Introduction

Running economy (RE), defined as the submaximal aerobic demand for a given speed of running, is strongly linked to distance running performance [4]. Researchers have reported a 20% to 30% range in economy for several running speeds among age-, gender-, and performance-matched groups of trained distance runners [4, 5, 7, 12]. After decades of research, a selection of biomechanical and physiological variables have been identified as factors related to RE, but little progress has been realized toward discovering global measures that are consistent between groups of runners. Biomechanical variables include flexibility [5], external mechanical work [3], and horizontal braking forces [10]. Spawned by the theory put forth by Kram and Taylor [8], that the energy cost of running is determined by the cost of supporting one's mass and the time course of generating force, researchers in biomechanics have focused more closely on the association between RE and muscle activity just before and during ground contact (i.e., stance phase). Kyrolainen and colleagues emphasized the importance of muscle action just before and during ground contact by showing links between RE and the magnitude of knee extensor muscle activity in mostly male subjects [9, 10]. Recently, Abe et al. [1] reported a significant negative correlation between VO2 per distance and temporal electromyographic data were evaluated. Greater on-time duration of rectus femoris during stance, and greater on-time coactivation duration of rectus femoris-gastrocnemius during stance were significantly associated with more economical runners (i.e., lower VO2 per distance). The coactivation of biarticular leg muscles during stance is clearly linked to running economy and this control strategy may elicit greater elastic energy return.

Abstract

Relationships between an index of running economy (VO2 per distance) and the temporal electromyographic characteristics of leg muscles were quantified in female runners. Sixteen women performed a 30-min treadmill run at a speed designed to elicit a hard rating of perceived exertion. Near the end of the run, oxygen uptake, video, and electromyographic data were collected simultaneously. Measures of muscle on-time durations, and on-time coactivation durations were calculated from the following muscles: gastrocnemius, vastus lateralis, rectus femoris, and biceps femoris. Nonparametric correlations between VO2 per distance and temporal electromyographic data were evaluated. Greater on-time duration of rectus femoris during stance, and greater on-time coactivation duration of rectus femoris-gastrocnemius during stance were significantly associated with more economical runners (i.e., lower VO2 per distance). The coactivation of biarticular leg muscles during stance is clearly linked to running economy and this control strategy may elicit greater elastic energy return.

Key words
- running economy
- biomechanics
- electromyography
- muscle activity

Authors

G. Heise 1, M. Shinohara 1, L. Binks 3

Affiliations

1 School of Sport and Exercise Science, University of Northern Colorado, Greeley, Colorado, United States
2 School of Applied Physiology, Georgia Institute of Technology, Atlanta, Georgia, United States
3 Division of Health, Physical Education, and Recreation, Mayville State University, Mayville, North Dakota, United States

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experienced, female runners. It was hypothesized that better RE is associated with greater coactivation of biarticular muscles due to concurrent stabilization of multiple joints during stance.

Materials and Methods

Subjects and testing overview

Sixteen, experienced female runners volunteered to be participants ($X_{age} = 24.4 \pm 5.8$ yr; $X_{mass} = 59.7 \pm 5.0$ kg; $X_{ht} = 1.66 \pm 0.06$ m). After obtaining written informed consent, subjects participated in four test sessions which were part of a larger, IRB-approved study designed to examine the influence of different running tights. Prior to volunteering, participants were told they must be fit enough to comfortably maintain an 8 min-mile$^{-1}$ pace for at least 3 min and, on three of the four visits, complete a 30-min treadmill run coupled with various other physical activities. All participants reported running at least 3 times per week and averaged 8.7 yr of running experience.

During the first test session, participants ran at three speeds ($2.32 \text{ m}\cdot\text{s}^{-1}, 2.82 \text{ m}\cdot\text{s}^{-1}, 3.44 \text{ m}\cdot\text{s}^{-1}$) on a motor-driven treadmill (Trackmaster, model TMX425C, Full Vision, Inc., Newton, KS, USA) for 4 min at each speed, and then repeated this routine for three different clothing conditions. For the present study, the first session was considered as accommodation to treadmill running, metabolic data collection, and electromyography measurement procedures. Sessions 2, 3, and 4 were identical, multiple-activity sessions which included vertical jumping (single attempts and continuous jumping), muscle testing in a dynamometer, postural sway evaluation, and a 30-min run. The only difference between these three sessions was clothing condition (shorts, tights1, tights2). The activities performed during these three sessions were done in the same order, with prescribed rest periods between all activities. All data for the present study were collected from the end of the 30-min run for the shorts condition, which occurred during session 2, 3 or 4 depending on the random assignment of the clothing conditions.

Prior to testing, pairs of silver/silver chloride surface electrodes (Blue Sensor N; Ambu Inc., Linthicum, MD, USA) were placed on the belly of the following muscles of the right leg after the skin was prepared: gastrocnemius (lateral head); rectus femoris; vastus lateralis; and the long head of biceps femoris. Electrode site preparation consisted of shaving and cleaning with alcohol. A ground electrode was placed over the tibia. Electrodes were secured by elastic bandages and electrode wires were secured to a belt worn by subjects to minimize disruption during movement. Transmission, amplification, and collection of electromyographic (EMG) data were accomplished with a Myopac Jr. system (Run Technologies, Mission Viejo, CA, USA) in conjunction with Motus analog module (Vicon, Centennial, CO, USA). The frequency response of the EMG channels was 10 Hz – 1000 Hz. EMG data were full-wave rectified and then smoothed with a low-pass, fourth order, zero lag Butterworth filter at 15 Hz. Muscle onset and cessation for the entire running cycle were identified using an interactive, computer-graphics program that plotted the linear envelope of each EMG channel against time. This approach has been used before for a similar study [7] and it has been argued by Walter [14] that this method of temporal EMG analysis allows the experimenter “to fully utilize the pattern recognition capabilities of the human brain” (p. 162) and is more desirable than an automated, iterative procedure based on absolute thresholds. Muscle on-time durations were calculated as a percent of stance, depending on when the muscles were active during the running cycle. Durations of coactivation were determined by calculating, as a percent of stance, the common durations of muscle on-time between pairs of muscle groups (rectus femoris – biceps femoris, rectus femoris – gastrocnemius, biceps femoris – gastrocnemius). Data for the swing phase of the running cycle are not reported.

Results

The mean running speed was 3.04 m\cdot s$^{-1}$ and the mean VO$_2$ per distance was 0.214 ml$\cdot$kg$^{-1}$\cdot$m$^{-1}$ (Table 1). There was no problem identifying the onset and cessation of muscle activity from the linear envelope of each EMG signal (Fig. 1). The onset times of gastrocnemius, vastus lateralis, and rectus femoris occurred near foot contact and typically were active for 50–65% of stance. In all participants, biceps femoris was active late in swing, but showed greater variability, when compared to other muscles, in the duration of activity during stance phase. The mean on-time durations during stance phase of individual muscles...
were shortest in biceps femoris (40%) and longest in gastrocnemius (66%) (Table 2).

Two temporal EMG measures showed statistically significant correlations with VO₂ per distance. More economical runners were associated with a longer on-time duration of rectus femoris during stance and a longer duration of coactivation of rectus femoris-gastrocnemius during stance.

**Discussion**

The most important finding of the present study is that coactivation of biarticular muscles rectus femoris and gastrocnemius is clearly linked to RE. In particular, the negative correlation between RE and the coactivation duration of rectus femoris – gastrocnemius supports the trend identified by Heise and colleagues [7] in a smaller sample of men and it underscores the importance of how runners adjust activity in multiple muscles during ground contact. In the present sample of 16 women, this measure of muscle coactivation duration explained 45% of the interindividual variability in RE. Most on-time durations of individual muscles and of coactivation of pairs of muscles were close to 10% higher in the present study when compared to Heise et al. [7]. The correlations, however, between temporal EMG measures and running economy were similar. Differences are likely due to factors associated with methodologies of the two studies (e.g., determination and control of running speed) and in the EMG response between men and women [13].

**Table 1** Mean running speed and physiological measures. VO₂, oxygen uptake

<table>
<thead>
<tr>
<th>Variable</th>
<th>M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running speed (m·s⁻¹)</td>
<td>3.04</td>
<td>0.32</td>
</tr>
<tr>
<td>VO₂ (ml·kg⁻¹·min⁻¹)</td>
<td>38.9</td>
<td>3.4</td>
</tr>
<tr>
<td>VO₂ per distance (ml·kg⁻¹·m⁻¹)</td>
<td>0.214</td>
<td>0.013</td>
</tr>
</tbody>
</table>

**Table 2** Mean on-time durations of individual muscles during stance, coactivation durations of muscle pairs during stance, and correlations with VO₂ per distance (durations are expressed as a percent of stance time). The negative correlation coefficient indicates that an increase in the on-time durations of muscle is correlated with a decrease in VO₂ per distance

<table>
<thead>
<tr>
<th>Muscle</th>
<th>M</th>
<th>SD</th>
<th>r RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrocnemius</td>
<td>65.6</td>
<td>11.6</td>
<td>0.02</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>58.2</td>
<td>17.8</td>
<td>−0.34</td>
</tr>
<tr>
<td>Rectus femoris</td>
<td>52.6</td>
<td>12.5</td>
<td>−0.62*</td>
</tr>
<tr>
<td>Biceps femoris</td>
<td>40.2</td>
<td>26.2</td>
<td>0.36</td>
</tr>
<tr>
<td>Rectus femoris – biceps femoris</td>
<td>37.4</td>
<td>14.9</td>
<td>0.19</td>
</tr>
<tr>
<td>Rectus femoris – gastrocnemius</td>
<td>50.3</td>
<td>11.0</td>
<td>−0.67*</td>
</tr>
<tr>
<td>Biceps femoris – gastrocnemius</td>
<td>38.5</td>
<td>16.0</td>
<td>0.21</td>
</tr>
</tbody>
</table>

*p < .05

**Fig. 1** Representative, filtered EMG response of one runner. The linear envelopes are normalized with respect to the maximum value of the respective muscle. The stance phase is centered along the horizontal axis and identified by foot contact (FC) and toe-off (TO).
of eccentric to concentric EMG activity in the uniarticular muscle vastus lateralis. In conclusion, greater coactivation of biarticular leg muscles rectus femoris and gastrocnemius was associated with improved running economy. This is most likely due to the effective use of stored elastic energy, which is a by-product of the observed muscle activity strategy. A future step will be to examine the efficacy of EMG-based biofeedback during the running stride in order to provide athletes information about their muscle activation patterns. Promoting increased coactivation among key, biarticular muscles may improve economy and thus performance.

Acknowledgements

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