutes of rest before a maximal strength test for a half-squat (90 degrees) movement, using a leg press machine. The test started at approximately 70% of the predicted 1RM. The loads were gradually increased until the athlete could no longer manage to lift the load.

### Allometric Scaling

The energy cost of a movement does not increase at the same rate as body weight. According to Bergh et al. (1) and Helgerud (11), comparisons of VO₂max should be expressed relative to body mass raised to the power of 0.75 when running, based on descriptive data. Allometric scaling has been reported to decrease the standard deviations in RE between subjects (11–13,16,17). Thus, in the present study, VO₂ values are usually expressed in mL/kg⁻⁰.⁷⁵/ min⁻¹.

### Statistical Analyses

Statistical analyses were performed using the software program SPSS, version 14.0 (Statistical Package for Social Science, Chicago, Illinois, U.S.A.). In all cases, P < 0.05 was taken as the level of significance in 2-tailed tests. Means, SDs,
and coefficients of variance were calculated through descriptive analyses. Linear regressions were performed, and the equations representing the linearity between selected parameters and oxygen cost of running were calculated. Correlations were calculated by the Pearson correlation test. The data were tested to confirm a normal distribution using quantile-quantile (QQ) plots.

RESULTS

The main variables (RE and 3,000-m race time) were found to be normally distributed and relatively homogenous, with interindividual variations of 6.6% and 7.5%, respectively. In addition, regarding \( \text{Vo}_{2\text{max}}, \text{BW}, \) and height, the athletes represented a rather homogenous group with interindividual variations of only 7.0, 8.5, and 1.8%, respectively (Table 1). A significant correlation between \( \text{Vo}_{2\text{max}} \) and 3,000-m performance \((p < 0.01, R = 0.85)\) was observed. RE did not correlate significantly with 3,000-m performance alone, but \( \text{Vo}_{2\text{max}} \) divided by RE correlated \((p < 0.01, R = 0.93)\) with 3,000-m performance (Figure 2). The HR at 15 km/h expressed as percentage of HR at \( \text{Vo}_{2\text{max}} \) correlated inversely with both RE \((p < 0.01, R = 0.92)\) and performance at 3,000 m \((p < 0.01, R = 0.72)\) (Figure 3). Correlations

Figure 1. Force characteristics in a single step in 1 runner. The graph at the top represents vertical forces, whereas the graph at the bottom represents horizontal forces.

Figure 2. The relationship between \( \text{Vo}_{2\text{max}}/C_R \) and 3,000-m time performance (seconds) among elite endurance athletes \((n = 11)\). \( \text{Vo}_{2\text{max}} = \) maximal oxygen consumption; \( C_R = \) oxygen cost of running. \( p < 0.01, R = 0.93. \)

Figure 3. The relationship between HR expressed as %HR at \( \text{Vo}_{2\text{max}} \) and \( C_R \) \((\text{mL/kg}^{0.75}\text{min}^{-1})\) among elite endurance athletes \((n = 11)\). HR = heart rate; \( \text{Vo}_{2\text{max}} = \) maximal oxygen consumption; \( C_R = \) oxygen cost of running. \( p < 0.01, R = 0.92. \)

Figure 4. The relationship between body fat expressed as total percentage and \( C_R \) \((\text{mL/kg}^{0.75}\text{min}^{-1})\) among elite endurance athletes \((n = 11)\). Body fat = percent body fat measured at 5 points with skin caliper. \( p < 0.05, R = 0.62. \)
DISCUSSION

The major finding in this study is that there is a significant inverse correlation between the sum of horizontal and vertical peak forces and both RE and 3,000-m running time performance.

A strong relationship between 3,000-m running time performance and $\text{VO}_{2}\text{max}/\text{RE}$ was observed in the present study. An $R$ of 0.93 indicates that $\text{VO}_{2}\text{max}/\text{RE}$ may explain about 86% of 3,000-m running time performance. This is in accordance with the model described by Pate and Kriska (23) that incorporates the 3 major factors accounting for interindividual variance in aerobic endurance performance—namely, $\text{VO}_{2}\text{max}$, lactate threshold (LT), and work economy (C). Numerous published studies support this model (3,5,6,8,24). In the present study, the relative importance of $\text{VO}_{2}\text{max}$ was 73%, whereas the relative importance of RE was found to be 13%. RE is of great importance for running performance among runners with similar $\text{VO}_{2}\text{max}$, as shown in a study by Conley and Krahenbuhl (5). In this study, RE determined 65% of the variation observed in performance in a 10-km race among highly trained runners with a similar $\text{VO}_{2}\text{max}$. In the present study, although the runners may be regarded as relatively homogenous concerning $\text{VO}_{2}\text{max}$, an interindividual variation of 7% was observed. This explains why the relative importance of RE in the present study is much smaller than in the study by Conley and Krahenbuhl (5). In the present study we also observed a strong negative correlation between 3,000-m time performance and HR at 15 km/h$^{-1}$ (expressed as %HR at $\text{VO}_{2}\text{max}$). This may indicate that the runners working at the lowest percent of their maximal working capacity at 15 km/h$^{-1}$ have the ability to tolerate the highest race speed above 15 km/h$^{-1}$, which is logical. In the present study, there was a significant inverse correlation between the sum of peak forces (eccentric, concentric, horizontal, and vertical) and 3,000-m running performance. The sum of peak forces also showed a significant inverse correlation with RE. However, because RE did not significantly correlate to 3,000-m time alone, the sum of peak forces should logically affect more than RE regarding 3,000-m time. Our present study shows that the same applies for percentage body fat.

In the present study, none of the force measures alone correlated significantly with RE. However, when added together, as the sum of horizontal and vertical eccentric and concentric peak forces ($\text{APF}_{\text{total}}$), a significant negative correlation was observed. Farley and McMahon (7) and Kram and Taylor (18) have found RE to be inversely proportional to the weight supported (i.e., directly dependent on the vertical forces). In the present study we found no such direct relationship. Chang and Kram (4) have found horizontal forces to constitute more than 33% of the total metabolic cost of horizontal running on a treadmill. Kyrolainen et al. (19) found that the average horizontal forces in the braking phase of the step could explain more than 80% of $C_{R}$ for track running.

\(\rho < 0.05\) were observed between height and RE \((R = 0.61)\) and between body fat percentage and 3,000-m performance \((R = 0.70)\) and RE \((R = 0.62)\) (Figures 4 and 5). No correlations were found between the anthropometric variables BW, leg length, ankle circumference, or hip width and RE or 3,000-m performance. A correlation \((\rho < 0.05)\) was found both between APF$_{\text{total}}$ and RE \((R = 0.66)\) (Figure 6) and between APF$_{\text{total}}$ and 3,000-m performance \((R = 0.71)\). No correlations were observed between the running mechanic variables step length (SL), SF, CT, time to peak force (TPF), APF horizontal eccentric, APF horizontal concentric, APF vertical eccentric, or APF vertical concentric and RE or 3,000-m performance.

Figure 5. The relationship between body height (cm) and $C_{0}$ \((\text{mL/kg}^{0.75}\text{min}^{-1})\) among elite endurance athletes \((n = 11)\). $C_{0}$ = oxygen cost of running. $\rho < 0.05$, $R = 0.61$.

Figure 6. The relationship between the sum of average peak forces, braking and propulsive, vertical and horizontal \((\text{APF}_{\text{total}} \text{in N/m}^{-1})\), and $C_{0}$ \((\text{mL/kg}^{0.75}\text{min}^{-1})\) among elite endurance athletes \((n = 11)\). $\text{APF}_{\text{total}}$ = total average peak force; $C_{0}$ = oxygen cost of running. $\rho < 0.05$, $R = 0.66$. 
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running. Again, no such direct relationship was found in the present study. The previous studies and the present one are not directly comparable because of differences in design and measures. Farley and McMahon (7) used simplied reduced gravity to calculate the relationship between vertical ground reaction forces and RE, whereas Kram and Taylor (18) found RE to be inversely proportional to the weight supported among different species of animals at different speeds. Chang and Kram (4) used a horizontal force alternation device attached to the runner’s waist, thus testing running with or without horizontal aiding or impeding forces on the treadmill. In the present study, we applied no extra vertical or horizontal forces to the runners, nor did we provide extra vertical or horizontal aiding.

As far as we know, the present study is the first to have used contact soles and a regular force platform to measure vertical and horizontal forces while running on a treadmill. The device developed for hanging up the rear end of the treadmill makes it possible to use a regular treadmill to conduct horizontal force measurements. In Chang and Kram (4) a force-treadmill was used while the runners were running at a speed of 11.9 km/h⁻¹. Average peak horizontal breaking force was 2272 N, average peak propulsive force was 193.3 N, and average peak vertical propulsive force was 1670 N. The corresponding average peak values from the present study at the speed of 15.0 km/h⁻¹ was 370.7 N, 261.4 N, and 1457 N, respectively. The average contact time measured in Chang and Kram (4) was 0.263 seconds, whereas the average contact time in the present study was 0.251 seconds. As the measurements of the present study were carried out at a 21% higher running speed, the difference in peak average force and in contact time measured in the 2 studies seems reasonable.

In previous studies by Nummela et al. (21) and Paavolainen et al. (22), an inverse relationship has been reported between CT and RE. In the present study, no such relationship was apparent. The present results are thus in accordance with results from Williams and Cavanagh (28) and Kyrolainen et al. (19), who found no significant correlation between CT and RE when comparing distance running mechanics, RE, and performance. In the present study, no correlation was apparent between TPF for each step, SL, or SF and RE. The latter is thus in accordance with Kyrolainen et al. (19), who did not find significant correlations between SF and RE.

The present study showed a moderate inverse correlation between percent body fat and RE. This is in accordance with the results from Bunc (2), who reports poorer RE with a higher percentage body fat among nontrained females. A moderate inverse correlation between height and RE was also observed. No correlations were observed between other anthropometric variables and RE in the present study. The present results are in opposition to those of Lucia et al. (20), who found an inverse correlation between calf circumference and RE. The present results are also not in accordance with those of Williams and Cavanagh (28), who found elite female runners to have narrower pelvis than a female student population of the same age, and Steudel-Numbers et al. (25), who have shown an inverse correlation between relative leg length and RE.

No correlation was observed between maximal strength measured as 1RM in leg press (90 degrees) and RE in the present study. There was still no correlation between the 2 variables when 1RM was expressed relative to body weight or relative to body weight scaled to the power of 0.67 or 0.75. Further, no correlation was observed between 1RM and CT or TPF. In intervention studies by Hoff and Helgerud (16) and Støren et al. (26), MST has improved RE by approximately 5%. Although increased maximal strength improves running economy, the strongest athletes do not necessarily display the best running economy.

Practical Applications

Based on the present study, it seems that minimizing the external vertical and horizontal forces during running may enhance running economy. Reducing vertical forces might influence the stride length and frequency, whereas reductions in horizontal peak forces might be an object for a motor skill approach. Therefore, we advise runners to minimize the vertical movement of the center of gravity and the horizontal braking in each running step to improve running economy and distance running performance.

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References


