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Submaximal neuromuscular economy is related to cardiorespiratory fitness in endurance-trained runners

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ABSTRACT

A number of factors determine neuromuscular economy (NE) and running economy (RE) in endurance-trained runners. The purpose of this investigation was to examine the relationship between aerobic fitness and NE in endurance-trained runners. Twenty-seven endurance-trained runners (25.1 ± 10.2 y) completed a maximal voluntary isometric contraction of the leg extensors to measure maximal electromyography (EMG_{max}) amplitude of the vastus lateralis (VL) and rectus femoris (RF), a steady-state treadmill run at 9.66, 11.27, and 12.87 km·hr^{-1} and a maximal graded exercise test. Participants were outfitted with surface electrodes over the VL and RF muscles to record EMG amplitude throughout each test. During the steady-state test, the EMG (as a percentage of EMG_{max}) and oxygen consumption (VO_2) over the final minute of each stage were established and considered NE and RE, respectively. Pearson product moment correlations were used to determine the relationships between VO_2max and velocity at VO_2max (vVO_2max) and NE and RE. The results revealed significant negative correlations between VO_2max and vVO_2max and relative NE and RE at all three speeds. In addition, there were significant correlations between relative RE and NE at all three speeds. These results indicate that faster runners have improved NE and RE when expressed as a relative measure.

1. Introduction

Running economy (RE), previously defined as the oxygen uptake at a given running speed (Conley and Krahenbuhl, 1980; Daniels, 1985), has been identified as one valuable factor in predicting running performance in a homogenous group of distance runners over the 10 km distance (Conley and Krahenbuhl, 1980; Morgan et al., 1989). Multiple factors are likely involved in determining RE and evidence suggests that RE is variable over time and influenced by adaptations in motor programming and neuromuscular recruitment, brought about by running training, (Anderson, 1996; Thoroughman, 1999; Osu et al., 2002). In an attempt to further clarify the numerous efficiency factors influencing RE, Barnes and Kilding (2015) suggested that neuromuscular efficiency in particular can be divided into two categories: (1) those factors that impact the neural signaling and motor programming of the running motion and (2) those factors that impact muscle force production.

In studies investigating the first of these, it has earlier been suggested that biomechanical factors related to motor programming and running motion may also account for a substantial portion of variations in RE. A faster runner is characterized by lower vertical oscillations than a slower runner (Gregor and Kirkendall, 1978), typically has longer strides (Hoshikawa et al., 1971; Cavanagh and Williams, 1982), has less change in velocity during ground contact (Kaneko et al., 1985), and tends to land more toward the midfoot during foot strike, which is associated with a lower first peak in the vertical component of the ground reaction force (Williams and Cavanagh, 1987).

As it pertains to factors involved with muscular force production, Bonacci et al. (2009) suggest that running training impacts motor programming and recruitment through the promotion of a learning effect. Barnes and Kilding (2015) separate muscle force production into two areas: (1) velocity of contraction and (2) the balance between concentric and eccentric contractions. To this point, Paavolainen et al. (1999) examined distance runners over the 10 km distance and found that those runners with faster times had higher relative pre-activation

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and lower relative integrated EMG activities during the propulsion phase of the stride suggesting that neural control of muscle force production may play an important role in determining distance running performance in well-trained endurance athletes. The result of this work suggests that to optimize these factors, which requires precise timing and integration, considerable practice and training must be involved.

Neuromuscular economy (NE) has been defined as the lower muscle activation, represented by electromyography (EMG) amplitude that is necessary to move a given, absolute load (Cadore et al., 2011a). There have been a number of investigations examining the relationship between aerobic fitness and muscular strength (Hoff et al., 1999, Paavolainen et al., 1999 Mikkola et al., 2007, Cadore et al., 2011b) where a negative relationship between aerobic fitness and muscular strength was demonstrated. There currently appears to be a lack of work to date investigating the electromyographic response to running at submaximal speeds in an effort to describe NE during a dynamic, static-state aerobic activity.

Finally, another performance variable that has been used to predict running performance is the velocity at which VO_2max (vVO_2max) occurs, or peak treadmill velocity during an incremental treadmill test. Athlete vVO_2max has been included along with other factors in regression-generated prediction equations of endurance performance. A number of studies have shown that vVO_2max has been the best predictor of running performance from the 3 km run to the marathon (Noakes et al., 1990; Grant et al., 1997; Slattery et al., 2006; Stratton et al., 2009; McCormack et al., 2018). To date there is a lack of information about the relationship between NE and measures of aerobic fitness. Therefore, the purpose of this investigation was to examine the relationship between aerobic fitness, measured by VO_2max and vVO_2max, and measures of economy, both running and neuromuscular, during steady-state treadmill running in endurance trained runners. The hypothesis for this investigation was that runners with a higher aerobic capacity would demonstrate an enhanced NE and RE at multiple, set submaximal running speeds.

2. Methods

2.1. Experimental design

The University Institutional Review Board approved all experimental protocols and signed informed consent was obtained from each participant prior to the performance of any experimental procedures. Participants reported to the Human Performance Lab for a single visit where they were asked to treat the testing day as a race day by reporting to the lab rested and performing only light activity the day prior. Initially, participants were outfitted with EMG electrodes and transmitter. After electrode placement, participants performed the following tests in order: maximum isometric knee extension testing to determine maximal muscular activity of the vastus lateralis and rectus femoris, a running economy test, and VO_2max test.

2.2. Participants

Twenty-seven endurance-trained individuals (male = 15; female = 12) volunteered for the study. Participant data is presented in Table 1. All participants were recruited via word-of-mouth or flyer advertisement throughout the university and local running communities. Inclusion criteria comprised being active in local road or track races and having completed a long run of at least 60 min in duration in the past month. Participants' mean training quantity over the past six months and longest run over the past month were recorded and are presented in Table 1. All participants were free of any physical limitations as determined by the Confidential Medical and Activity questionnaire and Physical Activity Readiness Questionnaire.

Table 1
Participant data (mean ± SD).

Variable	Group (n = 27)	Women (n = 12)	Men (n = 15)
Age (yrs)	25.1 ± 10.2	24.6 ± 8.7	25.6 ± 11.6
Height (cm)	171.3 ± 8.4	165.4 ± 7.9	176.1 ± 5.4*
Mass (kg)	62.1 ± 7.2	55.8 ± 4.2	67.1 ± 4.6*
VO_2max (ml·kg^{-1}·min^{-1})	61.0 ± 7.4	56.9 ± 5.1	65.4 ± 6.9*
vVO_2max (km·hr^{-1})	18.14 ± 2.90	16.46 ± 1.77	19.47 ± 2.96*
Weekly Mileage (km)	87.5 ± 29.6	83.7 ± 24.9	90.6 ± 33.5
Long Run (km)	23.0 ± 5.0	21.4 ± 5.3	24.3 ± 4.5
HR @ VO_2max (bpm)	188.0 ± 7.6	187.6 ± 7.5	188.3 ± 7.9
RER @ VO_2max	1.12 ± 0.09	1.12 ± 0.10	1.12 ± 0.09

* Indicates significant differences ($p < 0.05$) between men and women.

2.3. Electromyography placement

To measure EMG activity, a bipolar (4.0 cm center-to-center) surface electrode (EL501; BIOPAC Systems Inc.; Santa Barbara, CA) arrangement was placed over the right vastus lateralis (VL) and rectus femoris (RF) muscles for assessment of knee extensor and hip flexor activity respectively. Electrodes over the VL were placed two-thirds of the distance distally between the anterior superior iliac spine (ASIS) and the most lateral aspect of the patella and 5 cm lateral to this line with the participant in a standing position. Electrodes over the RF muscle were positioned halfway between the inguinal fold and the superior border of the patella, while the participant's hip and knee were flexed 90°. The RF muscle was palpated during a contracted state to ensure placement over the belly of the muscle. A ground electrode was placed over the ASIS. To ensure proper signal conductance, skin around the marked areas was shaved and cleaned by rubbing with alcohol prior to electrode affixation. A 2-channel wireless EMG transmitter (BIONOMADIX Dual-channel Wireless EMG Transmitter; BIOPAC Systems, Inc., Santa Barbara, CA) was used to transmit the EMG information to a receiver/amplifier (MP150 BIOPAC Systems, Inc.; Santa Barbara, CA). The transmitter was strapped to the thigh approximately 3 cm above the top electrode with Velcro straps. The electrodes and transmitter wires were wrapped with cohesive bandage (Coban; 3M; St. Paul, MN) to prevent wire-slap and electrode movement.

2.4. Maximum voluntary isometric contraction (MVIC) testing

Maximal voluntary muscular activity was measured utilizing an isokinetic device (HUMAC Norm; CSMi; Stoughton, MA). Participants were strapped into the device where proper alignment and positioning on the device was determined in accordance with device standard operating procedures. The maximal muscular activity of the knee extensors was determined while seated with a hip angle of 90° and knee flexion angle of 70°. Participants were given one, six second trial to practice and familiarize themselves with the maneuver. Following 60 s of rest, participants performed three knee extension isometric contractions lasting 6 s each, separated by 3 min of rest for recovery. Lab personnel provided verbal encouragement throughout each trial to encourage maximal effort and participants were allowed visual feedback through real-time data monitoring.

2.5. Running economy and VO_2max testing

Following a five min self-paced warm-up, RE testing was performed at 9.66, 11.27, and 12.87 km·hr^{-1}. Participants ran the three, five min stages in a continuous manner on a treadmill (4Front; Woodway; Waukesha; WI) with expired gases analyzed with a metabolic cart (Quark CPET; COSMED; Rome; Italy) for oxygen consumption and carbon dioxide production. The metabolic cart was calibrated prior to each test. For the VO_2 at each RE speed, the mean value of the final 1 min of VO_2 data was used for analysis. The RE was reported three ways: (1) as VO_2 in ml·kg^{-1}·min^{-1}; (2) as VO_2 in ml·kg^{-1}·km^{-1} at the three running velocities and (3) as a percentage of VO_2max. At the completion of the RE test, participants were given a 10 min rest period. The subsequent VO_2max testing consisted of 1 min stages with increasing speed until the participant could no longer continue. Speed increases between stages were 0.124 km·hr^{-1}. The initial speed of the treadmill was set at the final RE speed (12.87 km·hr^{-1}) with the goal of completing the test within 8–12 min. The criteria utilized to determine if a valid VO_2max test was performed included a leveling of VO_2, defined as an increase of less than 150 ml·min^{-1} with increasing intensity and a respiratory exchange ratio (RER) of ≥1.10 (Howley et al., 1995). The VO_2 data during this portion of the test were averaged over 30 s periods. The highest aggregate 30 s VO_2 data was considered VO_2max. The velocity corresponding to the 30 s period where VO_2max was observed was considered their vVO_2max. Verbal encouragement was provided by lab personnel throughout the VO_2max portion of the test.

2.6. Electromyography analysis

All EMG signals were expressed as root mean square (RMS) amplitude values (μVrms) by software (AcqKnowledge v4.4, BIOPAC Systems, Inc., Santa Barbara, CA). The RMS value from each maximal voluntary isometric contraction (MVIC) was analyzed using methods described by Cadore et al. (2010). The middle four seconds of the six second signal was visually scanned for the maximum signal. The one second of the signal surrounding the peak RMS value from the best trial was averaged and used as the maximum RMS signal (EMG_{max}). During the RE test, the mean RMS value for the 60 s from the 3:30 to the 4:30 segment of the stage was computed and then compared to the EMG_{max} value determined from the maximal leg extension trials to give a percentage of maximal muscular activity, or NE. During the VO_2max test, the mean RMS value during the middle 15 s of the 30 s portion of the test used to compute VO_2max was used to calculate EMG at VO_2max. In a similar fashion to EMG economy, the EMG at VO_2max value was compared against the maximal leg extension value to determine the percentage of maximum activity utilized during VO_2max.

2.7. Statistical analysis

All data are reported as mean ± standard deviation. All data were analyzed via Pearson Product Moment Correlations. Participant mass was controlled for in the correlation analysis. An alpha level of $p < 0.05$ was used to determine statistical significance. All statistical analyses were conducted utilizing the Statistical Package for Social Science (SPSS) software for Windows version 22 (SPSS, IBM Corp., Armonk, NY).

3. Results

RE and NE data are presented in Tables 2 and 3, respectively. The Pearson Product Moment Correlations between NE (as a percentage of maximum) and VO_2max and vVO_2max are presented in Table 4. As a group there were significant negative correlations between both

Table 2
Running Economy data presented in ml·kg^{-1}·min^{-1} and % of VO_2max.

Variable	Group (n = 27)	Women (n = 12)	Men (n = 15)
RE9.66 (ml·kg^{-1}·min^{-1})	35.5 ± 3.7	35.6 ± 4.1	35.5 ± 3.4
RE9.66 (%)	58.6 ± 10.9	62.9 ± 9.7	55.1 ± 10.7
RE11.27 (ml·kg^{-1}·min^{-1})	40.0 ± 4.0	40.1 ± 4.6	39.9 ± 3.6
RE11.27 (%)	65.9 ± 11.6	70.9 ± 5.1	61.9 ± 11.2*
RE12.87 (ml·kg^{-1}·min^{-1})	45.8 ± 4.2	45.3 ± 4.7	46.1 ± 3.8
RE12.87 (%)	74.8 ± 11.3	79.3 ± 9.6	71.4 ± 11.6

All data is presented as mean ± SD.
* Indicates significant differences ($p = 0.044$) between men and women.

Table 3
Neuromuscular economy data presented as absolute (μV) and relative measures (% of EMGmax).

Variable	Group (n = 27)	Women (n = 12)	Men (n = 15)
VLEMG9.66 (μV)	98.0 ± 38.5	119.5 ± 45.7	80.9 ± 19.9*
VLNE9.66 (%)	24.5 ± 15.2	32.3 ± 18.4	18.3 ± 8.3*
RFEMG9.66 (μV)	85.0 ± 58.4	122.6 ± 68.3	54.9 ± 22.2*
RFNE9.66 (%)	18.7 ± 19.0	27.8 ± 21.7	11.5 ± 13.2*
VLEMG11.27 (μV)	101.2 ± 38.7	124.3 ± 44.5	82.8 ± 20.2*
VLNE11.27 (%)	25.2 ± 15.4	33.6 ± 18.7	18.5 ± 7.7*
RFEMG11.27 (μV)	82.8 ± 63.7	120.6 ± 81.2	52.5 ± 12.1*
RFNE11.27 (%)	16.7 ± 13.2	25.1 ± 13.6	10.0 ± 8.3*
VLEMG12.87 (μV)	102.0 ± 28.2	119.2 ± 29.2	89.5 ± 20.2*
VLNE12.87 (%)	24.0 ± 8.8	29.5 ± 6.4	20.0 ± 8.2*
RFEMG12.87 (μV)	80.9 ± 36.5	108.3 ± 40.2	60.9 ± 14.5*
RFNE12.87 (%)	16.4 ± 11.0	23.2 ± 9.7	11.4 ± 9.2*

All data is presented as mean ± SD.
VL = Vastus Lateralis; RF = Rectus Femoris; EMG = Electromyograph; NE = Neuromuscular Economy.
* Indicates significant differences ($p < 0.05$) between men and women.

VO_2max, vVO_2max and measures of NE at all three speeds and for VL and RF. When NE was expressed as an amplitude measure (μV) there were no significant relationships with VO_2max or vVO_2max at any speed. When the data are separated by sex, the only significant relationships were between NE and vVO_2max for both muscles in men at all speeds and between VO_2max and RF at 9.66 km·hr^{-1} in the men along with VO_2max and NE at 11.27 and 12.86 km·hr^{-1} for VL in the women. The correlations between RE (as ml·kg^{-1}·km^{-1} and as a percent of VO_2max) and VO_2max and vVO_2max are presented in Table 5. For the group data, there were significant negative correlations between VO_2max and RE as a percent of VO_2max at all three running speeds as well as between vVO_2max and all measures of RE at all speeds except at 9.66 km·hr^{-1} when measured in ml·kg^{-1}·min^{-1}. Each sex had significant negative relationships between RE (in both relative and absolute measures) and vVO_2max. The men had significant negative correlations between VO_2max and relative measures of RE. The women only had a significant negative correlation between VO_2max and RE as a relative measure at 9.66 km·hr^{-1}, with trends toward a significant relationship at the other two speeds. Graphic representations of the correlations between NE and both VO_2max and vVO_2max are presented in Figs. 1 and 2, respectively.

There were significant correlations between RE (as a percent of VO_2max) and NE (as a percent of EMG_{max}) at all three speeds and for both VL and RF. At 9.66 km·hr-1 the correlation was 0.484 ($p = 0.018$) for VL and 0.587 ($p = 0.002$) for RF. At 11.27 km·hr-1 the correlation was 0.631 ($p = 0.001$) for VL and 0.465 ($p = 0.019$) for RF. At 12.87 km·hr-1 the correlation was 0.655 ($p < 0.001$) for VL and 0.515 ($p = 0.009$) for RF. The relationship between peak torque on the isokinetic dynamometer, and measures of aerobic fitness, VO_2max and vVO_2max was not significant (r = 0.245, $p = 0.227$, and r = 0.004, $p = 0.985$, respectively).

4. Discussion

The results of the NE correlations in this investigation indicate there is a significant negative relationship between NE and both VO_2max and vVO_2max in this cohort of endurance trained runners. This finding is independent of a muscular strength measure (an MVIC with an isokinetic dynamometer in this investigation) because there was no relationship between peak torque on the isokinetic dynamometer and VO_2max or vVO_2max. The data indicate that the runners with higher VO_2max values utilized a lower percentage of their maximal electrical activity as measured by EMG in the vastus lateralis and rectus femoris during treadmill running at set running speeds. In a similar fashion,

Table 4a
Group correlations between neuromuscular economy (as a percentage of EMGmax at the three speeds and VO_2max and velocity at VO_2max).

Group		VLNE9.66	RFNE9.66	VLNE11.27	RFNE11.27	VLNE12.87	RFNE12.87
VO_2max	r	−0.474	−0.480	−0.598	−0.465	−0.610	−0.484
	p	0.017	0.015	0.002	0.019	0.001	0.014
vVO_2max	r	−0.536	−0.530	−0.645	−0.555	−0.686	−0.695
	p	0.006	0.006	0.001	0.004	< 0.001	< 0.001

VL = Vastus Lateralis; RF = Rectus Femoris; NE = Neuromuscular Economy.

Table 4b
Correlations for the men between neuromuscular economy (as a percentage of EMGmax at the three speeds and VO_2max and velocity at VO_2max).

Men		VLNE9.66	RFNE9.66	VLNE11.27	RFNE11.27	VLNE12.87	RFNE12.87
VO_2max	r	−0.495	−0.564	−0.435	−0.510	−0.495	−0.484
	p	0.072	0.035	0.120	0.062	0.111	0.079
vVO_2max	r	−0.747	−0.666	−0.733	−0.714	−0.759	−0.720
	p	0.002	0.009	0.003	0.004	0.002	0.004

VL = Vastus Lateralis; RF = Rectus Femoris; NE = Neuromuscular Economy.

Table 4c
Correlations for the women between neuromuscular economy (as a percentage of EMGmax at the three speeds and VO_2max and velocity at VO_2max).

Women		VLNE9.66	RFNE9.66	VLNE11.27	RFNE11.27	VLNE12.87	RFNE12.87
VO_2max	r	−0.413	−0.274	−0.729	−0.079	−0.752	−0.112
	p	0.236	0.444	0.017	0.828	0.012	0.759
vVO_2max	r	−0.263	−0.247	−0.196	0.025	0.022	−0.276
	p	0.463	0.491	0.588	0.945	0.953	0.440

VL = Vastus Lateralis; RF = Rectus Femoris; NE = Neuromuscular Economy.

Table 5a
Group correlations between running economy and measures of aerobic fitness.

Group		RE9.66(ml)	RE9.66(%)	RE11.27(ml)	RE11.27(%)	RE12.87(ml)	RE12.87%
VO2max	r	−0.141	−0.768	−0.110	−0.787	−0.016	−0.783
	p	0.501	< 0.001	0.602	< 0.001	0.938	< 0.001
vVO2max	r	−0.378	−0.771	−0.536	−0.891	−0.468	−0.894
	p	0.062	< 0.001	0.006	< 0.001	0.018	< 0.001

RE9.66(ml), RE11.27(ml), and RE12.87(ml) are running economy measured as ml·kg^{-1}·min^{-1}.

Table 5b
Correlations for the men between running economy and measures of aerobic fitness.

Men		RE9.66(ml)	RE9.66(%)	RE11.27(ml)	RE11.27(%)	RE12.87(ml)	RE12.87%
VO2max	r	−0.452	−0.793	−0.321	−0.785	−0.203	−0.769
	p	0.105	0.001	0.263	0.001	0.486	0.001
vVO2max	r	−0.547	−0.732	−0.729	−0.917	−0.746	−0.951
	p	0.043	0.003	0.001	< 0.001	0.002	< 0.001

RE9.66(ml), RE11.27(ml), and RE12.87(ml) are running economy measured as ml·kg^{-1}·min^{-1}.

Table 5c
Correlations for the women between running economy and measures of aerobic fitness.

Women		RE9.66(ml)	RE9.66(%)	RE11.27(ml)	RE11.27(%)	RE12.87(ml)	RE12.87%
VO2max	r	−0.024	−0.643	0.045	−0.618	0.072	−0.609
	p	0.947	0.045	0.903	0.057	0.843	0.062
vVO2max	r	−0.686	−0.733	−0.715	−0.782	−0.665	−0.748
	p	0.029	0.016	0.020	0.008	0.036	0.013

RE9.66(ml), RE11.27(ml), and RE12.87(ml) are running economy measured as ml·kg^{-1}·min^{-1}.

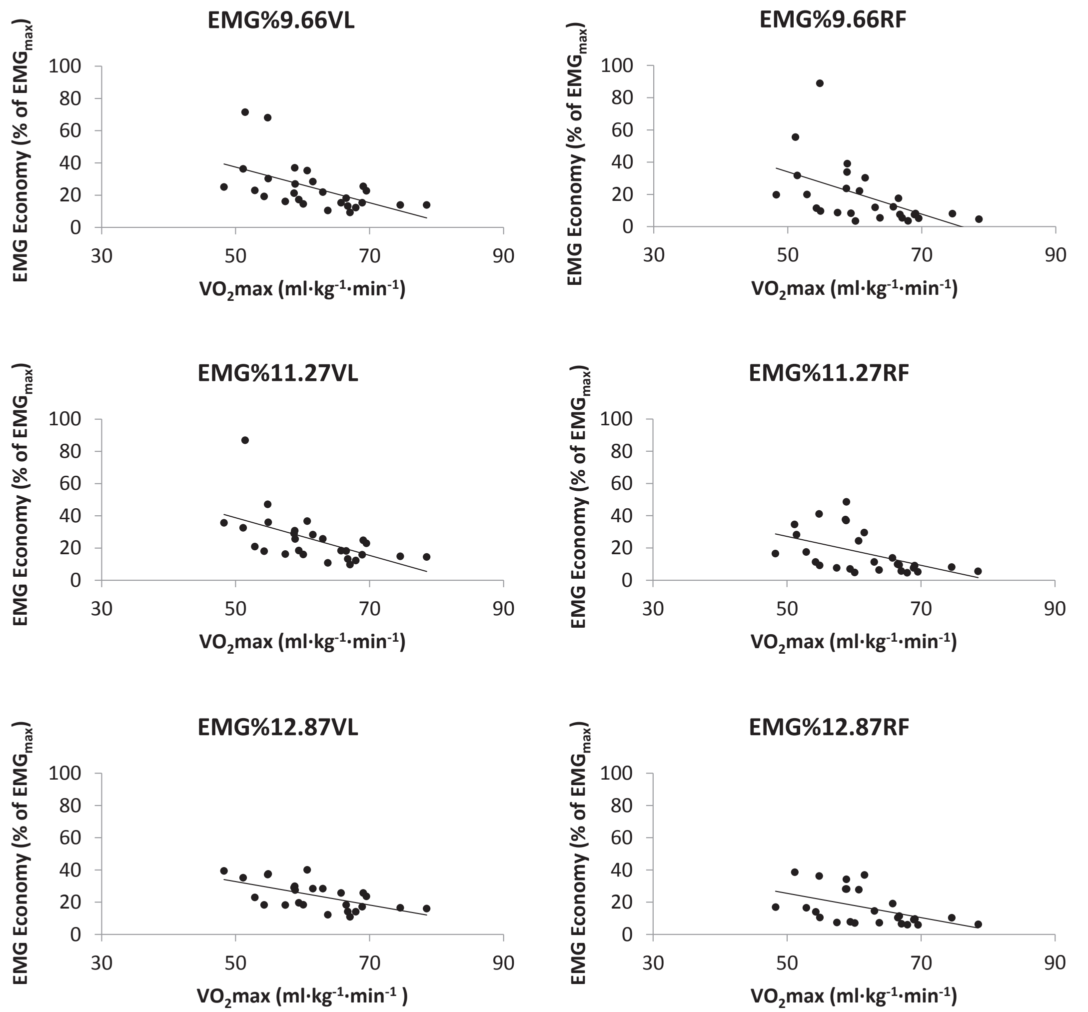

Fig. 1. Scatterplots of neuromuscular economy versus VO_2max at the three running speeds for Vastus Lateralis (VL) and Rectus Femoris (RF).

those runners that achieved a higher speed during their VO_2max test had lower relative EMG signals at the three NE speeds. These findings are in agreement with Cadore et al. (2011a,b) that reported more economical runners or cyclists utilized a lower percentage of their EMG_{max} amplitude at given speeds on the treadmill or resistance on the cycle. From the present investigation, the more economical runners were also the more aerobically fit runners as determined by VO_2max. Additionally, these findings are in agreement with Paavolainen et al. (1999) who showed that in a group of highly trained endurance runners, those runners with faster 5 and 10 km run times had lower relative EMG activity during the propulsion phase of the stride.

There are several possible explanations for this relationship, including improvements in the neural signaling and motor programming of the running motion and factors that impact muscle force production (Barnes and Kilding, 2015). Similar to adaptations producing improvements in the neural system seen with resistance training (Sale, 1988; Enoka, 1997; Carroll et al., 2001), Bonacci et al. (2009) suggest the same with running training, that there are improvements in motor programming and recruitment or a learning effect. This increase in efficiency may be responsible for the decreased EMG signal at a given running speed. The improvement in recruitment may contribute to better running biomechanics which would lead to a better NE as well as RE. A number of investigations have shown a relationship between RE and biomechanical factors, where the faster endurance runner exhibits better RE than slower endurance runners (Kyröläinen, 2016). Additionally, the NE differences seen in this investigation may be attributed to the differences in muscle force development, including the precise timing between eccentric and concentric contraction during the running stride (Barnes and Kilding, 2015).

Interestingly, there were significant relationships between the relative measures of NE and RE data. In this group of endurance-trained runners, those runners that had better NE additionally had better RE. This is in agreement with the work of Barnes and Kilding (2015) and Bonacci et al. (2009) presented previously. The factors that lead to better NE, in turn may lead to better RE. These factors include improvements in muscle recruitment and contraction timing, which may lead to better running biomechanics as well.

The relationships between VO_2max and RE have been reported in numerous studies (Pate et al., 1992; Morgan and Daniels, 1994; Tartaruga et al., 2012; Shaw et al., 2015). In studies where the variables were measured in $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, Pate et al. (1992) showed a small positive relationship ($r = 0.258$; $p = 0.0008$) in a group of recreational runners (men and women) with RE measured at $9.66\ km{\cdot}hr^{-1}$. This is different than the results from this investigation where no relationship was found ($r = -0.141$; $p = 0.501$). However, the VO_2max values of the Pate et al. study with recreational runners were much lower than in the present study. Specific to male participants Morgan and Daniels (1994) and Tartaruga et al. (2012) showed significant, positive relationships, $r = 0.59$; $p < 0.01$, $r = 0.525$; $p = 0.021$, between VO_2max and RE respectively. Shaw reported RE as an oxygen cost in $ml{\cdot}km^{-1}$ resulting in a significant relationship with VO_2max in both men ($r = 0.33$; $p = 0.001$) and women ($r = 0.33$; $p = 0.006$). When the data from the present investigation was similarly expressed as $ml{\cdot}km^{-1}$, the men showed significant relationships at all speeds while the women

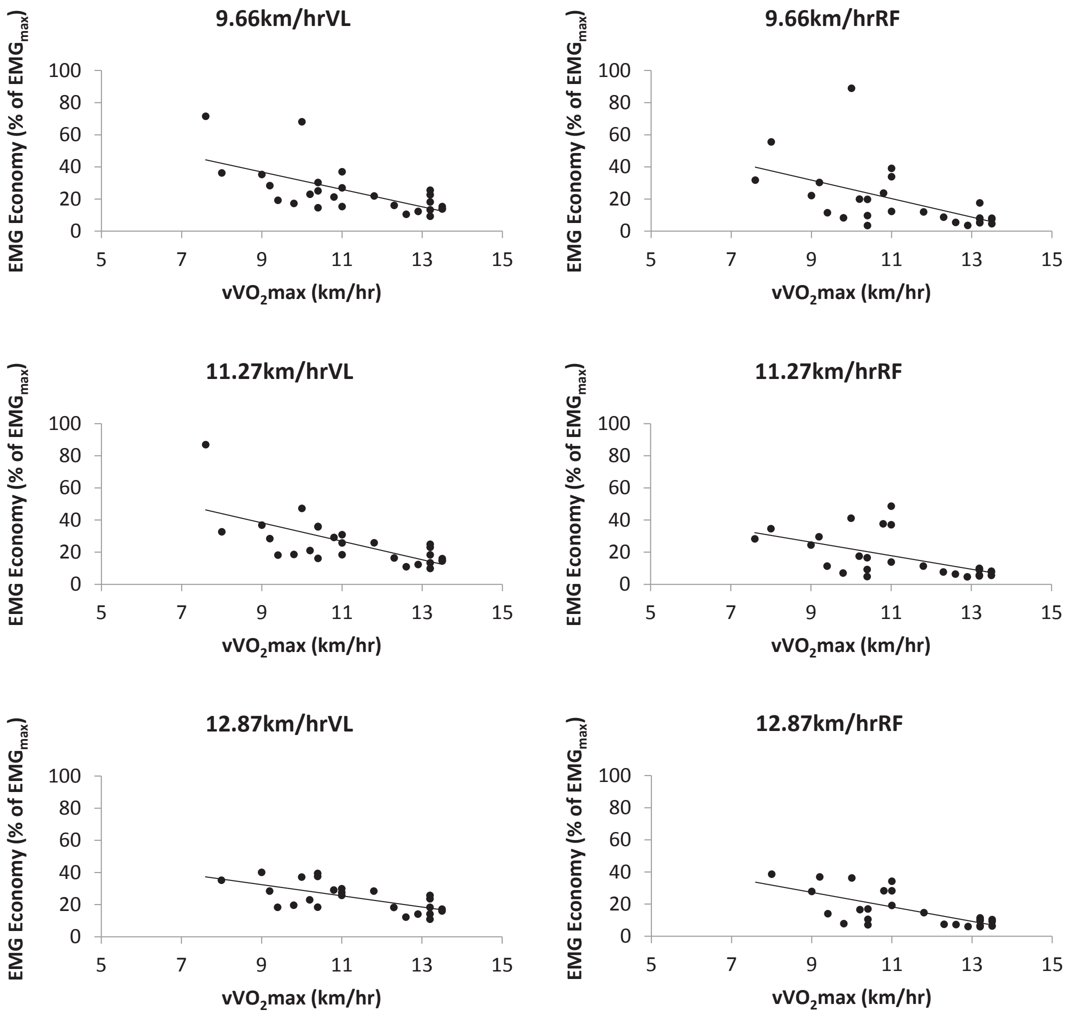

Fig. 2. Scatterplots of neuromuscular economy versus vVO_2max at the three running speeds for Vastus Lateralis (VL) and Rectus Femoris (RF).

contrastingly showed no such relationships.

Limitations to the present study include not having a concise running history of the participants, including the number of years of running and/or quantification of training volume over their running lives. This possibly would have allowed for a better examination of the timing of neural adaptations taking place due to running over time. Photo analysis of the treadmill test would have allowed for a more precise examination of the timing of the stride to better corroborate the EMG signal with the various portions of the stride. Best recent race performances of the participants (or a time trial) would have also been helpful.

In conclusion, in a group of heterogeneous endurance trained runners it appears that more aerobically fit runners have better NE than less fit runners. This relationship may be explained in part by better motor programming and muscular recruitment as well as muscle force production factors. Future research into the duration of time required to optimize these neural adaptations as well as how other factors such as resistance training impact NE and its relationship to VO_2max and vVO_2max is warranted.

Declaration of Competing Interest

The authors report no conflicts of interest. No funding was received for this investigation.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2019.06.006.

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