European Journal of Applied Physiology (2019) 119:791–800
https://doi.org/10.1007/s00421-018-04070-w

ORIGINAL ARTICLE

Changes in blood lactate and muscle activation in elite rock climbers during a 15-m speed climb

Feng Guo[1] · **Qingfu Wang**[2] · **Yuanlong Liu**[3] · **Nicholas J. Hanson**[3]

Received: 8 March 2018 / Accepted: 31 December 2018 / Published online: 28 January 2019

Abstract

Purpose The purpose of this study was to investigate the changes in blood lactate concentration (BL) and muscle activity patterns during a 15-m speed climbing competition that consisted of ten consecutive climbing actions on a standardized artificial wall in trained rock climbers.

Methods Twelve trained rock climbers participated in this study. Surface electromyography (sEMG) and video signals were synchronized and recorded during climbing. The blood lactate was also tested 3 min after completing the climb.

Results The average climbing time was 8.1 ± 2.1 s for the 15-m speed climb across all subjects, accompanied by a BL of 7.6 ± 1.9 mmol/L. The climbing speed and power firstly increased and then slightly decreased relative to peak value during the 15-m speed climbing. The results showed there was a positive correlation between the BL and the climbing time, $r = 0.59$, $P = 0.043$. The sEMG showed the flexor digitorum superficialis (FDS) electric activity was the highest, followed by the biceps brachii (BB) and latissimus dorsi. The instantaneous median frequency of sEMG of FDS and BB significantly decreased during the 15-m speed climbing. All the participants showed the higher sEMG RMS (%) in the terminal phase than that in the initial phase, especially with a greater increase in the left upper limbs. However, the lower limbs muscles presented no significant changes in the sEMG amplitude during climbing.

Conclusions The FDS and BB play an important role in completing the 15-m speed climbing. The median frequency of arm EMG decreased more than that of legs, suggesting more fatigue. The blood lactate concentration increases in the current study suggest that a certain amount of glycolysis supplies energy in completing 15-m speed rock climbing. Based on the current data, it is suggested that muscular endurance of FDS and BB muscles in upper limbs should be improved for our climbers in this study.

Keywords Competition speed climbing · Neuromuscular fatigue · Surface electromyography

Abbreviations

iEMG	Integrated electromyography
M.	Muscle
MF	Median frequency
MVC	Maximal voluntary contraction
RMS	Root mean square
sEMG	Surface electromyography
Δ	Delta
FDS	Flexor digitorum superficialis
EDC	Extensor digitorum communis
BB	Biceps brachii
TB	Triceps brachii
LD	Latissimus dorsi
TA	Tibialis anterior
GM	Gastrocnemius medialis
RF	Rectus femoris

Communicated by Toshio Moritani.

✉ Feng Guo
guofeng_first@aliyun.com

[1] College of Human Kinesiology, Shenyang Sport University, 36 Jinqiansong East Road Sujiatun District, Shenyang 110102, Liaoning, China

[2] Mountaineering Management Center, General Administration of Sport of China, Beijing, China

[3] Department of Human Performance and Health Education, College of Human Development and Education, Western Michigan University, Kalamazoo, USA

Introduction

Rock climbing has become increasingly popular and has recently been confirmed as a new sport for the Tokyo 2020 Olympic Games. Competitive climbing requires special skills and specific muscle strength (Janot et al. 1999). Specified training has become more and more important for optimization of rock climbing performances (Schweizer and Schneider 2006). Training protocols are based on the knowledge of characteristics of neuromuscular control on specific technical movements. Speed rock climbing is a specific type of competitive climbing that requires competitors to complete consecutive climbs on a 15-m artificial standardized wall as quickly as possible. Therefore, speed rock climbing demands a great amount of muscular power and endurance (Laffaye et al. 2014). To our knowledge, there are few studies investigating neuromuscular activation during rock climbing. Understanding the characteristics of neuromuscular activation in speed climbing would help coaches to make specialized training protocols and to further improve climbers' performance.

Surface electromyography (sEMG) has been extensively used to detect muscle activation patterns in various sports (Tiller et al. 2017; Clarys and Cabri 1993) as well as during rock climbing (Koukoubis et al. 1995; Watts et al. 2008a, b; Deyhle et al. 2015; Quaine et al. 2003). Deyhle et al. (2015) focused on upper-extremity sEMG in climbers during a pull-up movement with four fingers. Watts et al. (2008a) observed changes in maximum hang time and anterior forearm electromyography (EMG) during repeated maximum duration hangs from a simulated rock feature. The EMG of anterior forearm muscles indicated that long recovery intervals improved anterior forearm muscle recovery from fatigue. In another study (Watts et al. 2008b), sEMG was collected from forearm muscles during a specific movement in a difficult climbing session. The results showed that sEMG amplitudes of forearm muscles were significantly different during various hand configurations on rock points, showing the important role of forearm muscles in different hand positions. Quaine et al. (2003) evaluated the difference in finger flexor muscle endurance between non-climbers and elite rock climbers by performing a series of fingertip isometric contractions. They found that the median frequency of both the finger flexor and extensor sEMG power spectra decreased during isometric contractions. A smaller decrease in median frequency was also found in climbers compared to non-climbers, suggesting that climbers have better finger flexor and extensor endurance than non-climbers. Although sEMG has been used to assess the characteristics of neuromuscular control for rock climbing, most studies mainly focused on simulated, albeit difficult rock climbing in a laboratory setting. There have been no studies on neuromuscular activation patterns during an actual-speed rock climbing competition. Furthermore, previous studies have focused on upper-extremity muscles, and have not included lower extremities.

Specificity of physical training is important to maximize performance; however, little research has contributed to our understanding of physiological stresses encountered in speed rock climbing. Accumulation of blood lactate involved in speed rock climbing is a possible area of interest. Such information would be of value in the design of climbing-specific physical training programs. A few studies have attempted to describe the level of blood lactate concentration during climbing, but have implemented difficult rock climbing (Gáspari et al. 2015; Watts et al. 2000), or simulated climbing (Watts and Drobish 1998) rather than speed rock climbing specifically.

To further improve performance in speed rock climbing, it is important to understand the neuromuscular activation patterns and blood lactate concentrations involved to support their training programs. We hypothesized that small muscles in upper extremities might play an important role in completing the actual-speed climbing and blood lactate concentration responses might be different from previous studies in simulated climbs. Therefore, the purpose of this study was to identify the muscle activation patterns of upper and lower extremities muscles and blood lactate concentration responses in elite rock climbers during a 15-m speed climb.

Materials and methods

Subjects

Twelve trained rock climbers (6 male), age 22.3 ± 0.9 years, height 171.1 ± 2.4 cm, body mass 65.2 ± 7.8 kg, training experience 6.5 ± 1.1 years, and body fat (male 14.3 ± 2.4%, female 17.8 ± 2.1%), volunteered to participate in the study. They were all national elite athletes in China, and all were right-hand dominant. Prior to testing, all subjects were explained the procedure and were asked to read and sign an informed consent. The Human Subject Institutional Review Board (HSIRB) approved the experimental protocol.

Protocols

All subjects were instructed to perform one successful 15-m speed climb as quickly as possible. They were required to complete the task with ten consecutive climbing actions along a predetermined climbing route on a standardized artificial wall. Before the test, participants performed a 25-min full-body warm-up. This included 10 min of jogging, and 15 min of dynamic stretching (head rolls, windmills, side twists, and walking lunges). The sEMG signals from upper and lower extremity muscles and the video signals were synchronously recorded by wireless surface electromyography equipment and a camera. At rest and at 3 min after completing the climb, blood lactate was assessed via an ear prick. To reduce the effect of warm-up on the blood lactate at rest, the timing of the resting blood lactate sample was approximately 15 min after warm-up. Climbing time during the 15-m speed climbing was recorded by the mechanical–electric timing devices fixed on the ground and artificial wall.

sEMG collection and processing

A 16-channel wireless sEMG system (ME6000, Mega Electronics Ltd, Kuopio, Finland, with a bandwidth of 8–500 Hz, A/D converter of 14-bit, common mode rejection ratio (CMRR) of 110 dB, and pre-amplifier gain of 305 dB) was used to collect signals from 16 representative bilateral skeletal muscles including flexor digitorum superficialis (FDS), extensor digitorum communis (EDC), long head of biceps brachii (BB), long head of triceps brachii (TB), latissimus dorsi (LD), tibialis anterior (TA), gastrocnemius medialis (GM), and the rectus femoris (RF). Round-shaped bipolar pre-gelled silver chloride electrodes, 1 cm in diameter (Shanghai Shenfeng, China) were used. The electrodes, each with an inter-electrode distance of 2 cm, were placed over the middle of the muscle belly along the longitudinal axis, which was confirmed by palpations of muscle bulk during a brief maximal isometric contraction. This validated electrode placement, used by Winter et al. (1994), helps to minimize crosstalk. To keep the inter-electrode resistance low (< 2 kΩ), the skin was shaved, abraded with sandpaper, and cleaned with 60% alcohol. The cables were strapped to the limbs by elastic bandages to reduce the impact of movement artifact. Visual inspection for the raw sEMG baseline was acceptable, and was below 3 μV when subjects were under the state of relaxation. The sampling rate of the raw sEMG signals was 1000 Hz; bandpass filtering by 8–500 Hz was performed with MegaWin software. For calculating the sEMG amplitude parameters, the raw sEMG signals were low and high-pass filtered (300 Hz and 20 Hz cutoffs, respectively, with fourth order Butterworth filters) to reduce the impact of movement artefacts (Quaine et al. 2003; Konrad 2005). Finally, they were full-wave rectified. The sEMG data were smoothed using a moving average method (Konrad 2005). This method, based on a user-defined time window, refers to a certain amount of data averaged using the sliding window technique. In the study the sEMG was smoothed by moving average method with a time window of 0.05 s. Based on this sEMG data processed, average muscle contribution of individual muscle was calculated during the entire climbing across all subjects according to Caterisano's method (Caterisano et al. 2002), where muscle contribution is calculated as the percent of integrated EMG (iEMG) of each muscle to the total iEMG of the all muscles monitored. First, we calculated the iEMG percentage of each muscle for each subject, and then the average iEMG percentage for each muscle was calculated across all subjects.

To reduce the effects of physical and non-physical factors, all the sEMG data were normalized and expressed as percentages of referenced amplitudes during a maximal voluntary contraction (MVC) (Farina et al. 2014). The method of MVC techniques in the present study was adopted from Konrad (2005). The MVC test was performed for each investigated muscle separately. MVCs were performed against static resistance. The first step was to identify an exercise/position that allowed for an effective maximum isometric force, which were typically isolated single-joint activities statically fixated at middle positions within the range of motion. The participants were given verbal encouragement during the two maximal isometric efforts for 4 s. To avoid fatigue, 3 min rest was allowed between the two MVC trials. A 0.1-s time window was used to calculate the average of the maximal sEMG amplitude of each muscle by root mean square (RMS). The average maximal sEMG amplitude was used as the referenced sEMG RMS value for normalization. Then, the sEMG values after full-wave rectifying were normalized to the reference value, which were expressed as RMS (%). To detect the sEMG amplitude changes before and after the 15-m climbs, we observed the sEMG RMS (%) of right and left limbs in the initial phase (average of second and third climbing actions) and the terminal phase (average of ninth and tenth climbing actions).

To further assess muscle activation patterns, the instantaneous median frequency (MF) of sEMG spectrum for each contraction was calculated by time–frequency method (Bonato et al. 2001) and was based on the raw sEMG. Additionally, the time-related behavior of MF for muscles was plotted and the slope of the line of best fit was computed during the ten climbing actions. We also observed the MF changes, which was defined as ΔMF (%). The ΔMF (%) was defined as follows:

$$\Delta\mathrm{MF}\ (\%) = \frac{\mathrm{MF}_{10\mathrm{th\ action}} - \mathrm{MF}_{1\mathrm{st\ action}}}{\mathrm{MF}_{1\mathrm{st\ action}}} \times 100\%\,.$$

The $\mathrm{MF}_{1\mathrm{st\ action}}$ and $\mathrm{MF}_{10\mathrm{th\ action}}$ represent the median frequency of sEMG at the first climb and the last climbing actions, respectively.

The speed of the body during each climb was also calculated. First, the displacement of head and time was confirmed by video and sEMG signals during each climb. The climbing speed was then obtained by the ratio of displacement-to-time [speed (m/s) = elevation displacement of head (m) ÷ time (s)]. The video was input into the DV Coach software (Wuhan, China), which is used for analyzing kinematics of data. The vertical side length (1.7 m) of the rectangle board on the standardized artificial wall served as the scale for linear transformation. The time of each climb was defined as the time interval between contacting a rock for one leg and leaving the rock for the same leg, which was confirmed by sEMG of the RF and video. The vertical displacement of the centre of the head was used to quantify actual height climbed. Additionally, the power was also calculated, and defined as the speed of vertical displacement multiplied by the force needed to displace the body [power (W) = body mass × g × speed], where g (9.8 N/m) is acceleration due to gravity. The power was presented in absolute and normalized (i.e., relative to body mass) values [normalized power (W/kg) = g × speed].

Blood lactate collection and process

Twenty microliters of blood was collected at rest and at 3 min. after completing the 15-m climb. Prior to each test, the equipment (LT1710, Kyoto, Japan) was calibrated by a reagent strip. To further observe the changes in blood lactate concentration after completing the 15-m speed climb, the ΔBlood lactate (%) was calculated. The ΔBlood lactate (%), which reflects the level of increase of blood lactate, was defined as follows:

$$\Delta\text{Blood lactate }(\%) = \frac{\text{blood lactate}_{\text{at 3 min}} - \text{blood lactate}_{\text{at rest}}}{\text{blood lactate}_{\text{at rest}}} \times 100\%.$$

The blood $\text{lactate}_{\text{at rest}}$ and blood $\text{lactate}_{\text{at 3 min}}$ represent the blood lactate at rest and at 3 min after completing climbing, respectively.

Statistical analysis

Statistical software SPSS 16.0 and GraphPad Prism 5 were used to analyze the data. The distribution of the data was tested using the Shapiro–Wilk test. The Pearson correlation between blood lactate and total climbing time during the 15-m speed climb was calculated. A paired samples t test was used to determine whether there was a sEMG RMS (%) amplitude significant difference between the initial and terminal climbing phases. The significant changes in MF were also tested by a paired samples t-test. Additionally, a repeated-measures ANOVA was used to test the changes in climbing speed and power. To compare two mean values, the adjusted least significant difference test was performed.

Effect sizes (Cohen's D) are also reported, when appropriate, and are interpreted as: small effect > 0.2; medium effect > 0.5; large effect > 0.8. The significant level was 0.05.

Results

Climbing time, speed, and power

The climbers showed an average climbing time of 8.1 ± 2.1 s in completing the 15-m speed rock climbing sessions. As seen in Fig. 1, the climbing speed first increased and then slightly decreased relative to the peak value. The power values are displayed in Table 1.

EMG time domain indices

As shown in Fig. 2, compared with other muscles, the iEMG (%) of the BB and FDS had the highest contribution rates in completing the 15-m speed climb.

To observe changes in sEMG amplitude, we calculated sEMG RMS (%) changes between the initial phase and terminal phase for each muscle. As shown in Fig. 3, the difference primarily occurred in the upper limb muscles, specifically the right BB and FDS (initial phase vs. terminal phase, $P < 0.01$, Cohen's $D = 0.66$ and $P < 0.05$, Cohen's $D = 0.48$; Fig. 3a) and the left BB and FDS (initial

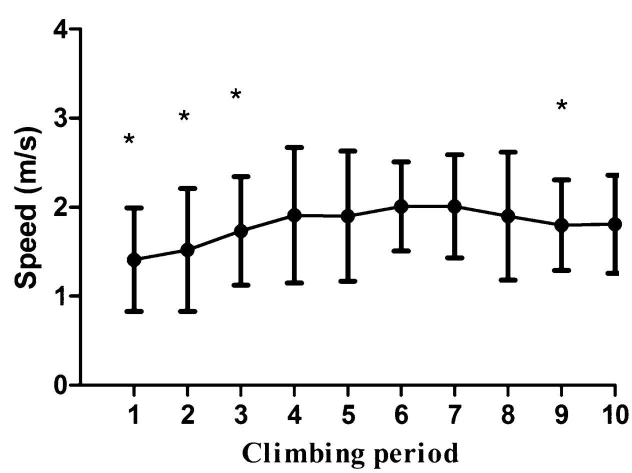

Fig. 1 Climbing speed changes during the climbing period for all subjects. Data are presented as mean ± SD. Speed values were compared with reference values—that is, peak speed value. *Significant difference from the peak speed value, $P < 0.05$

Table 1 Absolute power and normalized power during the ten climbing actions

	C 1	C2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	ANOVA
Absolute power (W)	891.3 ± 179.9*	960.8 ± 202.0*	1093.5 ± 251.5*	1207.3 ± 257.6	1201.0 ± 266.2	1272.5 ± 262.2	1270.4 ± 271.1	1206.3 ± 267.9	1137.8 ± 241.7	1144.1 ± 263.1	$P < 0.01$
Normalized power (W/kg)	13.8 ± 2.9*	14.9 ± 3.1*	17.0 ± 3.6*	18.7 ± 3.9	18.6 ± 3.9	19.7 ± 4.1	19.4 ± 4.2	18.7 ± 3.9	17.6 ± 3.7	17.7 ± 3.9	$P < 0.01$

C 1–C 10 represents ten climbing actions. Data are presented as mean ± SD. Power values were compared with reference value—that is, peak power value

*Significant differences from the peak power value, $P < 0.05$

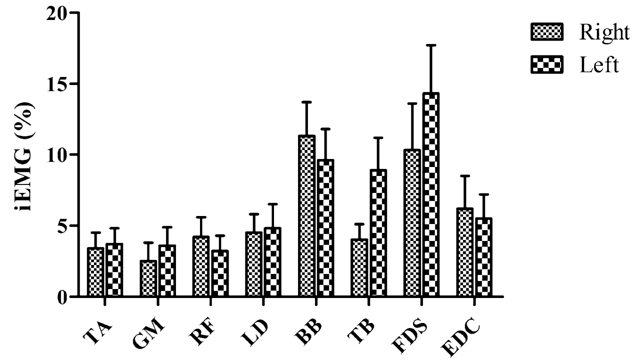

Fig. 2 Integrated electromyography (iEMG) (%) of each muscle sEMG in completing the 15-m speed climbing across all the climbing actions and all subjects. Values are presented as mean ± SD. *AT* anterior tibial, *GM* gastrocnemius medialis, *RF* rectus femoris, *LD* latissimus dorsi, *BB* long head of biceps brachii, *TB* long head of triceps brachii, *FDS* flexor digitorum superficialis, *EDC* extensor digitorum communis

phase vs. terminal phase, $P < 0.01$, Cohen's $D = 0.84$ and $P < 0.01$, Cohen's $D = 0.76$; Fig. 3b). We further analyzed the RMS (%) dynamic changes of BB and FDS during 15-m speed rock climbing. As seen in Fig. 4, the results indicated that the RMS (%) significantly increased with climbing time, left BB (slope = 1.59, $r^2 = 0.89$, $P < 0.0001$), left FDS (slope = 1.65, $r^2 = 0.92$, $P < 0.0001$), right BB (slope = 2.35, $r^2 = 0.89$, $P < 0.0001$), and right FDS (slope = 1.55, $r^2 = 0.83$, $P = 0.002$).

EMG frequency domain indices

As shown in Fig. 5, it was demonstrated that instantaneous MF of the sEMG significantly decreased during the climbs, left BB (slope = − 1.26, $r^2 = 0.91$, $P < 0.001$), left FDS (slope = − 0.95, $r^2 = 0.84$, $P = 0.002$), right BB (slope = − 0.61, $r^2 = 0.56$, $P = 0.013$), and right FDS (slope = − 0.83, $r^2 = 0.75$, $P = 0.001$). Additionally, the instantaneous MF of sEMG for left BB and left FDS declined more than the right biceps brachii and left flexor digitorum superficialis, respectively. As seen in Tables 2 and 3, the BB, TB, EDC, and FDS showed a significant decrease in MF.

Blood lactate

The pre-climb reading of 1.9 ± 0.6 mmol/L significantly increased to 7.6 ± 1.9 mmol/L at 3 min after completing the 15-m speed climb ($P < 0.001$, Cohen's $D = 4.04$). The positive correlation between blood lactate concentration and climbing time ($r = 0.59$, $P = 0.043$) indicated that longer climbing times led to higher lactate levels (Fig. 6).

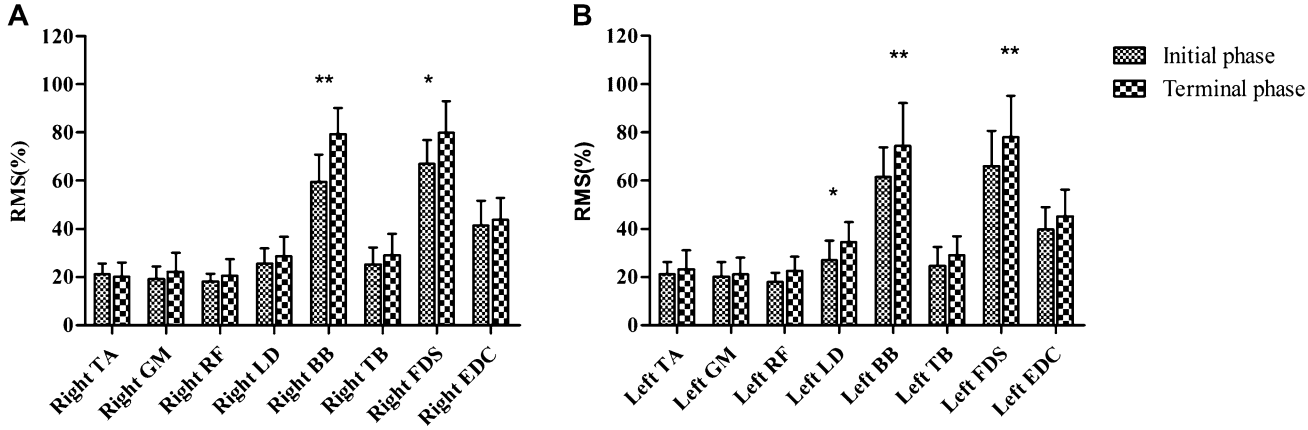

Fig. 3 Comparison of EMG root mean square (RMS) (%) of each muscle between the initial and terminal phases during 15-m speed climbing. *Initial phase vs. terminal phase, $P<0.05$, **$P<0.01$. Right upper and lower limbs (**a**); left upper and lower limbs (**b**). Data are presented as mean ± SD. *AT* anterior tibial, *GM* gastrocnemius medialis, *RF* rectus femoris, *LD* latissimus dorsi, *BB* long head of biceps brachii, *TB* long head of triceps brachii, *FDS* flexor digitorum superficialis, *EDC* extensor digitorum communis

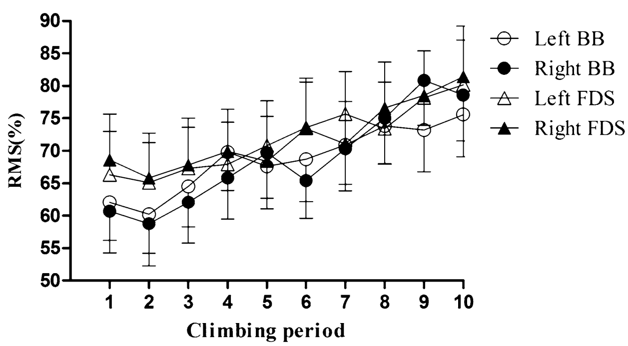

Fig. 4 Root mean square (RMS) (%) changes of average RMS in different repetitions for bilateral biceps brachii and flexor digitorum superficialis. *Left BB* left long head of biceps brachii, *left FDS* left flexor digitorum superficialis, *right BB* right long head of biceps brachii, *right FDS* right flexor digitorum superficialis

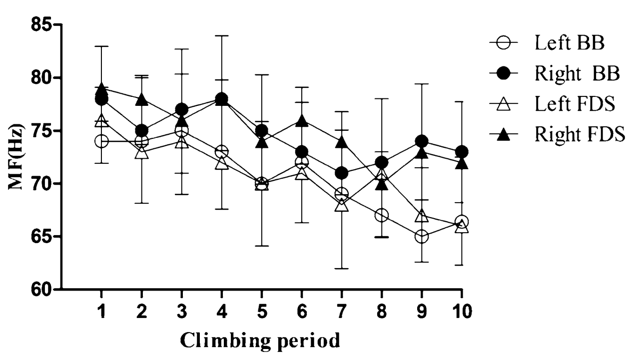

Fig. 5 Media frequency (MF) changes of average MF in different repetitions for bilateral biceps brachii and flexor digitorum superficialis. *Left BB* left long head of biceps brachii, *left FDS* left flexor digitorum superficialis, *right BB* right long head of biceps brachii, *right FDS* right flexor digitorum superficialis

Discussion

The present study was conducted to characterize the neuromuscular activation patterns of upper and lower limb muscles and blood lactate concentration responses after a 15-m competitive speed climb in trained rock climbers. The climbing time, speed, power, blood lactate, and neuromuscular recruitment adaptation were analyzed. The results demonstrate that the median frequency of upper-extremity sEMG decreased more than that of the lower extremities, suggesting more fatigue in the upper limbs during the climb. Specifically, the biceps brachii and flexor digitorum superficialis muscles showed the greatest changes in RMS and MF, especially in the left upper limbs, implying that these small muscles play an important role in speed climbing. Furthermore, blood lactate concentration showed a positive correlation with climbing time; slower climbers accomplished the task with a greater rise in blood lactate concentration.

sEMG has been extensively applied in sports science studies to analyze neuromuscular recruitment during various movements. In the current study, the rate of contribution of the BB and FDS was the highest in all muscles measured over the entire 15-m climb. Relative contribution of lower limb muscles was smaller than we expected. This may be associated with competition speed climbing technique, in which climbers' feet play a role of instantaneous support (Watts and Jensen 2003). This result is in accordance with the Koukoubis et al. (1995), who found that the highest iEMG values were generated by the FDS and BB muscles for elite climbers during a simple push-up. However, they did not measure the EMG activities of lower limbs' muscles with a foot support; therefore, their results may not reflect

Table 2 ΔMF (%) of each muscle in all subjects during 15-m speed climbing

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
R.FDS	−7.86	−7.09	−6.58	−6.54	−12.05	−12.21	−11.69	−11.25	−7.69	−6.95	−8.90	−8.57
R.EDC	−4.61	−3.32	−3.32	−2.33	−9.34	−8.39	−5.11	−6.77	−5.67	−1.28	−4.56	−4.56
R.BB	−11.69	−6.25	−8.64	−6.49	−10.99	−10.13	−7.89	−4.00	−6.39	−9.13	−8.03	−7.13
R.TB	−2.13	0.23	−3.11	1.22	−1.23	−3.21	−1.89	1.14	2.34	−2.34	−1.78	−1.10
R.LD	1.21	0.34	−0.45	−1.34	−4.17	−2.45	−3.21	2.02	1.08	0.87	−2.23	2.19
R.RF	1.22	2.32	−2.21	−1.21	1.22	−2.34	−3.05	2.10	−1.50	−0.39	−0.98	−1.21
R.TA	−1.21	−1.10	2.04	−2.11	−3.15	−1.11	1.38	−2.19	0.23	1.26	2.34	1.09
R.GM	1.02	−1.33	2.55	−2.01	2.11	−1.20	1.55	0.44	−1.24	−0.69	1.24	−1.45
L.FDS	−12.50	−16.92	−10.29	−9.86	−17.00	−10.22	−13.70	−13.89	−7.25	−10.32	−9.79	−14.53
L.EDC	−8.62	−10.12	−8.92	−8.21	−14.4	−5.36	−5.56	−5.67	−3.41	−5.89	−6.71	−8.80
L.BB	−14.49	−14.08	−10.00	−11.76	−13.94	−10.00	−11.27	−5.48	−5.48	−10.35	−7.45	−9.56
L.TB	−8.22	−6.12	−5.67	−5.12	−5.99	−6.79	−6.78	1.54	−0.53	−3.65	−3.44	−4.67
L.LD	−3.15	−5.67	−2.31	1.23	−3.27	2.07	2.37	−3.22	2.45	−1.29	1.45	−5.71
L.RF	1.33	−1.93	−3.08	−0.56	1.58	−2.19	−0.88	1.22	−1.24	−0.22	0.34	1.12
L.TA	−0.89	1.12	−0.35	−0.19	1.23	2.27	−1.47	2.45	3.30	2.27	−0.38	−1.24
L.GM	0.96	−0.33	1.65	−0.34	−1.34	−2.46	−3.56	2.35	1.03	0.98	−0.12	0.33

S1–S12, represents all 12 subjects

R.FDS/L.FDS right/left flexor digitorum superficialis, *R.EDC/ L.EDC* extensor digitorum communis, *R.BB/L.BB* right/left long head of biceps brachii, *R.TB/L.TB* right/left long head of triceps brachii, *R.LD/R.LD* right/left latissimus dorsi, *R.RF/L.RF* right/left rectus femoris, *R.AT/L.TA* tibialis anterior, *R.GM/L.GM* right/left gastrocnemius medialis

Table 3 Comparison of MF between $MF_{1st\ action}$ and $MF_{10th\ action}$

	$MF_{1st\ action}$	$MF_{10th\ action}$	*t*	*P*	Cohen's *D*
R.FDS	79.50 ± 3.09	72.41 ± 3.78**	13.77	< 0.0001	2.05
R.EDC	78.50 ± 3.58	74.60 ± 3.44**	7.45	< 0.0001	1.11
R.BB	78.25 ± 4.94	72.39 ± 4.74**	12.36	< 0.001	1.21
R.TB	78.00 ± 5.15	77.23 ± 5.22	1.68	0.12	0.15
R.LD	73.50 ± 4.50	73.08 ± 3.95	0.51	0.62	0.10
R.RF	74.33 ± 7.00	73.97 ± 7.29	1.04	0.31	0.05
R.TA	73.75 ± 7.11	73.56 ± 6.77	0.36	0.72	0.03
R.GM	69.50 ± 6.26	69.58 ± 6.68	0.26	0.79	−0.01
L.FDS	75.42 ± 4.06	66.19 ± 3.69**	12.85	< 0.0001	2.38
L.EDC	71.67 ± 9.11	66.29 ± 9.51**	10.12	< 0.0001	0.58
L.BB	73.92 ± 5.09	66.36 ± 6.10**	12.21	< 0.0001	1.35
L.TB	71.75 ± 7.02	68.37 ± 6.27*	5.16	0.0003	0.50
L.LD	72.83 ± 7.07	71.91 ± 7.28	1.42	0.18	0.13
L.RF	76.42 ± 3.29	76.11 ± 2.86	0.93	0.36	0.10
L.TA	73.08 ± 3.50	73.57 ± 3.50	1.62	0.13	−0.14
L.GM	74.00 ± 6.18	73.92 ± 5.95	0.01	1.00	0.01

$MF_{1st\ action}$, represents the MF at the first climbing action; $MF_{10th\ action}$, represents the MF at the tenth climbing action. The Cohen's *D*, represents the effect size

*$MF_{1st\ action}$ vs. $MF_{10th\ action}$, $P < 0.001$

**$MF_{1st\ action}$ vs. $MF_{10th\ action}$, $P < 0.0001$

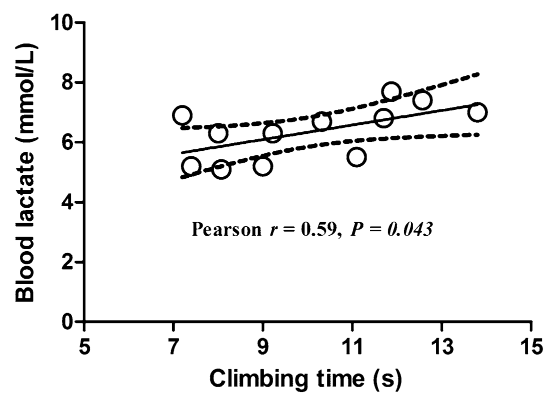

Fig. 6 Pearson correlation between blood lactate and climbing time during the 15-m speed climbing. Dot line represents 95% confidence interval

an authentic neuromuscular recruitment during an actual climbing session.

The RMS of sEMG is usually used to reflect the sEMG amplitude (Dideriksen et al. 2011; Cerqueira and Carvalho 2013). In a study by Cerqueira and Carvalho (2013), the reproducibility of the RMS of sEMG in static and dynamic contractions was assessed. The results indicated that the amplitude has high reliability in static and dynamic contractions, enabling the application of sEMG in the investigation of neuromuscular activation patterns and disorders. However, due to limited technology, there has not been enough research to study the neuromuscular activation patterns of climbers during a speed climbing event. In the current study, the RMS (%) amplitude of sEMG increases over the 15-m speed climb shows that the significant increase of sEMG amplitude mainly occurs in the FDS and BB muscles. In this study, the climbing speed and power showed a significant increase from the first to the seventh climbing action and a slight decrease relative to peak value toward the end. We assume that the increased RMS could be due to greater effort during the climb. In a recent study, we also found that the sEMG RMS of the flexor digitorum profundus increased with the increase of perceived effort during sub-maximal handgrip isometric contractions (Guo et al. 2017). Further analysis indicated that the greater effort closely relates to increase of the central motor command from the sensorimotor cortex (Guo et al. 2017). Therefore, in this study the increases of RMS (%) amplitude for FDS and BB over the 15-m competition speed climb might simply be elicited by a greater amount of effort. It has been found that the instantaneous MF of sEMG spectrum is more reliable for assessing muscle activation patterns during dynamic contractions by the time–frequency method (Bonato et al. 2001). Additionally, some studies have demonstrated that the sEMG spectrum component decreases during a fatiguing task (Córdova et al. 2017; Trajano et al. 2015; Izquierdo et al. 2009). As for the sEMG power spectrum in our study, the instantaneous MF of the FDS and BB declined during the speed climb and these muscles all represent a negative slope with the climbing time, which is similar to the Quaine's study (Quaine et al. 2003). They found that the MF of finger flexor and extensor sEMG power spectrum decreased during fingertip isometric contractions, but non-climbers showed a greater negative slope of MF compared to the climbers. Their results indicated that sEMG MF of the FDS declined by 23% compared to the beginning value under sub-maximal repetitive fingertip isometric contractions. However, in our study, the MF decreased by 15% from beginning to end of the 15-m speed climb. This may be associated with the difference in experimental protocols. Deyhle et al. observed the MF of sEMG power spectrum during a difficult climbing route task (Deyhle et al. 2015). They measured the sEMG of four muscle groups for rock climbers in performing an indoor climbing route task. In this task, sEMG MF for digit flexors and elbow flexors declined from beginning to the end of exercise. They concluded that the muscular endurance of digit and elbow flexor groups is especially important for rocking climbing on an artificial wall, which is in line with our findings.

Of note, regardless of sEMG amplitude or spectrum components in the speed climb, there was a tendency for greater changes in the left limb muscles compared to the right. The observed decrease of the MF of sEMG in the left limb muscles was 15% of the beginning value, whereas it amounted to 9% in the right limbs. This shows that the rate of decrease of the MF of BB and FDS in the left upper limb seems to be higher than that of the right upper limb. All the subjects in the current study were right-handed; this might suggest that in our study the climbers' left upper limbs muscles strength is less than that of the right upper limbs. Additionally, as shown in Table 2, the MF of arm sEMG decreased more than that of legs, suggesting more fatigue in the upper extremities during the speed climb.

Our subjects showed a high blood lactate concentration (7.6 ± 1.9 mmol/L) after the 15-m speed rock climbing event. To our knowledge, at present there have been no reports of blood lactate concentration changes surrounding speed rock climbing. Some researchers have reported blood lactate changes in difficult rock climbing, such as Watts and Drobish (3.6–5.9 mmol /L) (Watts and Drobish 1998), Billat (4.3–5.7 mmol /L) (Billat et al. 1995), and Mermier (3.1 mmol /L) (Mermier et al. 1997). The blood lactate concentration in our study was relatively very high. This could represent significant muscular metabolic activity since body fast movement during speed rock climbing is provided by the large muscles in upper and lower extremities. Furthermore, blood lactate concentration showed a positive correlation with climbing time; slower climbers showed a greater rise in lactate levels. Additionally, the female climbers in the current study were relatively slower, and accumulated more lactate compared to the male climbers. In the male climbers, faster climbs were associated with lower lactate values. Speed climbing is a high-intensity activity that is performed in the shortest possible time. Once the high-energy phosphates are depleted through the ATP-CP system, the glycolytic system is used for supplying energy and generates high levels of blood lactate, leading to relatively slower muscle contractions and decreased climbing times. It is suggested that the slower climbers in our study should improve their capacities of ATP-CP energy system.

Limitations

Although some interesting results were found in the present study, there were some limitations. It was found that the decreases in MF from the left limbs were greater than those from the right limbs. The differences in mechanical requirements between left and right limbs during the climbing may be the reason for the difference in MF between right and left limbs. Additionally, as Lynn et al. (1978) reported, the sEMG spectra is related to electrode spacing and fiber distance. In our study, the electrode size of 1 cm and interelectrode distance of 2 cm might have caused a low-pass filtering effect of EMG signals, which contributed to a low MF. In addition, we used an electrode placement over the middle of the muscle belly along the longitudinal axis with an inter-electrode distance of 2 cm; this may have caused a shift of the innervation zone below the skin during climbing and may have impacted the values of RMS and MF.

Conclusions

In conclusion, the flexor digitorum superficialis and biceps brachii have high levels of activity during a competitive 15-m speed climbing event. The median frequency of arm EMG decreased more than that of legs, suggesting more fatigue in upper extremities. In addition, the blood lactate concentration increases suggest that glycolysis supplies a fair amount of energy in completing the 15-m speed rock climbs. With these results, coaches will be better prepared to design appropriate training programs for speed climbing athletes. It is suggested that muscular endurance of FDS and BB muscles in upper limbs should be improved for the climbers in this study.

Acknowledgements The project was sponsored by Natural Science Foundation of China (31701043), "Liaoning BaiQianWan Talents Program", and the Center of Mountaineering Management in General Sport Administration of China (CMA2015-A-B06). And we also thanked the coaches in China climbing team, ZHANG Ning and CAI Luyuna, help to recruit the climbing athletes.

Author contributions FG and QW conceived and designed research. FG and QW conducted experiments. FG and YL analyzed data. FG wrote the first draft of the manuscript. NH edited and finalized the manuscript. All authors read and approved manuscript.

Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

Research data policy All data generated or analyzed during this study are included in this published article.

References

Billat V, Palleja P, Charlaix T, Rizzardo P, Janel N (1995) Energy specificity of rock climbing and aerobic capacity in competitive sport rock climbers. J Sports Med Phys Fit 35(1):20–24

Bonato P, Roy SH, Knaflitz M, De Luca CJ (2001) Time-frequency parameters of the surface myoelectric signal for assessing muscle fatigue during cyclic dynamic contractions. IEEE Trans Biomed Eng 48(7):745–753. https://doi.org/10.1109/10.930899

Caterisano A, Moss RF, Pellinger TK, Woodruff K, Lewis VC, Booth W, Khadra T (2002) The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. J Strength Cond Res 16(3):428–432

Cerqueira LS, Carvalho JF (2013) Electromyography of the biceps brachii during dynamic contractions. Revista Brasileira De Medicina Do Esporte 19(6):457–461

Clarys JP, Cabri J (1993) Electromyography and the study of sports movements: a review. J Sports Sci 11(5):379–448. https://doi.org/10.1080/02640419308730010

Córdova A, Nuin I, Fernández-Lázaro D, Latasa I, Rodríguez-Falces J (2017) Electromiografic (EMG) activity during pedaling, its utility in the diagnosis of fatigue in cyclists. Archivos De Medicina Del Deporte 34(4):217–223

Deyhle MR, Hsu HS, Fairfield TJ, Cadez-Schmidt TL, Gurney BA, Mermier CM (2015) Relative importance of four muscle groups for indoor rock climbing performance. J Strength Cond Res 29(7):2006–2014. https://doi.org/10.1519/JSC.0000000000000823

Dideriksen JL, Enoka RM, Farina D (2011) Neuromuscular adjustments that constrain submaximal EMG amplitude at task failure of sustained isometric contractions. J Appl Physiol 111(2):485–494

Farina D, Merletti R, Enoka RM (2014) The extraction of neural strategies from the surface EMG: an update. J Appl Physiol (1985) 117(11):1215–1230. https://doi.org/10.1152/japplphysiol.00162.2014

Gáspari AF, Berton R, Lixandrão ME, Piunti RP, Chacon-Mikahil MPT, Bertuzzi R (2015) The blood lactate concentration responses in a real indoor sport climbing competition. Sci Sports 30(4):228–231

Guo F, Sun YJ, Zhang RH (2017) Perceived exertion during muscle fatigue as reflected in movement-related cortical potentials: an event-related potential study. Neuroreport 28(3):115–122. https://doi.org/10.1097/WNR.0000000000000732

Izquierdo M, Ibanez J, Calbet JA, Gonzalez-Izal M, Navarro-Amezqueta I, Granados C, Malanda A, Idoate F, Gonzalez-Badillo JJ, Hakkinen K, Kraemer WJ, Tirapu I, Gorostiaga EM (2009) Neuromuscular fatigue after resistance training. Int J Sports Med 30(8):614–623. https://doi.org/10.1055/s-0029-1214379

Janot M, Parker DL, Robergs RA (1999) The relationship between muscular strength and endurance and rock climbing performance. Med Sci Sports Exerc 31(5):S169. https://doi.org/10.1097/00005768-199905001-00744

Konrad P (2005) The ABC of EMG: a practical introduction to kinesiological electromyography. Noraxon Inc, Scottsdale

Koukoubis TD, Cooper LW, Glisson RR, Seaber AV, Feagin JA Jr (1995) An electromyographic study of arm muscles during climbing. Knee Surg Sports Traumatol Arthrosc 3(2):121–124

Laffaye G, Collin JM, Levernier G, Padulo J (2014) Upper-limb power test in rock-climbing. Int J Sports Med 35(8):670–675. https://doi.org/10.1055/s-0033-1358473

Lynn PA, Bettles ND, Hughes AD, Johnson SW (1978) Influences of electrode geometry on bipolar recordings of the surface electromyogram. Med Biol Eng Comput 16(6):651–660

Mermier CM, Robergs RA, Mcminn SM, Heyward HV (1997) Energy expenditure and physiological responses during indoor rock climbing. Br J Sports Med 31(3):224–228

Quaine F, Vigouroux L, Martin L (2003) Finger flexors fatigue in trained rock climbers and untrained sedentary subjects. Int J Sports Med 24(6):424–427. https://doi.org/10.1055/s-2003-41174

Schweizer A, Schneider A (2006) Dynamic eccentric-concentric strength training of the finger flexors to improve rock climbing performance. Isokinet Exerc Sci 15(2):281–286

Tiller NB, Aggar TR, West CR, Romer LM (2017) Case studies in physiology: exercise-induced diaphragm fatigue in a paralympic champion rower with spinal cord injury. J Appl Physiol (1985). https://doi.org/10.1152/japplphysiol.00870.2017

Trajano G, Pinho C, Costa P, Oliveira C (2015) Static stretching increases muscle fatigue during submaximal sustained isometric contractions. J Sports Med Phys Fit 55(1–2):43–50

Watts PB, Drobish KM (1998) Physiological responses to simulated rock climbing at different angles. Med Sci Sports Exerc 30(7):1118–1122

Watts PB, Jensen RL (2003) Reliability of peak forces during a finger curl motion common in rock climbing. Meas Phys Educ Exerc Sci 7(4):263–267

Watts PB, Daggett M, Gallagher P, Wilkins B (2000) Metabolic response during sport rock climbing and the effects of active versus passive recovery. Int J Sports Med 21(3):185–190. https://doi.org/10.1055/s-2000-302

Watts PB, Jensen RL, Agena SM, Majchrzak JA, Schellinger RA, Wubbels CS (2008a) Changes in EMG and finger force with repeated hangs from the hands in rock climbers. Int J Exerc Sci 1(2):62–70

Watts PB, Jensen RL, Gannon E, Kobeinia R, Maynard J, Sansom J (2008b) Forearm EMG during rock climbing differs from EMG during handgrip dynamometry. Int J Exerc Sci 1:4

Winter DA, Fuglevand AJ, Archer SE (1994) Crosstalk in surface electromyography: theoretical and practical estimates. J Electromyogr Kinesiol 4(1):15–26