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Original Research Paper

Mechanomyographic Amplitude-Force Relationships of the Biceps Brachii Differ Between Sexes During Linearly Varying Muscle Actions and Provide Insight on Muscle Morphology

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ABSTRACT

***Objective*:** To investigate mechanomyographic amplitude (MMG_{RMS})-force relationships of the biceps brachii during moderate- and high-intensity motor unit activation and deactivation.
***Approach*:** Ten recreationally active males and ten recreationally active females performed maximal voluntary contractions (MVCs), followed by an isometric trapezoidal muscle action of the elbow flexors at 40% and 70% MVC. Surface MMG was recorded from the BB during isometric trapezoidal muscle actions. Individual *b* (slope) and *a* (gain) terms were calculated from the log-transformed MMG_{RMS}-force relationships during the linearly increasing and decreasing segments of the trapezoid. MMG_{RMS} was averaged during steady force and normalized to participant MVC. Ultrasonography assessed muscle cross-sectional area (mCSA) of the BB.
***Main results*:** The *b* terms collapsed across intensity and segment were greater for the males (0.665 ± 0.160) than the females (0.360 ± 0.184; $p < 0.001$). The *a* terms during 40% MVC were greater for the females (0.103 ± 0.101) than the males (0.018 ± 0.014; $p = 0.026$). The *a* terms for the females during the 40% MVC were greater than the 70% MVC (0.013 ± 0.007; $p = 0.019$). Steady force MMG_{RMS} collapsed across intensity was

greater for the males (0.256 ± 0.091 $m \cdot s^{-2}$) than the females (0.159 ± 0.041 $m \cdot s^{-2}$; $p = 0.006$). Steady force N-MMG_{RMS} collapsed across sex was greater for the 70% MVC (1.04 ± 0.27%) than 40% MVC (0.64 ± 0.26%; $p < 0.001$). mCSA was correlated with the *b* terms collapsed across intensity and segment ($p = 0.001$; $r = 0.67$) and MMG_{RMS} collapsed across intensity ($p < 0.001$, $r = 0.75$).

***Conclusion*:** The greater *b* terms for the males may be the result of larger MU force twitches during force modulation. Only the females exhibited intensity-related differences for the *a* terms, suggesting divergent MU control strategies when modulating force during linearly increasing muscle actions for moderate- and high-intensity contractions. MMG_{RMS}-force relationships for the BB differentiated sex during linearly increasing, steady force, and linearly decreasing muscle actions at moderate- and high-intensities. Furthermore, evidence is provided that MMG_{RMS} is sensitive to muscle size.

Keywords: Biceps brachii, Log-transform model; Mechanomyography; Motor unit activation and deactivation, Ultrasonography

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1. Introduction:

Surface mechanomyography (MMG) records low-frequency oscillations produced by muscle fibers during muscular contractions. MMG is described as the mechanical counterpart to neural activation (Coburn et al., 2004), and the amplitude of the signal can be influenced by active stiffness modulated by motor unit (MU) recruitment and firing rates of the active MUs (Coburn et al., 2005). It is suggested that MMG amplitude (MMGRMS)-force relationships may allow for easier interpretation of MU recruitment and firing rate behavior than electromyographic amplitude (EMGRMS), as the MMG signal is not influenced by as many non-physiological factors (Farina et al., 2010). Therefore, MMGRMS- force relationships are commonly used to assess MU control strategies across various muscles (Orizio et al., 1990; Akataki et al., 2003; Sontag et al., 2021), contraction intensities (Trevino & Herda, 2015), and muscle actions (Coburn et al., 2005; Akataki et al., 2001; Dalton & Stokes, 1991).

MMG_{RMS}-force/torque relationships for the vastus lateralis (VL) and biceps brachii (BB) have previously differentiated sexes during high-intensity linearly increasing muscle actions of the knee extensors and elbow flexors, respectively (Sontag et al., 2021; Nonaka et al., 2006). It has been suggested that differences in the patterns of response may indicate divergent MU control strategies when modulating force, such as the greater increase in MMG_{RMS} during force production displayed by males suggests a greater reliance on MU recruitment (Hill et al., 2018). However, previous findings suggest that muscle morphology may influence MMG_{RMS}-force relationships as well. For example, Nonaka et al. (2006) reported males, who possessed larger muscle cross-sectional area (mCSA) of the BB

compared to females, exhibited greater MMG_{RMS} values during a linearly increasing muscle action to 80% maximal voluntary contraction (MVC). More recently, Sontag et al. (2021) and Trevino et al. (2023) reported greater slopes calculated from the log-transformed MMG_{RMS}-torque relationships of the VL during a linearly increasing muscle action of the knee extensors to 70% maximal voluntary contraction (MVC) for individuals with larger mCSA and pennation angle, respectively. However, sex comparisons for MMG_{RMS} of the BB have yet to be investigated during moderate-intensity contractions, when the population of activated MUs would express type I- more so than type II-muscle fiber twitch characteristics (Trevino et al., 2016). Therefore, it remains unknown if sex-related differences exist at lower contraction intensities (≤ 70% MVC). Furthermore, differences in MU control strategies exist during MU activation and deactivation due to differences in the recruitment and derecruitment thresholds, and MU firing rates (De Luca et al., 1982; Herda et al., 2015; Jesunathadas et al., 2010). However, no study has examined if sex-related differences exist for MMG_{RMS}-force relationships during linearly decreasing muscle actions. Therefore, information is lacking regarding the mechanical behavior of the BB for males and females during moderate-intensity muscle actions of the elbow flexors, and for MU deactivation altogether.

Due to the relatively large amount of individual variability when analyzing MMG_{RMS}-force/torque relationships via polynomial regression and analysis of variance (ANOVA) models of composite MMG_{RMS} values at distinct %MVC levels (Herda et al., 2009), it has been suggested these relationships should be inspected on a subject-by-subject basis (Farina et al., 2004; Orizio et al., 1989; Zwarts & Keidel, 1991) as the individual patterns may not be accurately represented by the group means (Ryan et al., 2008). Subsequently, Herda et al. (2009) applied a natural log transformation to the MMG_{RMS}-force/torque relationship for each contraction to calculate slope values (*b* terms) and y-intercepts (*a* terms) to examine individual patterns. For instance, the log-transformation procedure generates the equation: $Y = a \cdot X^b$, where $Y = MMG_{RMS}$, X = force/torque, a = gain coefficient, and b = exponential coefficient. The *a* term (anti-log of the *y*-intercept) can be viewed as a "gain factor" since the exponential model forces the *a* term through the zero, and it reflects a downward or upward shift in MMG_{RMS} without altering the linearity of the relationship. Conversely, the 95% confidence intervals (CIs) calculate around the group means for the *b* terms (slope) provide additional information regarding the linearity of the original MMG_{RMS}-force/torque patterns. For example, the relationship is linear if the 95% CI include 1. Furthermore, 95% intervals that are less than 1 but greater than 0 indicate a nonlinear relationship with downward deceleration, as the rate of change is greater for the force/torque than MMG_{RMS}. During linearly increasing muscle actions up to moderate- and high-intensity targeted forces/torques (60 - 90% MVC), the *b* terms have successfully discriminated the mechanical behavior of the VL between chronic training statues, and males and females (Trevino & Herda, 2015; Herda et al., 2010; Trevino et al., 2023; Sontag et al., 2021). However, no study has used the *a* and/or *b* terms to investigate the influence of sex on MU activation and deactivation strategies for the BB.

Therefore, the purpose of this study was to examine mCSA, the log-transformed MMG_{RMS}-force relationships of the BB between males and females during the linearly increasing and decreasing segments of a 40% MVC and 70% MVC isometric trapezoidal muscle action of the elbow flexors and MMG_{RMS} at steady force. We hypothesized that the

males would possess greater: mCSA of the BB, *b* terms during the linearly increasing and decreasing segments of the 40% and 70% isometric trapezoidal muscle actions, as well as MMG_{RMS} at steady force during both intensities.

2. METHODS:

Subjects: Ten healthy females (mean±SD age=20±3 yrs, height=164.59±4.91 cm, body 80 mass=59.38±11.65 kg) and ten healthy males (age=23±4 yrs, height=177.80±7.30 cm, body 81 mass=91.31±9.55 kg) participated in this study. Participants reported no ongoing neuromuscular diseases, or musculoskeletal injuries specific to the shoulder, elbow or wrist. This study was approved by the University's institutional review board for human subject's research. All participants provided informed, written consent before the study.

Experimental Design: This study used a randomized, repeated measures design. Participants reported to the laboratory on two occasions separated by a minimum of two days, but no more than seven days. The experimental visit was scheduled at the same time of day (±1hr) from the familiarization visit. Visit one consisted of ultrasonography for the BB to determine mCSA, muscle echo intensity (EI) and sFAT, and familiarization of MVCs and the isometric trapezoidal muscle actions for the elbow flexors. Visit two consisted of participants performing MVCs, followed by a submaximal isometric trapezoidal muscle action of the elbow flexors at 40% and 70% MVC. MMG was recorded from the BB during visit two. Participants were instructed to refrain from any alcohol and caffeine consumption, and physical activity for 24 and 48 hrs, respectively, before each visit.

Ultrasonography: Ultrasound images of the BB were taken on the dominant arm using a portable brightness-mode (B-mode) Logiq® S8 ultrasound device (LOGIQ S8 GE Ultrasound System; GE Healthcare, Milwaukee, WI, USA) with a 4-15 MHz multi frequency linear array probe (ML6-15-D; 50 mm field of view; GE Healthcare system). Scan depth was set to 5 cm, gain was 58 dB, and transducer frequency was 17 MHz optimize image quality, and was held constant across all subjects. During testing, participants were examined on a padded table in the supine position with their arm abducted, relaxed and supported on a wooden table, and their forearm extended at the elbow. After ten minutes of rest to allow fluid shifts to settle (Berg et al., 1993; Trevino et al., 2022; Dimmick et al., 2018), a generous amount of water soluble transmission gel was applied to the skin to reduce possible near field artifacts and enhance acoustic coupling. Three images were captured at half the distance from the medial acromion to the fossa cubit (similar placement as the MMG sensor), with the average of the three scans utilized for subsequent analysis. Great care was taken to limit the compression of the muscle with the probe. ImageJ software (National Institute of Health, Bethesda, MD) was used to analyze all ultrasound images. Each image was scaled from pixels to cm using the polygon and straight-line function. For mCSA (cm^2), the muscle was outlined using the polygon function, with care taken to exclude the surrounding fascia. Additionally, using the straight-line function, sFAT was quantified as the distance between the skin and superficial aponeurosis of the BB. Lastly, EI was assessed by computer-aided gray-scale analysis using the standard histogram function and corrected for sFAT (Young et al., 2015; Dimmick et al., 2018; Miller et al., 2018; Herda et al., 2018; Herda et al., 2019; Parra et al., 2020; Sterczala et al., 2018).

Isometric Strength Testing: Isometric strength assessments of the dominant elbow flexors were performed on an isometric ergometer (MUC1; OT Bioelettronica SRL, Torino, Italy) fitted with a load cell (CCT Transducer, linear, full scale 100kg), and the signal recorded with the force transducer was amplified (500x) (Forza, OT Bioelettronica SRL, Torino, Italy). During testing, participants were seated in an upright position with their shoulder and elbow joint flexed at 90° and the upper forearm strapped to the ergometer.

For the experimental visit, participants first performed two, 3-4 seconds held submaximal isometric warm-up contractions at 40% and 70% of perceived maximal effort. Participants then performed two to three MVCs, each separated by 2 minutes of rest. During the MVCs, participants were instructed to "pull as hard and as fast as possible" and sustain the maximal contraction for 3-4 seconds. Additionally, verbal encouragement was provided during each attempt. The MVC with the highest force (N) averaged over a 0.25 s epoch determined maximal strength and the force level for the subsequent submaximal contractions. Following two minutes of rest, participants performed an isometric trapezoidal muscle action at 40% and 70% MVC in random order. For each isometric trapezoidal muscle action trajectory, baseline consisted of 5 s, followed by an increase in force at a rate of 10% MVC/s to the desired force level, a 12 s steady force segment, followed by a decrease of 10% MVC/s to baseline. Therefore, the duration of the 40% and 70% MVCs lasted 20 and 26 seconds, respectively (Figure 1).

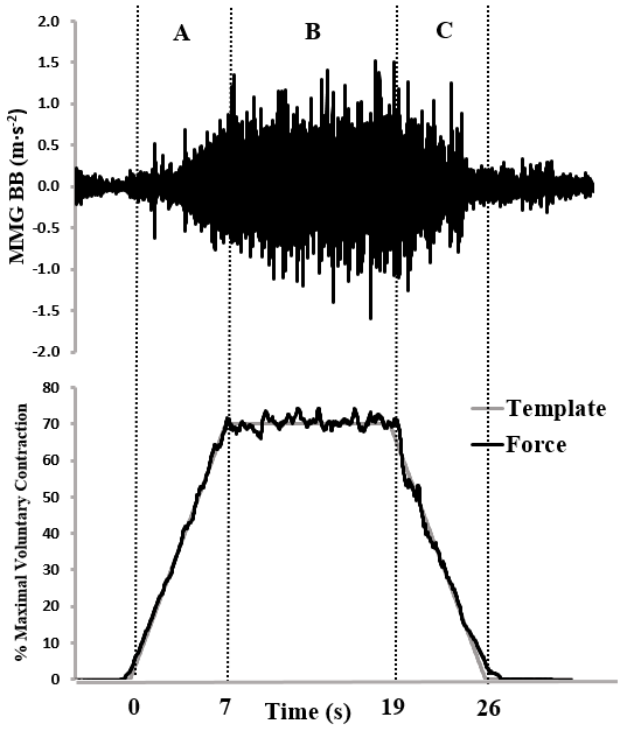

Figure 1. The mechanomyographic (MMG) signal from the biceps brachii (BB) during the 70% isometric trapezoidal contraction from one participant (top). The force signal (bottom) is overlaid onto the trapezoidal template as it appeared for the participant during the trial. The vertical lines represent the (A) linear force increasing, (B) steady force, and (C) linear force decreasing segments of the 70% isometric trapezoidal contraction. The MMG signals that corresponds with the contraction segments (A-C) were selected for analysis.

Two minutes of rest were provided between the 40% and 70% MVCs. During each trapezoidal muscle action, participants were instructed to maintain their force output as accurately as possible to the target force presented digitally in real time on a computer monitor. Participants were given a second attempt if unable to maintain the targeted force during the initial trial.

Mechanomyography: Surface MMG signals were collected using an active miniature accelerometer (model 352A24, bandwidth 1-8000 Hz, sensitivity 102.0 mV/g, dimensions 1.22 x 0.71 x 0.48 mm, mass 0.8 g, PCB Piezotronics, Inc, Depaw, NY). The accelerometer was placed over the muscle belly of the BB (Ye et al., 2015; Petersen et al., 2002; Kidgell et al., 2010). Double-sided adhesive tape was used to ensure consistent contact pressure of the MMG sensor. Before placement of the accelerometer, a disposable razor was used to shave the skin and alcohol was used to clean the area.

Signal Processing: Force (N) and MMG ($m \cdot s^{-2}$) signals were simultaneously sampled at 2 kHz with National Instruments sound and vibration module (NI-9234) that was interfaced with a National Instruments compact data acquisition system (NI cDAQ-9174) during each muscle action. All subsequent signals were stored and processed off-line with custom-written software (LabVIEW version 18; National Instruments, Austin, TX). The force signal was low-pass filtered using a second-order, zero-shift, Butterworth filter with a cut-off frequency of 10 Hz, whereas the MMG signal was bandpass filtered at 5-100 Hz (fourth-order, zero-shift, Butterworth). During the isometric trapezoidal muscle action, consecutive, non-overlapping 0.25-s epochs were analyzed for the force and MMG signals. Root mean square (RMS) was used to calculate the amplitude of the MMG signals.

Statistical Analysis: For the linearly increasing and decreasing segments of the isometric trapezoid, simple linear regression models were fit to the natural log-transformed MMG_{RMS}-force relationships (Trevino & Herda, 2015; Sontag et al., 2021; Sontag et al., 2023; Olmos et al., 2022, Trevino et al., 2023). The equations were represented as:

$$(1)\ \mathrm{Ln}[Y] = b(\ln[X]) + \ln[a]$$

where $\ln[Y]$ = the natural log of the MMG_{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 of both sides of the equation:

$$(2)\ Y = aX^{b}$$

where Y = predicted MMG_{RMS} values, X = force, b = slope of Eq. (1) and a = antilog of the y-intercept from Eq. (1). Individual slopes and the y-intercepts were calculated using Microsoft Excel® version 2016 (Microsoft, Inc., Redmond, WA, USA) to allow subject-by-subject analysis. For the steady force segment of the trapezoid, MMG_{RMS} and normalized MMG_{RMS} ($N\text{-}MMG_{RMS}$) was calculated by averaging the values from each 0.25-s epoch during the steady targeted contraction force (Trevino et al., 2016; Trevino et al., 2023; Sontag et al., 2023; Olmos et al., 2023) to minimize non-stationarity reported in MMG signals (Beck et al., 2010).

Six independent samples *t*-tests were performed to examine potential sex-related differences in MVC, mCSA, EI, mCSA/EI, MVC/EI, and sFAT. Separate, 3-way mixed factorial repeated measures analyses of variance (ANOVAs) (sex [males vs. females] x intensity [40% vs. 70%] x segment [increase vs. decrease]) was performed to examine possible differences in the *b*- and *a*-terms from the log transformed MMG_{RMS}-force relationships during the linearly increasing and decreasing segment of the 40% and 70% MVC isometric trapezoidal muscle actions. A 2-way mixed factorial repeated measures ANOVA (sex [male vs. female] x intensity [40% vs. 70%]) was used to analyze possible differences in MMG_{RMS} between sexes and intensities during the steady force segment of the isometric trapezoidal muscle actions. A separate 2-way mixed factorial repeated measures ANOVA (sex [male vs. female] x intensity [40% vs. 70%]) was used to analyze possible differences in N-MMG_{RMS} between sexes and intensities during the steady force segment of the isometric trapezoidal muscle actions. When appropriate, follow-up analyses included independent and paired samples *t*-tests with Bonferroni corrections. Lastly, to assess if sFAT may have biased MMG parameters, ten Pearson's product moment correlation coefficients were calculated comparing sFAT with MMG_{RMS} and N-MMG_{RMS} during the steady force segment, and the *b* terms and *a* terms from the log transformed MMG_{RMS}-force relationships during the linear increasing and decreasing segments of the isometric trapezoidal muscle actions for 40% and 70% MVC, respectively. The level of significance was set at $p \leq 0.05$. Greenhouse-Geisser corrections were applied when sphericity was not met according to Maulchy's Test of Sphericity. Effect sizes for interactions were estimated using partial eta squared and were classified as very small (0-0.01), small (0.01-0.06), medium (0.06-0.14), or large (>0.14). Additionally, effect sizes for between and within group comparisons were estimated using Hedges' *g* and were classified as minimal (0-0.2), small (0.2-0.5), medium (0.5-0.8) or large (>0.8). All statistical analyses were performed using SPSS 20 (IBM Corporation, Armonk, New York, USA).

3. RESULTS

Table 1 contains a summary of the independent-samples *t*-tests and means ± SD for the voluntary strength and ultrasonography data.

	P Value	*g* Value	Males	Females
MVC, N	< 0.001*	2.64	324.83 ± 55.17	194.26 ± 37.93
mCSA, cm^2	<0.001*	3.15	12.73 ± 2.16	6.01 ± 1.92
EI, AU	0.103	0.74	74.72 ± 14.10	84.61 ± 11.54
sFAT, cm	0.154	0.64	0.16 ± 0.08	0.22 ± 0.11
MVC/EI, N/AU	<0.001*	2.57	4.46 ± 0.98	2.33 ± 0.55
mCSA/EI, cm^2/AU	<0.001*	2.76	0.18 ± 0.04	0.07 ± 0.03

Table 1. Data are *P* values, Hedge's *g* effect sizes, and means ± SD for maximal voluntary contraction (MVC), muscle cross-sectional area (mCSA), echo intensity (EI), and subcutaneous fat (sFAT) for the males and females. AU, arbitrary units. *$P < 0.05$ indicates significant difference between males and females.

Maximal Strength and Ultrasound Measurements

Independent-samples *t*-tests indicated that the males had significantly greater values for MVC ($p < 0.001$, $g = 2.64$), mCSA ($p < 0.001$, $g = 3.15$), mCSA/EI ($p < 0.001$, $g = 2.76$), and MVC/EI ($p < 0.001$, $g = 2.57$). There was no significant difference between groups for sFAT ($p = 0.163$, $g = 0.64$) or EI ($p = 0.097$, $g = 0.74$).

Linear Increasing and Decreasing MMG_{RMS}-Force Relationships

During the 40% MVC, 9 of 10 (90%) and 9 of 10 (90%) relationships for the males were significant during the linearly increasing ($p<0.05$; r range=0.45–0.87) and decreasing segments ($p<0.05$; r range=0.43–0.82), respectively. For the females, 6 of 10 (60%) and 4 of 10 (40%) relationships during the 40% MVC were significant during the linearly increasing ($p<0.05$; r range=-0.57–0.90) and decreasing segments ($p<0.05$; r range=0.46–0.71), respectively. For the 70% MVC, 10 of 10 (100%) and 5 of 10 (50%) relationships were significant for the males during the linearly increasing ($p<0.05$; r range=0.67–0.94) and decreasing segments ($p<0.05$; r range=0.86–0.92), respectively. For the females, 4 of 10 (40%) and 4 of 10 (40%) relationships during the 70% MVC were significant during the linearly increasing ($p<0.05$; r range=0.71–0.90) and decreasing segments ($p<0.05$; r range=0.68–0.83), respectively. The upper and lower limits of the 95% CI intervals for the b terms when separated by contraction, sex, and segment were all > 0 and < 1, indicating nonlinear relationships where force increased at a greater rate than MMG_{RMS}. Figure 2

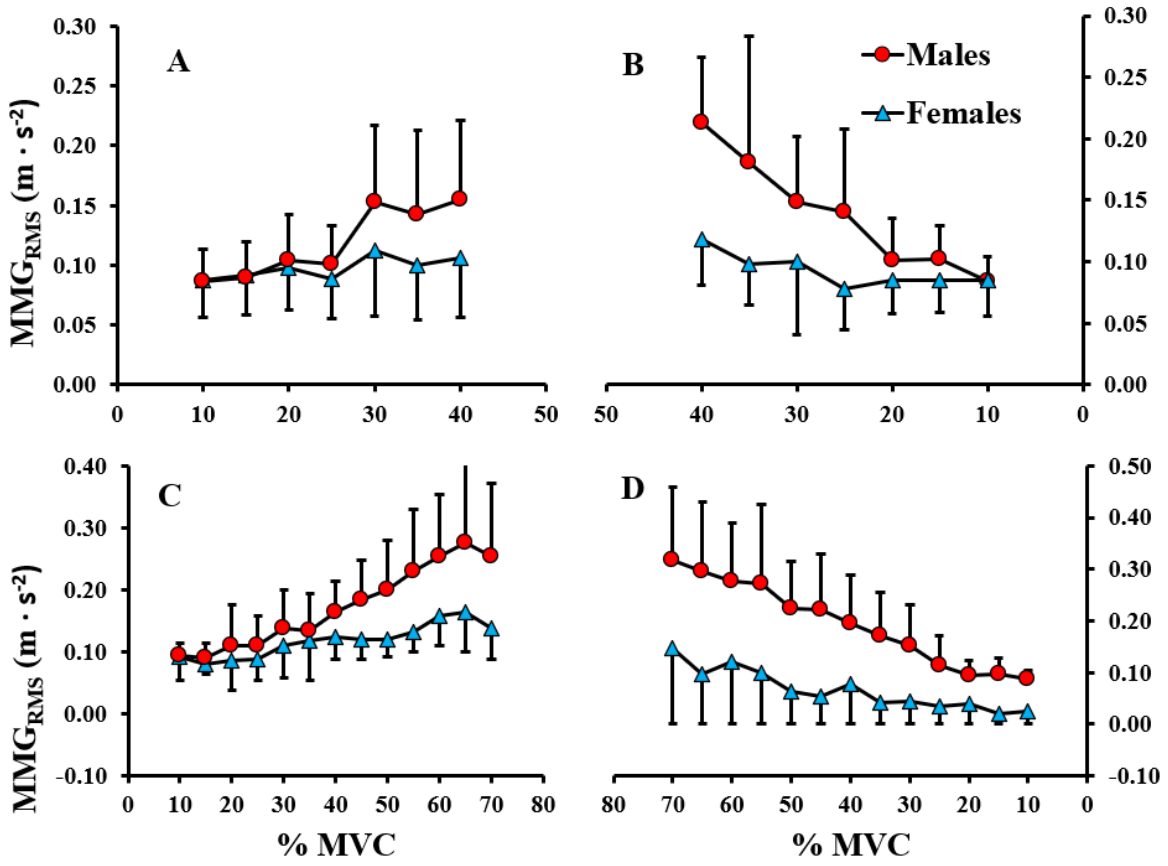

Figure 2. Plotted means and standard deviations for the males (circles) and females (triangles) during the linearly increasing (A, C) and decreasing (B, D) segments of the 40% (top) and 70% (bottom) MVC for the mechanomyographic amplitude (MMG_{RMS})-force relationship.

Illustrates the MMG_{RMS} patterns of response during the linearly increasing and decreasing muscle actions for the males and females during the 40% and 70% MVCs.

For the *b* terms, there was no significant three-way interaction (intensity x segment x sex; $F_{[1,18]} = 1.63$; $p = 0.218$; $\eta p^2 = 0.083$). Additionally, there were no two-way interactions for intensity and segment ($F_{[1,18]} = 0.223$; $p = 0.642$; $\eta p^2 = 0.012$), segment and sex ($F_{[1,18]} = 0.481$; $p = 0.497$; $\eta p^2 = 0.026$), intensity and sex ($F_{[1,18]} = 0.732$; $p = 0.403$; $\eta p^2 = 0.039$), and no main effect for segment ($F_{[1,18]} = 1.38$; $p = 0.255$; $\eta p^2 = 0.071$). However, there was a main effect for sex ($F_{[1,18]} = 15.62$; $p < 0.001$; $\eta p^2 = 0.465$) and intensity ($F_{[1,18]} = 23.11$; $p < 0.001$; $\eta p^2 = 0.562$). The *b* terms for the males (0.665 ± 0.160) were greater than the females (0.360 ± 0.184) when collapsed across intensity and segment. In addition, the *b* terms were greater for the 70% MVC (0.672 ± 0.229) than the 40% MVC (0.352 ± 0.311) when collapsed across sex and segment (Figure 3).

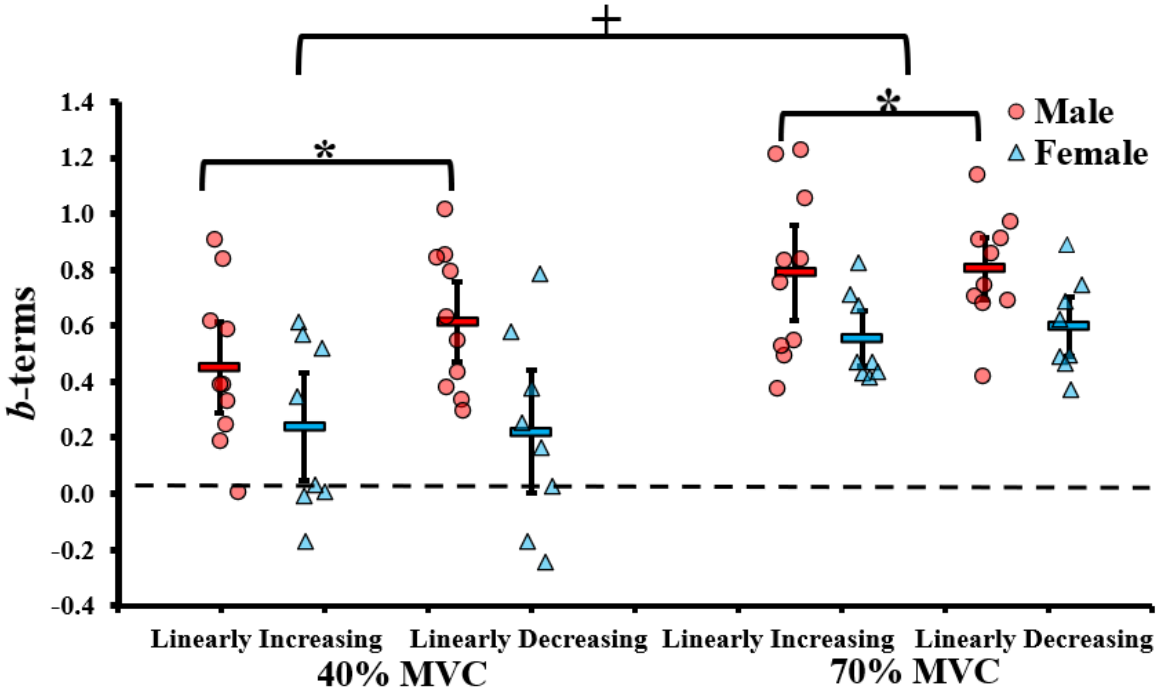

Figure 3. Plotted individual values for the *b* terms from the mechanomyographic amplitude vs. force relationships for males (circles) and females (triangles) from the linearly increasing and decreasing segments of the isometric trapezoidal contraction at 40% and 70% maximum voluntary contraction (MVC). Bars represent the means with standard deviations displayed for the *b* terms. *Indicates greater *b* terms for the males than females when collapsed intensity and segment ($p < 0.001$). +Indicates greater *b* terms for the 70% MVC than the 40% MVC when collapsed across sex and segment ($p < 0.001$).

For the *a* terms, there was no significant three-way interaction (intensity x segment x sex; $F_{[1,18]} = 0.153$; $p = 0.700$; $\eta p^2 = 0.008$). Additionally, there were no two-way interactions for intensity and segment ($F_{[1,18]} = 0.88$; $p = 0.360$; $\eta p^2 = 0.047$), or segment and sex ($F_{[1,18]} = 0.415$; $p = 0.528$; $\eta p^2 = 0.023$). However, there was a significant two-way interaction for intensity and sex ($F_{[1,18]} = 6.91$; $p = 0.017$; $\eta p^2 = 0.277$). For the 40% MVC, the *a* terms were greater for the females (0.103 ± 0.101) than the males (0.018 ± 0.014; $p = 0.026$; $g = 1.13$). For the females, the *a* terms during the 40% MVC (0.103 ± 0.101) were greater than the 70% MVC (0.013 ± 0.007; $p = 0.019$; $g = 0.82$). There were no sex-related difference in *a* terms

for the 70% MVC (p = 0.909; g = 0.050), or between the 40% and 70% MVCs for the males (p = 0.720; g = 0.107) (Figure 4).

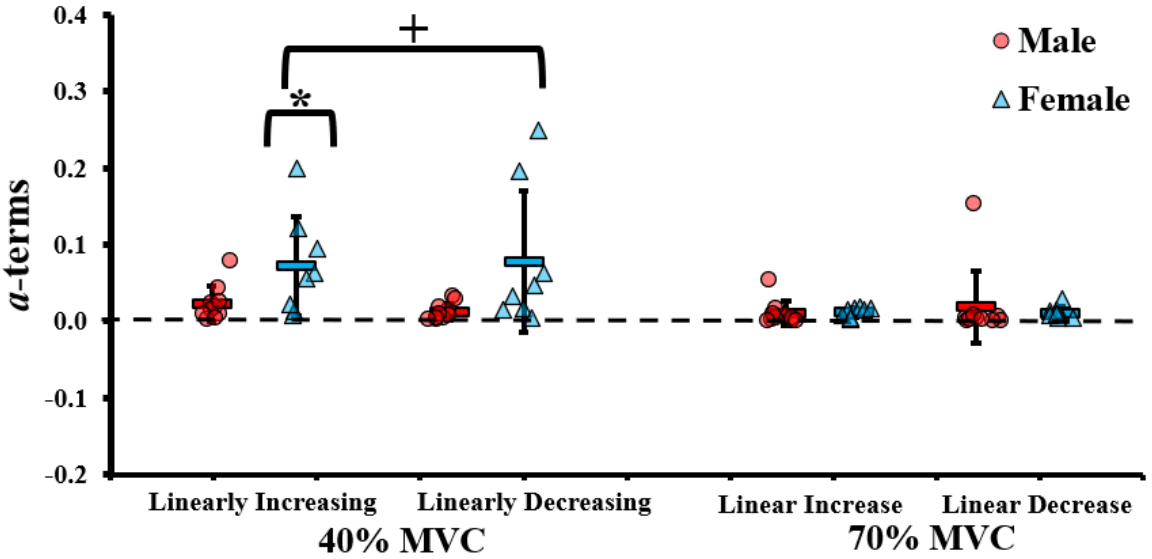

Figure 4. Plotted individual values for the a terms from the mechanomyographic amplitude vs. force relationships for males (circles) and females (triangles) from the linearly increasing and decreasing segments of the isometric trapezoidal contraction at 40% and 70% maximum voluntary contraction (MVC). Bars represent the standard deviations displayed for the a terms. * Indicates the a terms during the linearly increasing segment at 40% MVC were greater for females in comparison to the males (p = 0.026). + Indicates the a terms for females during the 40% MVC were greater in comparison to the 70% MVC (p = 0.019).

Steady Force Segment: For MMG_{RMS}, there was no significant two-way interaction (intensity x sex; $F_{[1,18]}$ = 1.53; p = 0.232; ηp^2 = 0.078). However, there was a main effect for intensity ($F_{[1,18]}$ = 42.02; p < 0.001; ηp^2 = 0.700) and sex ($F_{[1,18]}$ = 9.61; p = 0.006; ηp^2 = 0.348). MMG_{RMS} was greater for the 70% MVC (0.262 ± 0.117 $m \cdot s^{-2}$) than 40% MVC (0.152 ± 0.061 $m \cdot s^{-2}$; g = 1.18) when collapsed across sex. In addition, MMG_{RMS} was greater for the males (0.256 ± 0.091 $m \cdot s^{-2}$) than the females (0.159 ± 0.041 $m \cdot s^{-2}$; g = 1.37) when collapsed across intensity (Figure 5).

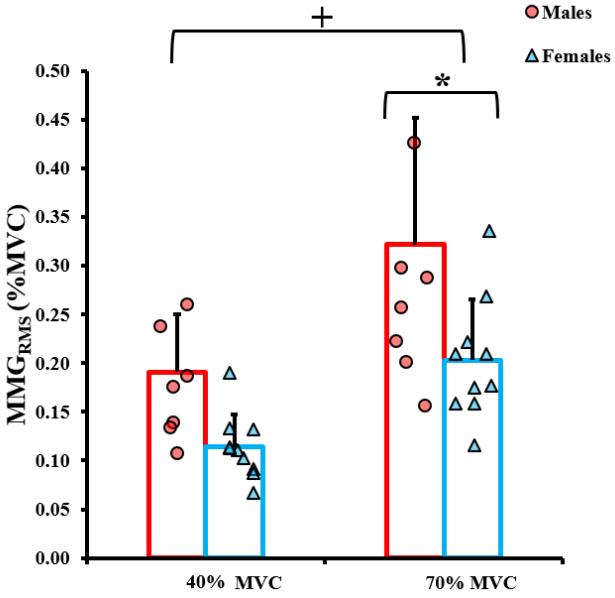

Figure 5. Plotted individual values for mechanomyographic amplitude (MMG_{RMS}) from the 40% and 70% MVCs for the males (circles) and females (triangles) during the steady force segments of the isometric trapezoidal contraction. Bars represent the means and standard deviations. *Indicates greater MMG_{RMS} for the males than females when collapsed across intensities ($p < 0.001$). +Indicates greater MMG_{RMS} for the 70% MVC than 40% MVC when collapsed across sex ($p < 0.006$).

For N-MMG_{RMS}, there was no significant two-way interaction (intensity x sex; $F_{[1,18]} = 0.070$; $p = 0.795$; $\eta p^2 = 0.004$), and no main effect for sex ($F_{[1,18]} = 2.65$; $p = 0.121$; $\eta p^2 = 0.128$). However, there was a main effect for intensity ($F_{[1,18]} = 73.90$; $p < 0.001$; $\eta p^2 = 0.804$). N-MMG_{RMS} was greater for the 70% MVC (1.04 ± 0.27 %) than the 40% MVC (0.64 ± 0.26 %; $g = 1.51$) when collapsed across sex (Figure 6).

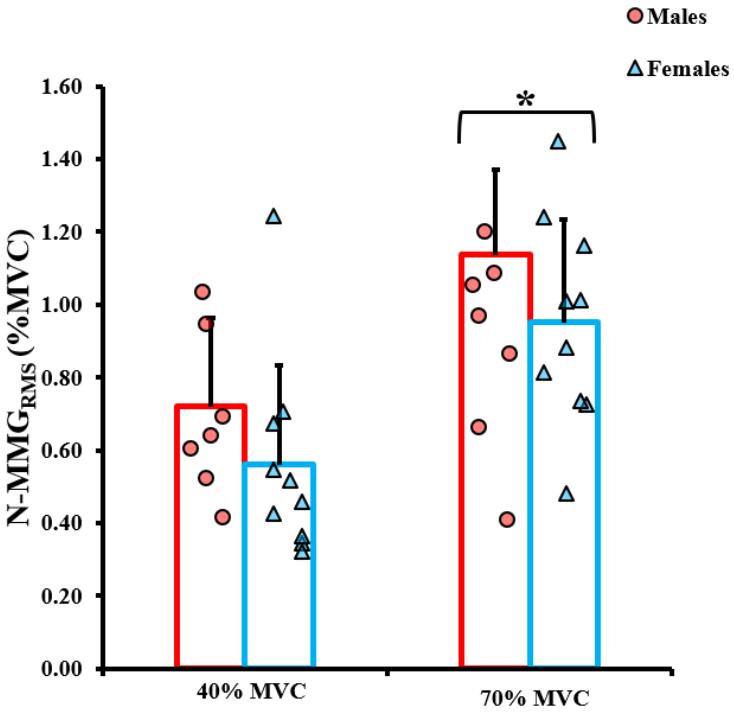

Figure 6. Plotted individual values for normalized mechanomyographic amplitude (N-MMG_{RMS}) from the 40% and 70% MVCs for the males (circles) and females (triangles) during the steady force segments of the isometric trapezoidal contraction. Bars represent the means and standard deviations. *Indicates greater N-MMG_{RMS} for the 70% MVC than 40% MVC when collapsed across sex ($p < 0.001$).

Correlations: Only 1 of 10 Pearson's product moment correlations were significant (p = 0.031; r = -0.484) for sFAT among the *a* and *b* terms during the linearly increasing and decreasing segments and MMG_{RMS} at steady force for the 40% and 70% MVCs (p = 0.053 – 0.873; r = -0.439 – 0.245). Therefore, the similar sFAT between males and females coupled with the lack of correlations between sFAT and MMG_{RMS} parameters provides confidence the findings were not the result of sFAT filtering of the MMG signal (Sontag et al., 2021; Perez et al., 2022; Olmos et al. 2022; Olmos et al. 2023; Sontag et al. 2023). However, sFAT was correlated with N-MMG_{RMS} for the 40% (p = 0.019; r = -0.520) and 70% MVCs (p = 0.041; r = -0.460).

4. DISCUSSION

This study examined potential sex-related differences in MMG_{RMS}-force relationships during MU activation, constant force, and deactivation during a moderate-intensity (40% MVC) and high-intensity (70% MVC) isometric muscle action. In agreement with previous studies, the *b* terms (slopes) for the linearly increasing and decreasing muscle actions, and MMG_{RMS} at steady force were greater during the higher- compared to the lower-intensity contraction for the males and females, and males exhibited greater MMG_{RMS} than the females at steady force. Significant and novel findings related to MMG parameters for the BB include: 1) greater *b* terms from the MMG_{RMS}-force relationship for the males compared to the females during the linearly increasing and decreasing muscle actions of the 40% and 70% MVCs, 2) greater *a* terms from the MMG_{RMS}-force relationship for the females compared to the males during the linearly increasing segment of the 40% MVC, and 3) only the females showed intensity-related differences for the *a* terms, such as greater values during the 40% MVC compared to 70% MVC. Therefore, MMG_{RMS}-force relationships of the BB differentiated MU activation, constant force, and deactivation between sexes during moderate- and high-intensity muscle actions.

Ultrasonography revealed no differences in EI for the BB between males and females; therefore, muscle quality (infiltration of noncontractile tissue) was similar between sexes. However, males displayed significantly greater mCSA. Consequently, mCSA/EI was also greater for the males, suggesting they possessed more contractile tissue than the females, which is in agreement with previous studies (Miller et al., 1993; Nonaka et al., 2006). Interestingly, when MVC was normalized to EI, males also possessed greater values. Thus, the greater MVCs for the males may be due to greater mCSA, as well as greater force generating capabilities of their contractile tissue.

During the linearly increasing and decreasing segments of the 40% and 70% MVCs, the *b* terms were greater for the males, indicating MMG_{RMS} increased at a greater rate relative to force compared to the females. MMG_{RMS} is influenced by active stiffness modulated during MU recruitment, as well as the firing rates of active MUs (Coburn et al., 2005). For example, MMG_{RMS} increases with MU recruitment; however, it will plateau or decrease with higher firing rates due to MU tetanus (Guo et al., 2010; Beck et al., 2004). During

linearly increasing muscle actions of the elbow flexors, Akataki (2003) reported MMG_{RMS} for the BB displayed an initial slow decrease followed by a rapid increase at 23% MVC, and a progressive decrease beyond 61% MVC. The BB continues to recruit MUs up to 90% MVC, with 94% of the MU pool recruited at 70% of maximal strength (De Luca & Kline, 2011). Therefore, Akataki (2003) hypothesized MU recruitment was a major mechanism for modulating force to ~60% MVC, whereas rate coding played a prominent role thereafter.

MMG_{RMS}-force relationships have discerned muscles with functional role differences, such as the first dorsal interosseous displaying an earlier plateau in the pattern of response compared to the BB (Akataki et al., 2003) and vastus lateralis (Cooper & Herda, 2014) during linearly increasing muscle actions up to 70% and 100% MVC, respectively. However, this is the first study to report sex-related differences in MMG_{RMS}-force relationships during MU activation and deactivation for a moderate- and high-intensity contraction. Even though MMGRMS may reflect MU recruitment (Guo et al., 2010; Beck et al., 2004), it is possible that other factors, such as muscle morphology influenced our findings. For example, Sontag et al. (2021) reported males possessed greater mCSA and *b* terms for MMGRMS-torque relationships recorded from the VL during a linearly increasing muscle action compared to females. Additionally, the authors reported positive relationships between mCSA and the *b* terms. Indeed, mCSA and the *b* terms of the BB for the males in the current study were greater (211% and 185%, respectively) than the females. Furthermore, a secondary analysis indicated the *b* terms (collapsed across contraction and segment) were correlated with mCSA ($p = 0.001$; $r = 0.67$) (Figure 7).

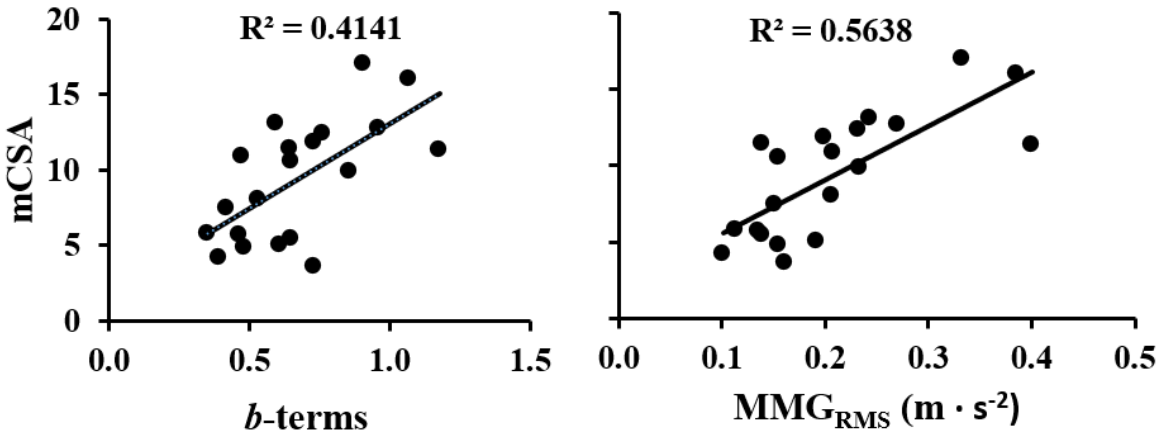

Figure 7. Plotted relationships for muscle cross sectional area (mCSA) among and the *b* terms when collapsed across intensity and segment (left), and mechanomyographic amplitude (MMG_{RMS}) (right) when collapsed across intensity.

Although MMG_{RMS} can be negatively influenced by type I% MHC expression due to greater MU firing rates (Trevino et al., 2016; De Luca et al., 1982), previous literature has reported similar fiber-type distribution (ratio of type I and II fibers) and fiber area (area of the muscle occupied by the fiber-types) (Miller et al., 1993; Sale et al., 1987), as well as MU firing rates of the BB between sexes (Hill et al., 2018). Conversely, males have displayed more muscle fibers (Sale et al., 1987) and greater mean muscle fiber areas for the BB (Miller et al., 1993; Sale et al., 1987; Lulic-Kuryllo & Inglis, 2022; Harwood & Rice, 2014). Of note, when the *b* terms were normalized to mCSA, there were no significant differences between sexes ($p =$

0.377), further supporting the influence of muscle size on the MMG_{RMS}-force patterns. Therefore, the sex-related differences for the *b* terms may be the result of males possessing larger MUs, which would produce greater force twitches and result in greater MMG_{RMS} values throughout the force spectrum (Bichler, 2000).

It is suggested the *a* terms represent a "gain factor" that reflects upward/downward shifts in the log-transformed MMG_{RMS}-force relationships independent of the *b* terms (Herda et al., 2009). During the 40% MVC, the *a* terms were greater for females in comparison to the males. Our findings are consistent with Gillen et al. (2019), that reported individuals with greater maximal strength and muscle mass exhibited lower *a* terms. The authors speculated that greater muscle mass may have limited the amplitude of the MMG signal and resulted in a downward shift of the MMG_{RMS}-force relationship, which is tentatively supported by our findings. Additionally, females displayed greater *a* terms during the 40% MVC in comparison to the 70% MVC. Gillen et al. (2019) also suggested that greater muscle stiffness may attenuate MMG_{RMS}, resulting in a smaller *a* term. Recently, Olmos et al. (2024) reported females required greater normalized electromyographic amplitude compared to males during the steady force segment of an isometric trapezoidal muscle action performed at 70% MVC. It has been well observed that increases in excitation result in a concomitant increase in motor unit firing rates (Olmos et al., 2024; Trevino et al., 2016, De Luca & Hostage, 2010). Indeed, the amplitude of the MMG signal can be negatively affected by firing rate increases (Bichler, 2000). Therefore, it is possible that females increased firing rates to a greater degree than the males during the 70% MVC in comparison to the 40% MVC, resulting in a downward shift (lower *a* term) of their MMG_{RMS}-force relationships. The lack of contraction-related differences in *a* terms for the males may suggest similar neuromuscular control strategies during the 40% and 70% MVC. It should be noted that the *a* terms may be associated with the filtering effects of sFAT (Trevino et al., 2023; Olmos et al., 2023; Sontag et al., 2023). However, the non-significant group differences for sFAT and lack of correlations for sFAT with the *a* terms during the linearly increasing and decreasing segments of the 40% and 70% MVC suggests that the observed differences were not the result of filtering.

During the steady force segment of the isometric trapezoidal muscle actions, MMG_{RMS} of the BB was greater for the males compared to the females during the 40% and 70% MVCs. Garcia et al. (2008) reported similar findings during isometric contractions at five different intensities (20%, 40%, 60%, 80%, and 100% MVC). However, when normalized, N-MMG_{RMS} during the steady force segment of the isometric trapezoidal muscle actions was no longer greater for the males when compared to the females, regardless of intensity. Both MMG_{RMS} and N-MMG_{RMS} during the steady force segment of the isometric trapezoidal muscle actions were greater at 70% MVC compared to 40% MVC. Similar to the *b* terms, a secondary analysis indicated MMG_{RMS} during steady force (collapsed across contractions) was correlated with mCSA ($p < 0.001$, $r = 0.75$) (figure 7). Therefore, muscle size for the BB influences MMG_{RMS} recorded during steady force, as well as MMG_{RMS}-force relationships during linearly varying muscle actions.

5. CONCLUSION

This is the first study to report sex-related differences for the *a* and *b* terms from the log-transformed MMG_{RMS}-force relationships of the BB during MU activation and

deactivation. The greater *b* terms (i.e., slope) for the males during the linearly increasing and decreasing segments of the 40% and 70% MVCs may be the result of larger higher-threshold MUs producing greater force twitches. For example, males possessed greater mCSA, as well as greater force generating capabilities of their contractile tissue. Additionally, positive relationships existed between mCSA with the *b* terms, further supporting the influence of muscle size on MMG_{RMS}. Conversely, females exhibited greater *a* terms (i.e. gain) during the 40% MVC compared to the males, which may be a function of the larger mCSA for the males resulting in greater muscle stiffness and attenuation of the MMG signal. Only the females displayed contraction-related differences for the *a* terms, such as greater values during the 40% MVC in comparison to the 70% MVC. The decrease in *a* terms for the females may suggest different MU control strategies when modulating force during high- in comparison to moderate-intensity contractions, such as an increased reliance on MU rate coding. In summary, MMG_{RMS}-force relationships of the BB differentiated sexes during MU activation and deactivation, as well as constant force during moderate- and high-intensity contractions of the elbow flexors. Future research should investigate if a high-intensity resistance training intervention for females can decrease the sex-related discrepancies for muscle morphology and MU activation and deactivation strategies as measured by ultrasound and MMG_{RMS}-force relationships, respectively.

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