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The effects of training status and muscle action on muscle activation of the vastus lateralis

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This study examined the electromyographic amplitude–force relationships for 5 (age = 19.20 ± 0.45 yrs) aerobically-trained, 5 (age = 25 ± 4.53 yrs) resistance-trained, and 5 (age = 21.20 ± 2.17 yrs) sedentary individuals. Participants performed an isometric trapezoidal muscle action at 60% maximal voluntary contraction of the leg extensors that included linearly increasing, steady force, and linearly decreasing muscle actions. Electromyography was recorded from the vastus lateralis. The *b* (slopes) and *a* (y-intercepts) terms were calculated from the natural log-transformed electromyographic amplitude–force relationships (linearly increasing and decreasing segments) for each participant. An average of the electromyographic amplitude was calculated for the entire steady force segment. The *b* terms for the resistance-trained (1.384 ± 0.261) were greater than the aerobically-trained (0.886 ± 0.130, $P = 0.003$) and sedentary (0.955 ± 0.105, $P = 0.008$) participants during the linearly increasing segment, whereas, there were no differences in *b* terms among training statuses for the linearly decreasing segment. The *b* terms for the resistance-trained were greater ($P = 0.019$) during the linearly increasing segment than decreasing segment (1.186 ± 0.181), however, the *b* terms for the aerobically-trained were lower ($P = 0.017$) during the linearly increasing than decreasing segment (1.054 ± 0.176). The *a* terms from the log-transformed electromyographic amplitude–force relationships and electromyographic amplitude during the steady force segment were not different among training statuses ($P = 0.187$, $P = 0.910$). The linearity of the electromyographic amplitude patterns of response (*b* terms) recording during increasing and decreasing muscle actions may provide insight on motor unit control strategy differences as a result of exercise training status and muscle action, however, the *a* terms of these patterns and electromyographic amplitude during a steady force contraction did not distinguish among training statuses.

Key words: *electromyography, isometric trapezoidal muscle action, log-transform method, motor unit control, vastus lateralis*

1. Introduction

Surface electromyography (EMG) is the recording of the motor units' (MU) action potentials that activate skeletal muscle fibers as detected by electrodes placed on the skin overlying the muscle [10]. The amplitude of the surface EMG signal reflects muscle activation and is composed of both the number of active MUs and their firing rates [6]. Therefore, EMG is often considered a global measure of MU activity, which contains information regarding both peripheral and central properties of the neuromuscular system [10].

Numerous studies have utilized EMG amplitude to compare MU control strategies between isometric linearly increasing ramp [13], [21], [23] and step muscle actions [8], [9], [15], [22], [23]. Ramp and step muscle actions have yielded different EMG amplitude–force relationships [4], [11], [20], suggesting that each may require different MU control strategies. For example, EMG amplitude is typically greater across the force/torque spectrum for linearly increasing ramp than step muscle actions [4], [11], [20]. Guo et al. [11] and Orizio et al. [20] investigated linearly decreasing ramp muscle actions and reported that EMG amplitude recorded during such muscle actions were significantly lower than linearly increasing muscle ac-

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tions. The authors [11], [20] proposed that the greater EMG amplitude during the linearly increasing muscle action may be the result of greater MU recruitment, MU firing rates and fast-twitch fiber activation than the linearly decreasing muscle activation.

It has been reported that acute and chronic resistance and endurance training alters MU behavior [5] and, therefore, may influence EMG amplitude during linearly increasing and decreasing muscle actions. However, there is limited evidence that muscle fiber type and/or exercise training status has influenced the EMG amplitude–force relationships recording during linearly increasing muscle actions. Woods and Bigland-Ritchie [28] reported that the EMG amplitude–force relationships for mixed fiber type muscles tended to be curvilinear, whereas smaller muscles with uniform fiber type exhibited linear increases. In contrast, Herda et al. [13] reported no significant differences in the slopes from the EMG amplitude–force relationships between individuals with different exercise training backgrounds and known fiber type differences, albeit the P value was 0.051. Subsequently, further research is necessary for a better understanding of the influence of exercise training may have on the EMG amplitude–force relationships. In addition, no one has examined the influence of exercise training background on linearly decreasing muscle actions.

Herda et al. [13] have demonstrated that the log-transformed EMG amplitude–force relationship provided a quantitative method for describing the force-related patterns of responses for EMG amplitude. The b term (slope) of the log-transformed method indicates the linearity of the relationship [16]. If the b term is equal to 1, or its 95% confidence intervals (CI) of the slope includes 1, then the rate of change in Y and X are equal and the relationship is linear. If the b term is greater than 1 and the 95% CI of the slope does not contain 1, the rate of change in Y is greater than the rate of change in X and the curve accelerates across the force spectrum. Previously, it has been reported that the EMG amplitude–force relationships are either linear or nonlinear with an acceleration in the EMG amplitude–force relationships [13], [15]. Furthermore, the a term (y-intercept) of the log-transform method can be viewed as a "gain factor" that reflects upward or downward shifts in the exponential relationship without changing the shape of the patterns of response. It has previously been reported that individuals with thicker skinfolds had lower a terms than those with less thick skinfolds [13]. Therefore, the a and b terms from the log-transform EMG–force relationship may provide an opportunity to quantify and monitor changes in the force-related patterns of responses for EMG amplitude as a function of chronic exercise training and between linearly increasing and decreasing muscle actions.

Therefore, the purpose of this study was to monitor EMG amplitude during an isometric trapezoidal muscle action that contains linearly increasing and decreasing muscle actions prior to and after a 12 second steady force segment at 60% maximal voluntary contraction (MVC) in aerobically-trained (AT), resistance-trained (RT), and sedentary (SED) individuals. The steady force segment is similar to an isometric step contraction [3], [8], [14], [23], [24] and, subsequently, will allow for comparisons of EMG amplitude among the AT, RT, and SED. Following 6 weeks of resistance training, Macaluso et al. [19] reported greater EMG amplitude for the biceps brachii during a 12 second steady force isometric contraction at 80% maximal voluntary contraction (MVC) in women aged 18–30 years and 70–79 years. Therefore, it is plausible that EMG amplitude recorded during a steady force contraction may be able to distinguish between training statuses. Subsequently, an isometric trapezoid muscle action may be an ideal mechanism for differentiating between MU control strategies among individuals with different training backgrounds.

2. Material and methods

Subjects

Fifteen healthy participants (mean ± SD age = 21.80 ± 3.67 yrs; body mass = 73.59 ± 22.79 kg; height = 172.85 ± 11.71 cm) volunteered for this investigation. Depending on training status, participants were categorized as AT (five participants; age = 19.20 ± 0.45 yrs; body mass 59.02 ± 11.98 kg; height = 171.89 ± 15.81 cm), RT (five participants; age = 25 ± 4.53 yrs; body mass = 99.22 ± 17.87 kg; height = 178.74 ± 8.09 cm), or SED (five participants; age = 21.20 ± 2.17 yrs; body mass 62.52 ± 10.69 kg; height = 167.90 ± 9.45 cm) group for further statistical analysis. The AT participants had consistently engaged in a structured running program for at least 3 years prior to the study and ran an average of 61 ± 15 miles$\cdot$wk^{-1} for 7–10 h$\cdot$wk^{-1} and none of them reported engaging in resistance training. The RT participants had consistently engaged in a structured weight training program for at least 4 years prior to the study and performed resistance training 4–8 h$\cdot$wk^{-1} and none of them reported engaging in any aerobic activity that included jogging, cycling, swimming, etc. All but one RT subject (i.e., 1.5 times their bodyweight) were capable of a one repetition maximum back squat at least twice their body mass. The SED subjects did not participate in any form of structured physical activity or exercise for 3 years prior to this study. According to Herda et al. [13], we would expect these categorized individuals to exhibit differences in the myosin heavy chain (MHC) expression of the vastus lateralis (VL). In addition, Herda et al. [13] reported differences in neuromuscular function, as measured with mechanomyography (MMG), with a sample size of 5 for each of these groups. None of the participants reported any current or ongoing neuromuscular diseases or musculoskeletal injuries specific to the ankle, knee, or hip joints. This study was approved by the University's institutional review board for human subjects research and each subject signed a written informed consent.

Isometric testing

Each participant was seated with restraining straps over the pelvis, trunk, and left thigh, and the right femur was aligned with the input axis of the Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA) in accordance with the Biodex User's Guide (Biodex Pro Manual, Applications/Operations, 1998) for testing of the right leg extensors. All isometric leg extensor strength assessments were performed on the right leg at a flexion of 90°. Isometric leg extensor strength assessments were measured using the force signal from a load cell (LC402, Omegadyne, Inc., Sunbury, OH, USA) that was fitted to the Biodex System 3 isokinetic dynamometer.

Each participant visited the laboratory for one experimental trial. During the experimental trial participants performed three isometric MVCs with strong verbal encouragement followed by a submaximal isometric trapezoid muscle action at 60% MVC. The highest force output among the three MVC trials was used to determine the force level for the 60% isometric trapezoid muscle action. The trapezoid trajectory contained a linear increase from baseline at a rate of 10% MVC/sec, a constant force of the targeted %MVC for 12 sec, and a linear decrease to baseline at 10% MVC/sec. Therefore, the duration of the contraction lasted 24 sec for the isometric trapezoid muscle action. Prior to the 60% MVC, participants practiced the isometric trapezoid muscle actions at 20% MVC. In addition, a muscle action was performed one additional time if the first attempt was not successful. Three to five minutes of rest was given between each muscle action. Participants were instructed to maintain their force output as close as possible to the target force presented digitally in real time on a computer monitor.

Electromyography

During the trapezoid muscle actions, surface EMG signals were recorded from the VL using a 5 pin array sensor (Delsys, Boston, MA, USA). Each pin was a diameter of 0.5 mm and were at the corners of a 5 × 5 mm square, with the fifth pin in the center of the square. Prior to sensor placement, the surface of the skin was prepared by shaving, removing superficial dead skin with adhesive tape, and sterilized with alcohol. The sensor was placed over the belly of the VL of the muscle at 50% distance between the greater trochanter and lateral condyle of the femur with adhesive tape. The reference electrode was placed over the right patella. The signals from the four pins (i.e., 4 channels) of the sensor electrodes were differentially amplified and filtered with a bandwidth of 20 Hz to 9.5 kHz. The EMG signal collected from channel 1 was used for all subsequent analyses and statistical comparisons.

Signal processing

For the EMG patterns, the EMG (μV) and force (N) signals were simultaneously sampled at 20 kHz with a Delsys data acquisition system (Bagnoli-16 EMG system, Delsys, Boston, MA) during each muscle action. All subsequent signals were stored and processed off-line with custom-written software (LabVIEW, version 11; National Instruments, Austin, TX). The EMG signals were bandpass filtered (fourth-order Butterworth) at 10–500 Hz. During the isometric trapezoidal contraction, consecutive, non-overlapping 0.25 sec epochs were analyzed for the force and EMG signals. The amplitude for the EMG signals was calculated with root mean square (RMS).

Skinfold thickness

Skinfold thickness measurements were taken after the isometric force assessments in the location of the EMG electrode placement for the VL. Measurements were taken according to the recommendations of Jackson and Pollock [17] and were performed by an experienced investigator using a calibrated Harpenden caliper (John Bull, UK). Three skinfold measurements were taken, and the average of the three measurements was used as the representative skinfold thickness for each participant. It has been suggested that subcutaneous fat may serve as a low-pass filter of the EMG signal [2], [13].

Statistical analyses

For the linear increase and decrease in force segments of the trapezoid (Fig. 1), simple linear regression models were fit to the log-transformed EMG_{RMS}–force relationships [13], [15], [16]. The equations were represented as

$$\ln[Y] = b(\ln[X]) + \ln[a] \quad (1)$$

where $\ln[Y]$ = the natural log of the EMG_{RMS} values, $\ln[X]$ = the natural log of the force values, b = slope and $\ln[a]$ = the natural log of the y-intercept. This can also be expressed as an exponential equation after the antilog transformation

$$Y = aX^b \quad (2)$$

where Y = the predicted EMG_{RMS} values, X = force, b = slope of equation (1), and a = the antilog of the y-intercept from equation (1). Slopes and the y-intercepts were calculated using Microsoft Excel® version 2010 (Microsoft, Inc., Redmond, WA).

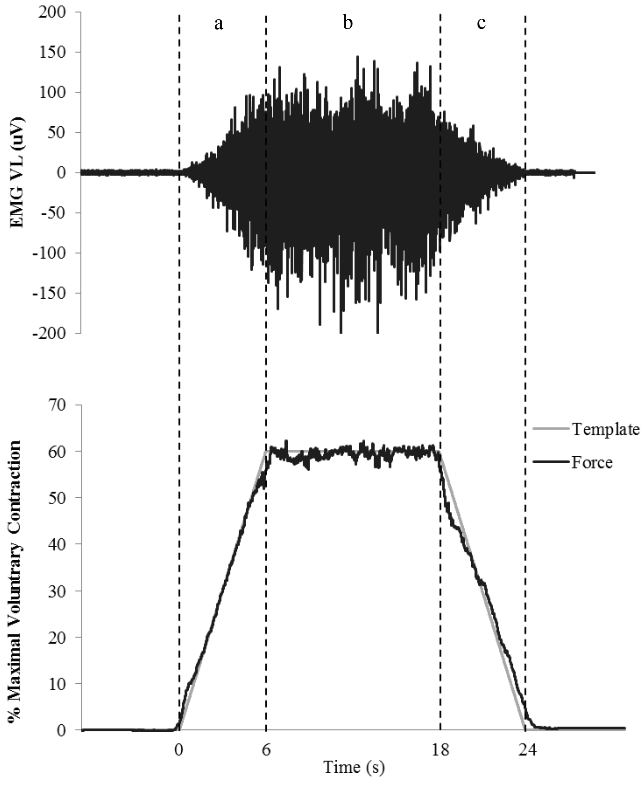


Fig. 1. An example of the electromyographic (EMG) signals from the vastus lateralis (VL) during a 60% isometric trapezoidal contraction for one participant. The force signal (bottom) is overlayed onto the trapezoidal template as it appeared for the participant during the trial. The vertical lines represent (a) the linear force increase, (b) the steady force, and (c) the linear force decrease segments of the 60% isometric trapezoidal contraction. The EMG signals that correspond with the contraction segments (a–c) were selected for analysis

For the steady force segment of the trapezoid (Fig. 1), EMG_{RMS} was calculated by averaging the values from each 0.25 sec epoch during the entire 12 sec targeted contraction force.

Two separate 2-way mixed factorial ANOVAs (training status [AT vs. RT vs. SED] × segment [linear increase vs. linear decrease]) were used to examine differences in the b and a terms from the EMG_{RMS}–force relationships during the linearly increasing and decreasing segments of the submaximal isometric trapezoid muscle actions. A 1-way ANOVA was used to examine possible differences in EMG_{RMS} among the AT, RT, and SED during the steady force segment of the submaximal isometric trapezoid muscle actions. In addition, a 1-way ANOVA was used to examine possible differences in skinfold thicknesses among the AT, RT, and SED. When appropriate, follow-up analyses were performed using paired and independent samples t-test with Bonferroni corrections. The level of significance was set at $P \leq 0.05$ and all statistical analyses were performed using SPSS 20 (IBM Corporation, Armonk, New York, USA).

3. Results

Linearly increasing and decreasing segments EMG_{RMS}–force relationships

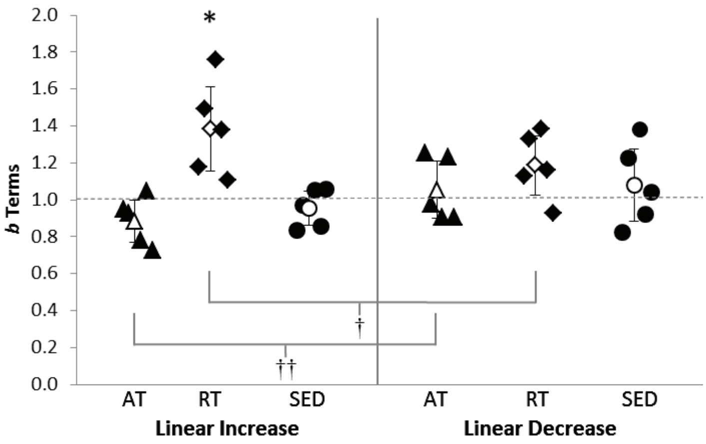
The analyses indicated a significant two-way interaction (training status × segment; $P < 0.001$). The b terms for the RT were greater during the linearly increasing segment than decreasing segment ($P = 0.019$, increase = 1.384 ± 0.261, decrease = 1.186 ± 0.181), the b terms for the AT were lower during the linearly increasing than decreasing segments ($P = 0.017$, increase = 0.886 ± 0.130, decrease = 1.054 ± 0.176), and the b terms for the RT were greater than the AT ($P = 0.003$) and SED (0.955 ± 0.105, $P = 0.008$) during the linearly increasing segment (Fig. 2). There were no other differences reported among training statuses or between muscle actions. Figure 3 illustrates the mean EMG_{RMS} pattern of the response during the linearly increasing and decreasing muscle actions for the AT, RT, and SED.

For the a terms, the analyses indicated no two-way interaction (training status × segment; $P = 0.187$) and no main effects for segment ($P = 0.052$) or training status ($P = 0.136$) (Fig. 4).

Steady force segments

For the steady force segment, the analyses indicated there were no significant differences ($P = 0.910$) among the AT (69.628 ± 21.063 μV), RT (81.356 ± 35.582 μV), and SED (72.470 ± 64.359 μV) (Fig. 5).

Fig. 2. Plotted means ± 95% confidence intervals for the *b* terms from the electromyographic amplitude (EMG_{RMS}) vs. force relationship for the aerobic-trained (AT), resistance-trained (RT), and sedentary (SED) from the linearly increasing and decreasing segments of the isometric trapezoidal contraction. Clear marker represents the mean value for the respective group. * indicates greater *b* terms for the RT than the AT ($P = 0.003$) and SED ($P = 0.008$) during the linearly increasing segment. † indicates greater *b* terms for the RT during the linearly increasing segment than linearly decreasing segment ($P = 0.019$). †† indicates the greater *b* terms for the AT during the linearly decreasing segment than linearly increasing segment ($P = 0.017$)



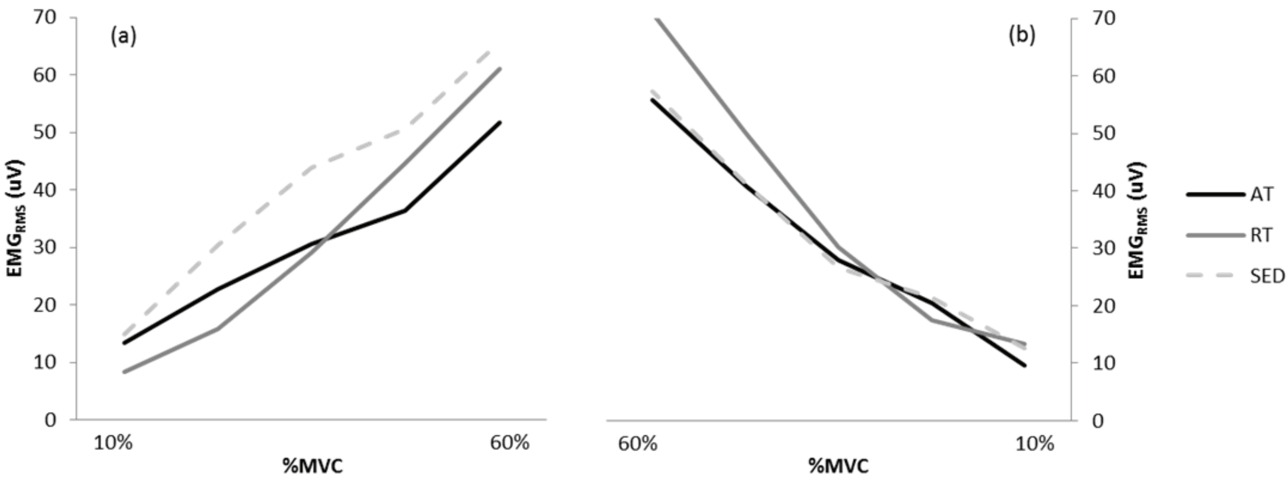


Fig. 3. Plotted means for the aerobically – (AT; black line), resistance-trained (RT; grey line), and sedentary (SED; dashed line) linearly increasing and decreasing segment plotted absolute values for (a) the electromyographic (EMG_{RMS})–force relationship from 10% to 60% MVC for the linearly increasing segment, and (b) EMG_{RMS}–force relationship from 10% to 60% MVC for the linearly decreasing segment

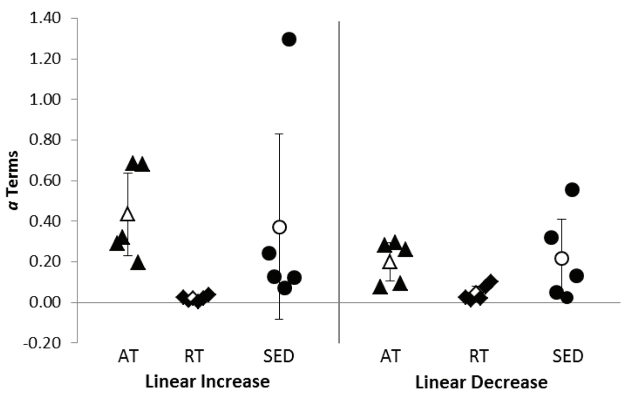


Fig. 4. Plotted individual values and means ± 95% confidence intervals for the *a* terms from the electromyographic amplitude (EMG_{RMS})–force relationships for the aerobically-trained (AT), resistance-trained (RT), and sedentary (SED) from the linearly increasing and decreasing segments of the isometric trapezoidal contraction. Clear marker represents the mean value for the respective group

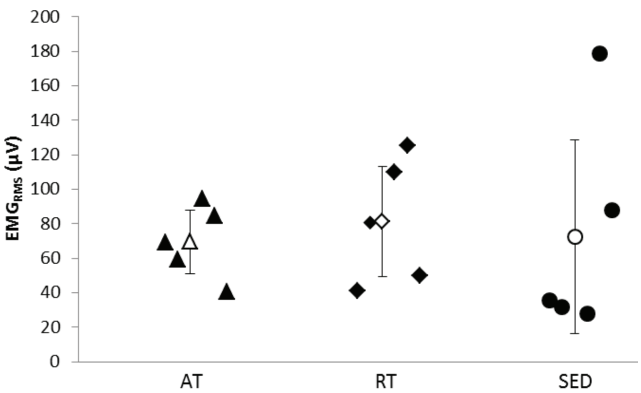


Fig. 5. Plotted individual values and means ± 95% confidence intervals for electromyographic amplitude (EMG_{RMS}) from the steady force segment of the isometric trapezoidal contraction for the aerobically-trained (AT), resistance-trained (RT), and sedentary (SED). Clear marker represents the mean value for the respective group

Skinfold thickness

For skinfold thickness, the analyses indicated there were no significant differences ($P = 0.200$) among the AT (10.660 ± 6.124 mm, RT (14.800 ± 2.532 mm), and SED (21.374±12.080 mm) (Fig. 6).

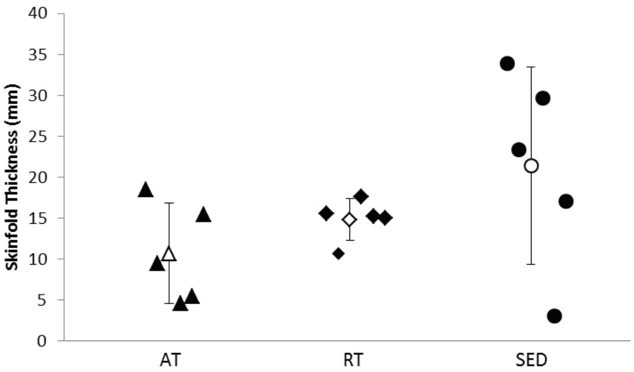


Fig. 6. Means ± standard deviations for the skinfold thicknesses of the aerobically-trained (AT), resistance-trained (RT), sedentary (SED)

4. Discussion

For the log-transformed EMG_{RMS}–force relationship, all 30 relationships (100%) were significant for the linearly increasing ($P < 0.05$, R range = 0.937 – 0.988) and decreasing ($P < 0.05$, R range = 0.891 – 0.983) muscle actions. For the linearly increasing and decreasing muscle actions, the 95% CIs constructed around the b terms for the RT were > 1, thus, indicating the patterns of response were nonlinear with acceleration in EMG_{RMS} across the force spectrum (Fig. 3). In contrast, the 95% CIs constructed around the b terms for the AT and SED included 1 for the linearly increasing and decreasing muscle actions and, therefore, the EMG_{RMS} patterns of response were linear for the AT and SED. In addition, the RT had greater b terms than the AT and SED during the linearly increasing muscle actions, however, there were no differences among training statuses during the linearly decreasing muscle actions. Furthermore, there were muscle action-related differences in the b terms within the training statuses. The b terms were greater from the linearly increasing muscle actions in comparison to linearly decreasing muscle actions for the RT. The converse was true for the AT where the b terms from the linearly increasing muscle actions were lower than the linearly decreasing muscle actions. There were no differences in b terms for the SED between linearly increasing and decreasing muscle actions.

There is limited evidence suggesting that muscle fiber type composition may alter the EMG_{RMS}–force relationships. For example, muscles with a mostly uniformed type I muscle fiber composition, such as the adductor pollicis and soleus, have displayed linear EMG_{RMS}–force relationships while muscles composed of a mixed fiber type composition (i.e., biceps and the triceps brachii) have demonstrated nonlinear patterns [18], [28]. Previously, Herda et al. [13] reported no differences ($P = 0.051$) in the b terms from the EMG_{RMS}–force relationships during a linearly increasing muscle action up to 90% MVC in a similar cohort of subjects used in the present study despite there being significant differences in muscle fiber type composition. Therefore, this is the first study to report *significant* differences in the linearity of EMG_{RMS}–force relationships as a function of exercise training status during a linearly increasing muscle action. De Luca [6] suggested that the EMG–force relationship reflects the concurrent increases in the MU recruitment and firing rates (i.e., activation) that modulate muscle force. Thus, the larger b terms for the RT suggest a greater rise in MU activation during the linearly increasing muscle action in comparison to the AT and SED. There were no statistical differences between the AT and SED despite the likely differences in muscle fiber type composition (i.e., Type I and Type IIX %MHC) as reported in Herda et al. [13]. Subsequently, this provides further support that muscle fiber type may not be the sole contributor to the linearity of the EMG_{RMS}–force relationships from an increasing muscle action. Nonetheless, the findings from the present study suggest that the log-transformed EMG_{RMS}–force relationship may be sensitive to neural adaptations as a result of chronic resistance training.

Previously, Guo et al. [11] reported that EMG_{RMS} was less during the linearly decreasing than linearly increasing muscle action and, thus, indicated a reduction in neural activation during the linearly decreasing muscle action. In the present study, there was greater deceleration for the RT while the AT demonstrated greater acceleration in EMG_{RMS} during the linearly decreasing muscle actions in comparison to the linearly increasing muscle actions. These electrophysiological differences between muscle actions may depict alterations in MU behavior as a function of training status. One possible explanation may be the 12 second steady force segment between the ramp muscle actions resulted in MU potentiation for the RT, but not for the AT. Potentiated MUs would be derecruited at greater force levels than their initial recruitment level during the linearly increasing muscle action [5], [7], [12]. Thus, MU potentiation would reduce the influence of high-threshold MUs during the linearly decreasing muscle action and, consequently, alter the linearity of the EMG_{RMS}–force relationship. The SED displayed no differences in *b* terms between the linearly increasing and decreasing muscle actions and, therefore, providing further support that alterations in neural activation occur during chronic resistance and endurance training. Future research is necessary to make clearer the mechanisms that would result in training status-related differences in muscle activation and deactivation strategies.

Steady force segments

The isometric trapezoid muscle action contains a 12 second steady force segment following the linearly increasing segment and prior to the linearly decreasing segment. The steady force segment is similar to an isometric step contraction [1], [3], [8], [14], [23]–[25] and allowed for comparisons of EMG_{RMS} among the AT, RT, and SED at 60% MVC. There is evidence that short-term endurance and resistance training may alter MU behavior during a steady force contraction. For example, Vila-Cha et al. [27] reported increases in EMG_{RMS} for the VL and the vastus medialis obliquus (VMO) during 10 second isometric knee extensions at 10% and 30% MVC for endurance and resistance training groups after 6 weeks of training. In further support, Vila-Cha et al. [26] reported increases in EMG_{RMS} for the VL and VMO during fatiguing contractions at 10% and 30% MVC for endurance and resistance training groups after 6 weeks of training with no differences in skinfold thicknesses between groups or post-training. It should be noted, however, that Vila-Cha et al. [22], [23] did not report EMG_{RMS} to be significantly different between the groups. Similarly, there were no differences in EMG_{RMS} between the chronic exercisers (AT and RT) and SED during the 60% MVC in the present study. Skinfold thicknesses were not significantly different among the groups and, thus, tentatively suggested that skinfold thickness was not an explanation for the lack of differences in EMG_{RMS}. However, it is possible with a greater sample size there would have been significant differences in skinfold thickness and EMG_{RMS} among groups. In addition, future studies should include ultrasonography to better understand the influence of skinfold thickness of the amplitude of the EMG signal. Nonetheless, skinfold thickness was not a primary contributor for the lack of differences in EMG_{RMS} among training statuses during the steady force segment. The findings from the current study suggest that using the *b* terms from the log-transfomed EMG_{RMS}–force relationships during a linearly increasing muscle action may be more appropriate than recording EMG_{RMS} during steady force muscle action when trying to distinguish among neural adaptations as a result of chronic training. Furthermore, our results indicated that there are no differences in EMG_{RMS} among AT, RT, and SED for the VL during a steady force muscle action at 60% MVC.

5. Conclusion

The *b* terms from the log-transformed EMG_{RMS}–force relationships during the linearly increasing muscle action indicated differences among training statuses, such as the RT displayed greater acceleration throughout the force spectrum than the AT and SED. In addition, there were training status specific alterations in the *b* terms as a function of muscle action (linearly increasing vs decreasing). The RT demonstrated greater deceleration while the AT demonstrated greater acceleration during the linearly decreasing muscle actions in comparison to the linearly increasing muscle actions while there were no muscle action-related changes for the SED. Our data suggested that the type of chronic exercise training resulted in specific adaptations to neural activation and deactivation strategies. Future research should investigate the mechanisms that would result in such training status-related differences in muscle activation and deactivation strategies.

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