Biarticular Leg Muscles and Links to Running Economy

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

Abstract

Relationships between an index of running economy ($\dot{V}O_2$ 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 of 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 $\dot{V}O_2$ 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 $\dot{V}O_2$ 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.

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 RE and the ratio of eccentric-to-concentric vastus lateralis muscle activity measured during ground contact (i.e., lower aerobic demand related to higher ratio) in novice male runners. Beyond the findings of Abe et al. [1], which focused on a single knee extensor muscle (vastus lateralis), Heise and colleagues [7], in examining rectus femoris, gastrocnemius, and medial and lateral hamstrings, observed a trend that greater muscle coactivation between biarticular muscles was associated with better RE (i.e., lower metabolic cost) in nine male subjects.

The present study was designed to further investigate the trend identified by Heise et al. [7], by including more subjects, so that any links identified between RE and muscle coordination are more robust, and by monitoring the response of women, who are rarely studied in this context. Specifically, the purpose of this investigation was to quantify the relationships between RE and temporal EMG characteristics of leg muscles during stance, with special attention to the coactivation of biarticular leg muscles in a sample of

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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 ($\bar{x}_{age}$ = 24.4 ± 5.8 yr; $\bar{x}_{mass}$ = 59.7 ± 5.0 kg; $\bar{x}_{ht}$ = 1.66 ± 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 m·s^{-1}, 2.82 m·s^{-1}, 3.44 m·s^{-1}) on a motor-driven treadmill (Trackmaster, model TMX425C, Full Vison, 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 collected for a duration of 5 s at 1020 Hz. The sampling rate enabled EMG data to be synchronized with video data. All four channels of EMG data, along with a synch signal, were stored in digital format on a computer. For the present study, the video record from a 60-Hz digital camcorder (Panasonic PV-G55PKE, Secaucus, NF, USA) aimed at the anterior right side of the body (i.e., diagonal view) was used to identify the following temporal events during a running cycle: right foot contact (RFC); right toe-off (RTO); left foot contact (LFC); left toe-off (LTO).

Data collection for the 30-min run

After electrode wires were secured, subjects ran for 30 min at a speed which corresponded to a rating of perceived exertion (RPE) of 6, which corresponds to "hard" on a scale of 0 – 10 (0 = rest, 3 = moderate, 10 = maximum). This running speed was determined in the initial 8 min of the 30-min run and was mostly self-selected, which means that the experimenter coached each participant to ensure that an RPE of 6 was attained.

$\dot{V}O_2$ data and EMG data were collected over the final 2 min of the 30-min run. Expired gas was collected and sampled with a MedGraphics metabolic cart (SHDK, Medical Graphics Corp., St. Paul, MN, USA). As an index of RE, mean $\dot{V}O_2$ measured between minutes 28 and 30 was determined and normalized to body mass and running speed ($\dot{V}O_2$ per distance, ml·kg^{-1}·m^{-1}). It should be noted that a low $\dot{V}O_2$ per distance corresponds to an economical runner [1, 3].

Data analysis

From video records and with the aid of the digitizing features of the Motus motion analysis software, the pictures in which RFC and RTO took place were identified for a single running cycle. Subsequent measures of muscle on-time durations were determined as a percent of right leg stance time.

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.

Measures of on-time duration and coactivation during stance were correlated with $\dot{V}O_2$ per distance using the Spearman rank correlation technique. This nonparametric technique was used because the variability of EMG measures was generally much greater than the variability observed in $\dot{V}O_2$ per distance. The probability associated with a type I error was set at 0.05.

Results

The mean running speed was 3.04 m·s^{-1} and the mean $\dot{V}O_2$ per distance was 0.214 ml·kg^{-1}·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 of individual muscles

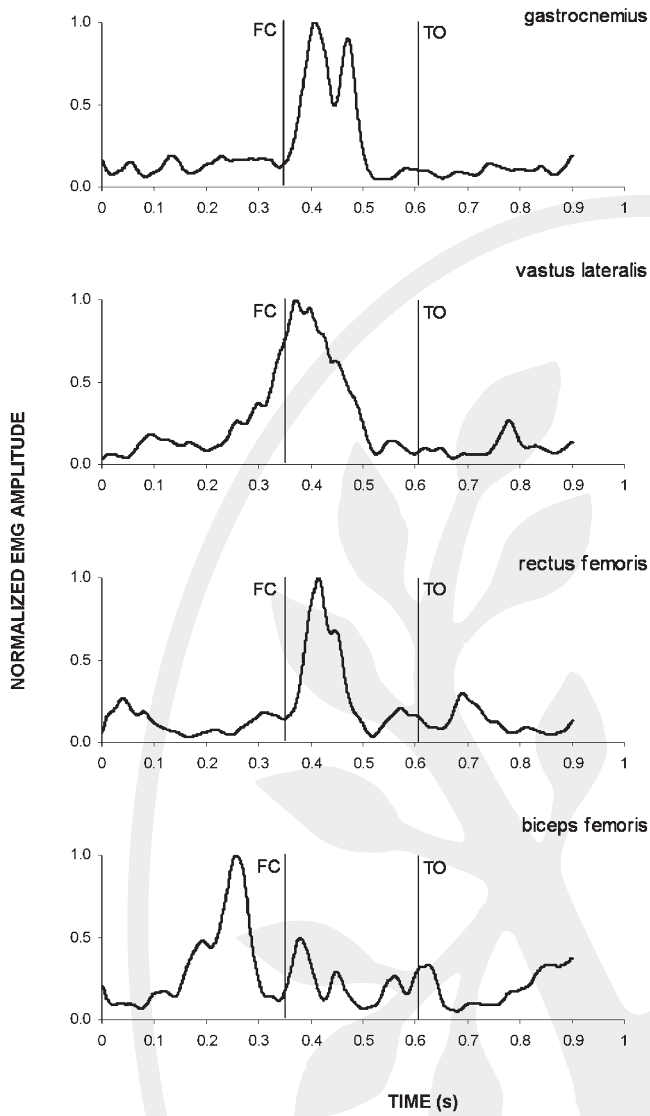

Fig. 1 Representative, filtered EMG response of one runner. The linear envelopes are normalized with respect to the maximum value of the respective muscle. The stance phase is centered along the horizontal axis and identified by foot contact (FC) and toe-off (TO).

Table 1 Mean running speed and physiological measures. $\dot{V}O_2$, oxygen uptake

Variable	M	SD
Running speed ($m \cdot s^{-1}$)	3.04	0.32
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	38.9	3.4
$\dot{V}O_2$ per distance ($ml \cdot kg^{-1} \cdot m^{-1}$)	0.214	0.013

Table 2 Mean on-time durations of individual muscles during stance, coactivation durations of muscle pairs during stance, and correlations with $\dot{V}O_2$ 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 $\dot{V}O_2$ per distance

Muscle	M	SD	r_{RE}
Gastrocnemius	65.6	11.6	0.02
Vastus lateralis	58.2	17.8	– 0.34
Rectus femoris	52.6	12.5	– 0.62*
Biceps femoris	40.2	26.2	0.36
Rectus femoris – biceps femoris	37.4	14.9	0.19
Rectus femoris – gastrocnemius	50.3	11.0	– 0.67*
Biceps femoris – gastrocnemius	38.5	16.0	0.21

* $p \leq .05$

were shortest in biceps femoris (40%) and longest in gastrocnemius (66%) (**Table 2**).

Two temporal EMG measures showed statistically significant correlations with $\dot{V}O_2$ 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].

The effective timing of muscle activation and relaxation during the stance phase of running is a prerequisite for effective force application between the body and the ground [9]. More effective strategies for this force production result in more economical motion. The present study shows that longer duration of muscle coactivation between rectus femoris and gastrocnemius during stance provides a better metabolic solution to stability at multiple joints when compared to the single-joint muscle solution. This strategy is in agreement with the suggestion that biarticular muscles redistribute mechanical power from proximal joints to distal joints and ultimately to the ground [2].

Muscle coactivation increases joint stiffness, and greater joint stiffness allows for efficient use of stored elastic energy [11]. Hence, more economical runners may coactivate biarticular muscles to use increased joint stiffness to their advantage by utilizing more stored elastic energy. Indirect evidence of this link between increased joint stiffness and better RE can be found from studies which examined passive flexibility and RE. Runners exhibiting less flexibility during static stretching were more economical than those who were more flexible [5,6]. In addition, the association between the utilization of stored elastic energy and RE during running is suggested from researchers who examined the ratio of eccentric to concentric EMG activity in knee extensor muscles [1,3]. The only significant finding from those studies, however, was the correlation between RE and the ratio 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.

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