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Effects of Joint Angle on Inter- and Intra-individual Variability for Women During Isometric Fatiguing Tasks Anchored to a Perceptual Intensity

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Abstract The purpose of this study was to compare the composite, inter-individual, and intra-individual differences in the fatigue-induced torque, electromyographic (EMG), and mechanomyographic (MMG) patterns of responses during sustained, isometric fatiguing tasks anchored to a rating of perceived exertion (RPE) at elbow joint angles (JA) of 75° and 125°. Nine women (age: 21.0±3.0 yrs; height: 169.3±8.1 cm; body mass: 68.4±7.4 kg) performed 2,3s forearm flexion maximal voluntary isometric contractions (MVIC) before and after sustained, isometric forearm flexion tasks anchored to RPE = 8 to task failure (defined as torque reduced to zero) at JA75 and JA125. The EMG and MMG signals were recorded from the biceps brachii (BB). Polynomial regression analyses (linear and quadratic) were performed to examine the patterns for the torque, neuromuscular responses, and neuromuscular efficiency (NME) vs. time relationships. Six, separate 2 (Joint Angle: 75° vs 125°) x 2 (Time: Initial vs 5%TTF) repeated measures ANOVAs were performed to assess the mean differences for the torque and neuromuscular parameters values between the initial value and the value at 5%TTF. At JA75, there were significant ($p \leq 0.05$) negative torque (quadratic), EMG amplitude (AMP) (linear), EMG mean power frequency (MPF) (quadratic), MMG MPF (linear), and NME (linear) vs. time relationships. At JA125, there were significant ($p \leq 0.05$) negative torque (quadratic), EMG AMP (quadratic), EMG MPF (linear), MMG MPF (linear), and NME (linear) vs. time relationships. MMG AMP, however, did not change across time ($p \geq 0.05$) at JA75 or JA125. The individual neuromuscular responses varied from the composite data within and between JA75 and JA125. These findings indicated that for torque, joint angle did not affect the composite and individual responses when anchored to RPE = 8. There was, however, substantial inter- and intra-individual variability in the neuromuscular responses that may be specific to the joint angle at which the tasks were performed.

Keywords: *female, ratings of perceived exertion, fatigue, electromyography, mechanomyography, forearm flexion, neuromuscular*

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1. Introduction

Fatigue has been described as “…an acute impairment of performance that includes both an increase in the perceived effort necessary to exert a desired force and an eventual inability to produce this force” [[1], p. 1631]. This definition indicates that there are both perceptual and performance related components of fatigue that can influence the ability to perform a task. More recently, Kluger et al. [2] and Enoka and Duchateau [3] proposed complementary, unified taxonomies of fatigue that included the domains of perceived fatigability and performance fatigability. Perceived fatigability includes modulating factors related to homeostasis, as well as the psychological state of the individual [3]. Performance fatigability, however, includes modulating factors associated with contractile function and muscle activation that contribute to fatigue-induced changes in objective measures of performance including maximal voluntary isometric contractions (MVIC), the time to complete a task, and power output [3]. While perceived fatigability and performance fatigability are separate domains of fatigue, they often influence one another [2]. Enoka and Duchateau [3] emphasized the importance of examining the interactions between perceived fatigability and performance fatigability to understand the task-dependent causes of fatigue “…as most voluntary actions performed by humans involve significant interactions between the two domains” (p. 2230).

Previous studies [4,5,6] have examined the interactions between perceived fatigability and performance fatigability during sustained, isometric tasks anchored to torque or force by assessing time-dependent changes in ratings of perceived exertion (RPE), electromyographic amplitude (EMG AMP), mechanomyographic amplitude (MMG AMP), EMG mean power frequency (EMG MPF), and MMG MPF throughout the task. Recent studies [4,7-16] have also utilized the RPE Clamp Model of Tucker [17] to examine the interactions between perceived fatigability and performance fatigability when anchoring exercise intensity to RPE values instead of torque. When sustained, isometric tasks are anchored to force, the neuromuscular patterns of responses are representative of the ability to maintain the target force value and are, typically, characterized by increases in EMG AMP and MMG AMP with decreases in EMG MPF and MMG MPF [18,19]. When anchored to RPE, the neuromuscular patterns of responses are less predictable and reflect the ability to maintain the prescribed RPE [9,11,13].

Typically, composite neuromuscular data (averaged across all subjects) have been used when making inferences regarding fatigue-induced changes in motor unit activation strategies [19,20]. Anders et al. [21], however, suggested that when interpreting motor unit activation strategies, individual and composite responses should be examined due to inter- and intra-individual variability. Recently, Smith et al. [13] described substantial inter-individual variability in neuromuscular responses during a sustained, isometric forearm flexion task anchored to an RPE of 7 on the 0 – 10 omnibus resistance (OMNI-RES) scale at an elbow joint angle of 100°. Specifically, Smith et al. [13] reported that 54.5% (EMG AMP, EMG MPF, and MMG AMP) and 18.2% (MMG MPF) of the individual responses ($n = 11$) matched the composite responses. No previous studies, however, have examined the effects of joint angle on the composite responses, inter-individual, and intra-individual variability in the fatigue-induced torque and neuromuscular patterns of responses during sustained, isometric forearm flexion tasks anchored to RPE for women.

Joint angle influences the overlap of actin and myosin cross-bridges and has been shown to affect the force production capabilities and neuromuscular responses of the muscle during isometric tasks [22,23]. For example, it has been reported [24,25,26] that the greatest isometric forearm flexion force production occurs between approximately 90° and 120° of elbow flexion, and is less at the extremes of the range of motion. In addition, Weir et al. [27] examined the slope of the EMG and MMG responses at short (5° dorsiflexion) and long (40° plantarflexion) muscle lengths during sustained, isometric dorsiflexion tasks at 50% MVC for 60 s. It was reported that the changes in EMG AMP and MMG AMP were greater at the long muscle length, but there were no differences between the short and long muscle lengths for the EMG MPF and MMG MPF responses [27]. These findings suggested that during dorsiflexion tasks, fatigue-induced changes in neuromuscular responses may be dependent on the joint angle at which the task is performed due to joint angle-specific motor unit recruitment strategies. Few studies [12,15], however, have examined the effects of joint angle on the torque and neuromuscular responses during sustained, isometric tasks anchored to RPE. Therefore, the purpose of this study was to compare the composite, inter-individual, and intra-individual differences in the fatigue-induced torque, EMG AMP, EMG MPF, MMG AMP, and MMG MPF patterns of responses during sustained, isometric fatiguing tasks anchored to an RPE of 8 at elbow joint angles of 75° and 125°. Based on previous studies [9,11,13,21], it was hypothesized that: 1) The patterns of torque responses would be similar for the composite and individual data at both joint angles; 2) comparisons among the individual subjects would indicate a high degree of inter-individual variability for the neuromuscular patterns of responses; and 3) comparisons between composite and individual responses as well as individual responses between joint angles would indicate a high degree of intra-individual variability for the neuromuscular patterns of responses.

2. Methods

2.1. Subjects

Nine women (age: 21.0 ± 3.0 yrs; height: 169.3 ± 8.1 cm; body mass: 68.4 ± 7.4 kg) volunteered to participate in this study. The subjects were university students and recreationally active [28], which included participating in resistance and/or aerobic exercise at least 3 $d \cdot wk^{-1}$. In addition, the subjects were required to be right hand dominant (based on throwing preference), and all testing was performed using the right arm. The subjects were free of upper body pathologies that would affect performance. Based on previously reported performance fatigability data by Keller et al. [4], an a priori sample size calculation (G*Power version 3.1.9.4, Düsseldorf, Germany) indicated that a power of 0.96 required 9 subjects. The subjects in the present study were part of a large multiple independent and dependent variable investigation, but none of the collected data has been previously published. The study was approved by the University Institutional Review Board for Human Subjects (IRB Approval #: 20201220785FB), and all subjects completed a Health History Questionnaire and signed a written Informed Consent document prior to testing.

Table 1. The time course of procedures

Orientation Session	Testing Visits 1 and 2
1. Informed Consent.	1. Standardized warm-up.
2. Health History Questionnaire.	2. Read the standardized anchoring instructions (OMNI-RES scale).
3. Age, height, and body mass recorded.	3. Pre-test: 2, 3 s MVICs at joint angles of 75° and 125°, in randomized order.
4. Familiarized to testing procedures.	
5. Read the standardized anchoring instructions (OMNI-RES scale).	4. Sustained, isometric forearm flexion task anchored to RPE = 8 (OMNI-RES scale) performed at an elbow joint angle of 75° or 125° until task failure.
6. Standardized warm-up: 4, 3 s submaximal (50-75% of max effort) isometric forearm flexion muscle actions.	
7. 2, 3 s isometric forearm flexion MVICs to set a perceptual anchor of RPE = 10.	5. Post-test: 2, 3 s MVICs at joint angles of 75° and 125°, in randomized order.
8. Brief (~ 1 min) sustained isometric task anchored to RPE = 8.	

2.2. Time Course of Procedures

The subjects visited the laboratory on three occasions (orientation session and two testing visits) separated by 24 – 96 hours. The initial visit was an orientation session, and the next two were testing visits that included the standardized warm-up, pre- and post-test MVIC measurements, and a sustained, isometric forearm flexion task anchored to an RPE of 8 (RPE = 8) at randomly ordered elbow joint angles (JA) of 75° (JA75) and 125° (JA125) (Table 1). During both sustained forearm flexion tasks, EMG and MMG signals were simultaneously recorded from the biceps brachii (BB) muscle of the dominant arm.

2.3. OMNI-RES Scale Standardized Anchoring Instructions

The anchoring instructions used in the present study for the sustained, isometric tasks anchored to RPE = 8 were originally developed by Gearhart et al. [29] as a standardized method to gauge training intensity during lower body tasks. The instructions were modified for use during isometric forearm flexion tasks [13]. To promote the proper use of the OMNI-RES scale, the following standardized anchoring instructions were read to each subject during the familiarization visit and prior to the sustained, isometric tasks anchored to RPE = 8: “You will be asked to set an anchor point for both the lowest and highest values on the perceived exertion scale. To set the lowest anchor, you will be asked to lay quietly without contracting your forearm flexor muscles to familiarize yourself with a RPE of zero. Following this, you will be asked to perform a maximal voluntary isometric contraction to familiarize yourself with an RPE of 10. When instructed to match a perceptual value corresponding to the OMNI-RES scale, perceived exertion should be relative to these defined anchors.”

2.4. Orientation Session

During the orientation session, the subjects’ age, height, and body mass values were recorded. In addition, the subjects were oriented to the testing position on the isokinetic dynamometer (Cybex II, Cybex International Inc., Medway, MA, USA) in accordance with the Cybex II user’s manual on an upper body exercise table (UBXT) with the lateral epicondyle of the humerus of the dominant arm aligned with the lever arm of the dynamometer. The subjects were familiarized with the 0 – 10 OMNI-RES scale [30] and read the standardized OMNI-RES instructions that were used during the testing visits [30,31]. The OMNI-RES (0 – 10) RPE scale has been shown to be valid and reliable for the quantification of perception of exertion during resistance exercise [30]. The subjects then completed the standardized warm-up as well as 2, 3 s isometric forearm flexion MVICs to set a perceptual anchor corresponding to RPE = 10. The subjects then performed a brief (approximately 1 min), sustained, isometric forearm flexion task anchored to RPE = 8 to become familiarized with the testing and anchoring procedures.

2.5. Testing Visits

During the RPE = 8 testing visits, the subjects were positioned in accordance with the Cybex II (Cybex II, Cybex International Inc. Medway, MA) user’s manual. Once positioned, the subjects performed the standardized warm-up, followed by 1 min of rest. The subjects were then read the OMNI-RES instructions relating to the anchoring procedures and performed 2, 3 s forearm flexion pre-test MVICs on a calibrated dynamometer at JA75 and JA125 in a randomized order. Strong verbal encouragement was provided during each MVIC trial. The MVICs also served to remind the subjects of the perceptual anchor corresponding to RPE = 10. The elbow joint angles of 75° and 125° for the MVIC measurements were selected to reflect a range of isometric torque production [25]. Following the pre-test MVIC trials, the sustained, isometric forearm flexion tasks anchored to RPE = 8 (OMNI-RES scale) were performed at JA75 and JA125 (randomly ordered). During the sustained isometric tasks at RPE = 8, the subjects were unaware of torque and elapsed time to avoid pacing strategies [4,32]. The RPE = 8 trials were sustained until task failure, which was defined as torque being reduced to zero. During the RPE = 8 trials, the subjects were free to change torque to maintain the required RPE = 8. In addition, during the sustained isometric tasks, the subjects were reminded to be attentive to sensations such as strain, intensity, discomfort, and fatigue felt during the contraction to maintain appropriate levels of exertion [31,33]. Furthermore, the subjects were continuously advised that there were no incorrect contractions or perceptions and were reminded to relate levels of exertion to the previously set anchors. Throughout the sustained isometric tasks, the subjects were asked for their RPE every 30 s to assure compliance with RPE = 8. Upon task failure, the time to task failure (TTF) was recorded. Immediately after task failure, the post-test MVIC trials were performed at JA75 and JA125 in a manner identical to the pre-test MVIC trials.

2.6. Electromyographic, Mechanomyographic, and Torque Acquisition

During all testing visits, bipolar (30-mm center-to-center) EMG electrodes (pre-gelled Ag/AgCl, AccuSensor; Lynn Medical, Wixom, MI, USA) were attached to the BB of the dominant arm based on the recommendations of the Surface Electromyography for the Non-Invasive Assessment of Muscles [34]. Prior to electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The active electrodes were placed over the BB at one-third of the distance between the medial acromion process and the antecubital fossa. A reference electrode was also placed on the styloid process of the radius of the forearm. Using double-sided adhesive tape, a miniature accelerometer (Entras EGAS FT 10, bandwidth 0-200 Hz, dimensions 1.0 x 1.0 x 0.5 cm, mass 1.0 g, sensitivity 550.4 $mV \cdot g^{-1}$) was placed between the bipolar EMG electrodes to detect the MMG signals for the BB muscles.

The raw EMG and MMG signals were digitized at 2000 samples/second with a 12-bit analog-to-digital converter

(Model MP150; Biopac Systems, Inc.) and stored on a personal computer (Acer Aspire TC-895-UA91 Acer Inc., San Jose, CA, USA) for analyses. The EMG signals were amplified (gain: × 1000) using differential amplifiers (EMG2-R Bionomadix, Biopac Systems, Inc. Goleta, CA, USA; bandwidth: 10-500 Hz). The EMG and MMG signals were digitally bandpass filtered (fourth-order Butterworth) at 10-500 Hz and 5-100 Hz, respectively. Signal processing was performed using custom programs written with LabVIEW programming software (version 20.0f1, National Instruments, Austin, TX, USA). The TTF (0 – 100%) was divided into 5% increments and a 1 s epoch from the center of each 5% increment (i.e., 500 ms before and 500 ms after) was used to calculate the AMP (root mean square) for EMG (μVrms) and MMG ($m \cdot s^{-2}$) signals as well as the MPF (in Hz). The MPF was selected to represent the power density spectrum and was calculated as described by Kwatny et al. [35]. The torque signals were sampled from the digital torque of the Cybex II dynamometer and stored on a personal computer (Acer Aspire TC-895-UA91 Acer Inc., San Jose, CA, USA) for analyses. Previously, Smith et al. [16] indicated that during isometric tasks anchored to a constant RPE there can be precipitous drops in the torque, neuromuscular (EMG AMP, EMG MPF, MMG AMP, and MMG MPF), and neuromuscular efficiency (NME) values from the beginning of the task (initial value) to 5% TTF. In the present study, the initial values were defined as the torque and neuromuscular values from the first 1 s of the sustained, isometric forearm flexion tasks anchored to RPE = 8. To examine the initial precipitous drop in torque as well as changes in neuromuscular parameters and NME, the responses from the initial values to were compared to those at 5% TTF. A 1 s epoch from the center of the 3 s pre-test forearm flexion MVICs with the greatest torque production was used to normalize the torque and neuromuscular values.

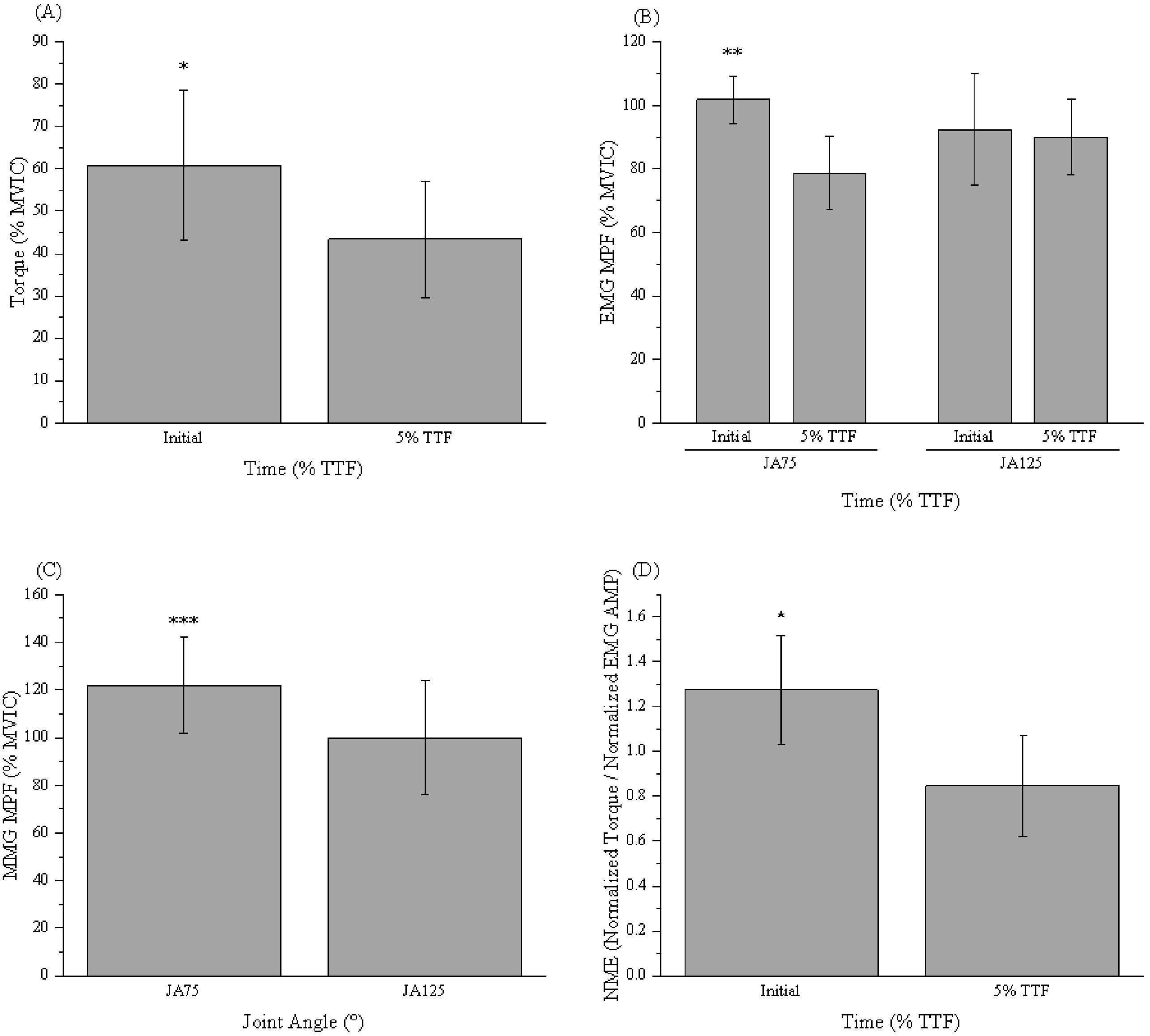

Figure 1. (A) Initial torque values and torque values at 5% time to task failure (TTF) (collapsed across Joint Angle (JA): 75° and 125°). (B) EMG MPF initial values and values at 5% TTF at JA75 and JA125. (C) MMG MPF values at JA75 and JA125 (collapsed across Time: initial value and value at 5% TTF). (D) Neuromuscular Efficiency (NME) initial values and values at 5% TTF (collapsed across Joint Angle). (* (A) and (D) Initial values significantly ($p < 0.05$) greater than 5% TTF values. ** (B) Initial value significantly ($p < 0.001$) greater than 5% TTF value for JA75. *** (C) MMG MPF significantly ($p = 0.049$) greater at JA75 than JA125)

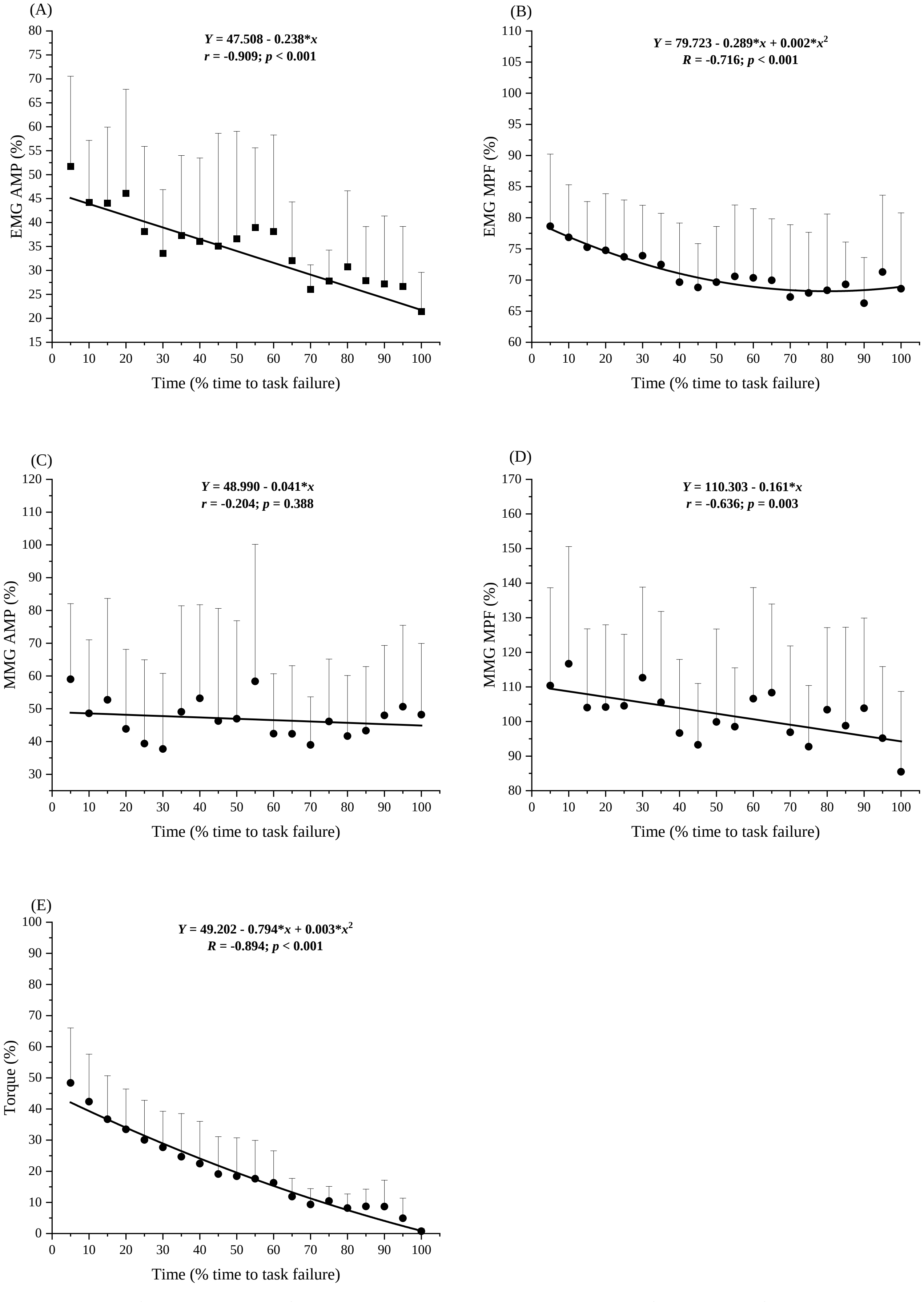

Figure 2. Time course of changes (mean ± SD) for the normalized neuromuscular and torque values (% of pre-test MVIC) for the sustained, isometric forearm flexion fatiguing task anchored to RPE = 8 at an elbow joint angle of 75°. (A) Electromyographic amplitude (EMG AMP), (B) Electromyographic mean power frequency (EMG MPF), (C) Mechanomyographic amplitude (MMG AMP), (D) Mechanomyographic mean power frequency (MMG MPF), (E) Torque

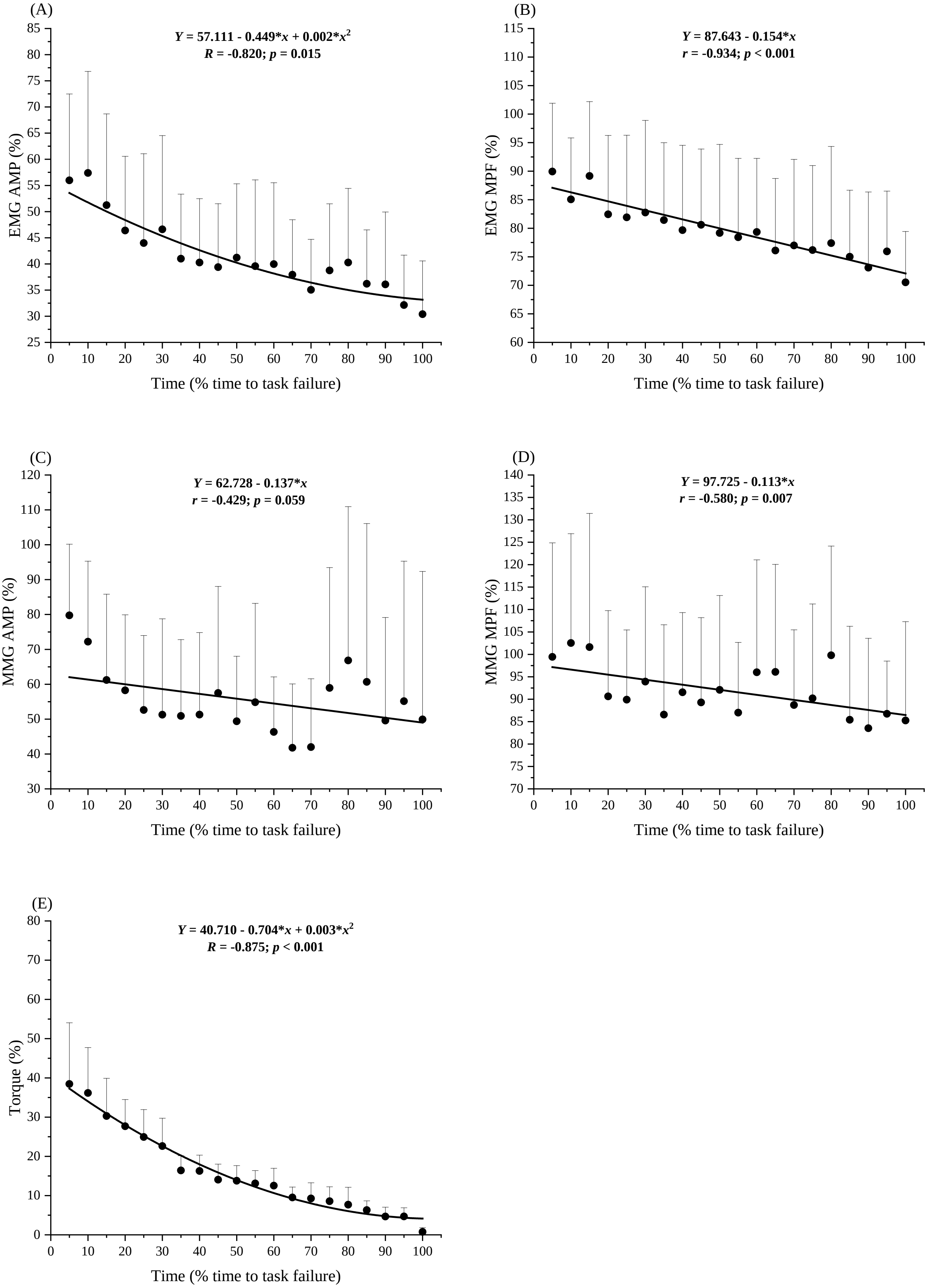

Figure 3. Time course of changes (mean ± SD) for the normalized neuromuscular and torque values (% of pre-test MVIC) for the sustained, isometric forearm flexion fatiguing task anchored to RPE = 8 at an elbow joint angle of 125°. (A) Electromyographic amplitude (EMG AMP), (B) Electromyographic mean power frequency (EMG MPF), (C) Mechanomyographic amplitude (MMG AMP), (D) Mechanomyographic mean power frequency (MMG MPF), (E) Torque

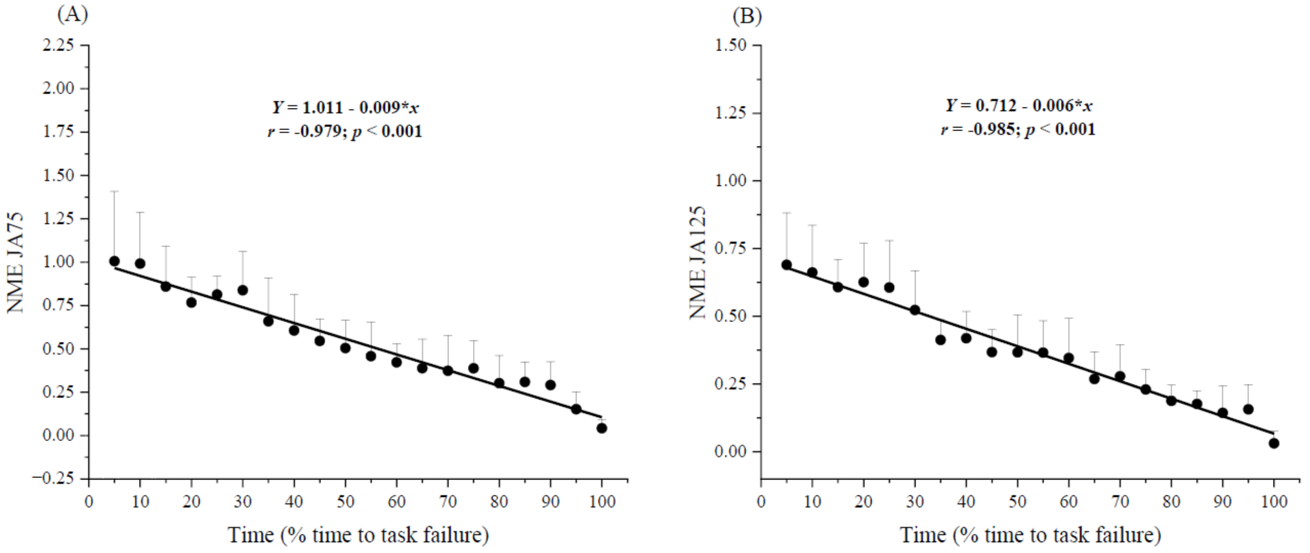

Figure 4. Time course of changes (mean ± SD) for neuromuscular efficiency (NME) during the sustained, isometric forearm flexion fatiguing tasks anchored to RPE = 8. NME was defined as normalized torque (% of pre-test MVIC) divided by normalized EMG AMP at each respective time point. (A) NME at an elbow joint angle of 75° (JA75), (B) NME at an elbow joint angle of 125° (JA125)

3. Statistical Analysis

The test-retest reliability for the MVICs, EMG AMP, EMG MPF, MMG AMP, and MMG MPF at JA75 and JA125 were assessed with a repeated measures ANOVA to evaluate systematic error with a 2,1-model used to determine the intraclass correlation coefficient (ICC) [36]. The pre-test forearm flexion MVIC with the greatest torque production was used to normalize the torque and neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) for each 5% of the TTF, as well as the initial torque and neuromuscular parameters of the first 1 s of the sustained, isometric forearm flexion fatiguing tasks anchored to RPE = 8 at JA75 (Figure 2) and JA125 (Figure 3). Separate polynomial regression analyses (linear and quadratic) were used to define the individual and composite relationships for the normalized neuromuscular and torque values versus normalized time (every 5%) relationships during the sustained, isometric forearm flexion fatiguing tasks anchored to RPE = 8 at JA75 and JA125. In addition, separate polynomial regression analyses (linear and quadratic) were used to define the individual and composite relationships for NME (defined as normalized torque divided by normalized EMG AMP, as described by Jones et al. [37]), versus normalized time (every 5%) relationships during the sustained, isometric forearm flexion fatiguing tasks anchored to RPE = 8 at JA75 and JA125 (Figure 4). The mean differences for the initial values versus the 5% TTF values for torque, neuromuscular parameters, and NME were determined using six, separate 2 (Joint Angle: 75° vs 125°) x 2 (Time: Initial vs 5% TTF) repeated measures ANOVAs. Significant interactions were decomposed with follow-up ANOVAs and post-hoc, Bonferroni corrected, paired t-tests [38,39]. Effect sizes were reported as partial eta squared (η_p^2) and Cohen's *d* for the ANOVAs and pairwise comparisons, respectively. An alpha value of $p \leq 0.05$ was considered statistically significant and all the data were reported as mean ± SD. All statistical analyses were completed in IBM SPSS v. 28 (Armonk, NY, USA).

4. Results

4.1. Reliability

Table 2 includes the test-retest reliability parameters (P-value for systematic error and ICC) for MVIC, EMG AMP, EMG MPF, MMG AMP, and MMG MPF. There were no mean differences ($p > 0.05$) for test versus retest for MVIC or the neuromuscular parameters and the ICC values ranged from 0.171 (EMG MPF at 125°) to 0.882 (MVIC Forearm Flexion at 125°).

4.2. Torque Responses

During the sustained task at JA75, the normalized individual and composite torque responses indicated that there were significant negative linear relationships for torque vs. time (r = -0.959 and -0.976) for 2 of the 9 subjects, negative quadratic relationships (R = -0.631 to -0.948) for 7 of the 9 subjects, and a negative quadratic relationship (R = -0.894) for the composite data (Table 3).

During the sustained task at JA125, the normalized individual and composite torque responses indicated that there were significant negative linear relationships for torque vs. time (r = -0.903 to -0.983) for 4 of the 9 subjects, negative quadratic relationships (R = -0.764 to -0.873) for 5 of the 9 subjects, and a negative quadratic relationship (R = -0.875) for the composite data (Table 4).

The results of the repeated measures ANOVA for torque indicated that there was no significant 2-way interaction ($p = 0.983$, $\eta_p^2 = 0.000$) or main effect for Joint Angle ($p = 0.143$, $\eta_p^2 = 0.247$). There was, however, a significant main effect for Time ($p = 0.012$, $\eta_p^2 = 0.568$). The follow-up pairwise comparison for the main effect for Time (collapsed across Joint Angle) indicated that the initial torque value (60.8 ± 17.7% MVIC) was significantly greater ($p = 0.012$, $d = 1.097$) than the torque value at 5% TTF (43.4 ± 13.8% MVIC) (Figure 1).

Table 2. Reliability data for maximal voluntary isometric contraction (MVIC) torque and neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) during the pre-test forearm flexions at elbow joint angles of 75° and 125°

MVIC (mean ± SD)	**Visit 1**	**Visit 2**	***P***	**ICC**
Forearm Flexion$_{75}$ (Nm)	25.8 ± 6.0	26.7 ± 4.8	0.476	0.831
Forearm Flexion$_{125}$ (Nm)	24.4 ± 6.7	24.9 ± 6.0	0.629	0.882
Neuromuscular Parameters (mean ± SD)				
EMG AMP$_{75}$ (μVrms)	609.9 ± 167.0	596.2 ± 125.7	0.794	0.495
EMG AMP$_{125}$ (μVrms)	684.5 ± 272.9	687.4 ± 209.2	0.960	0.780
EMG MPF$_{75}$ (Hz)	80.0 ± 7.4	78.2 ± 9.2	0.571	0.462
EMG MPF$_{125}$ (Hz)	65.8 ± 8.7	67.0 ± 7.2	0.726	0.171
MMG AMP$_{75}$ (m·s^{-2})	0.35 ± 0.17	0.31 ± 0.10	0.455	0.223
MMG AMP$_{125}$ (m·s^{-2})	0.31 ± 0.11	0.26 ± 0.09	0.164	0.353
MMG MPF$_{75}$ (Hz)	20.0 ± 4.9	18.6 ± 4.4	0.535	0.412
MMG MPF$_{125}$ (Hz)	21.9 ± 5.1	21.5 ± 5.6	0.814	0.646

P = Alpha from the ANOVA (2,1 model) for systematic error; ICC = intraclass correlation coefficient; EMG AMP = electromyographic amplitude; EMG MPF = electromyographic mean power frequency; MMG AMP = mechanomyographic amplitude; MMG MPF = mechanomyographic mean power frequency.

Table 3. Polynomial regression model, Correlation (Corr.), *p* - value for normalized EMG AMP, EMG MPF, MMG AMP, MMG MPF, and Torque vs. Time during the sustained, isometric forearm flexion fatiguing task anchored to RPE = 8 at a joint angle of 75°

Subjects	EMG AMP			EMG MPF			MMG AMP			MMG MPF			Torque		
	Model	Corr.	*p* - value	Model	Corr.	*p* - value	Model	Corr.	*p* - value	Model	Corr.	*p* - value	Model	Corr.	*p* - value
1	Quadratic	-0.562	< 0.001	Linear	-0.793	< 0.001	-	-	NS	-	-	NS	Quadratic	-0.909	0.013
2	Quadratic	-0.764	< 0.001	Quadratic	-0.637	< 0.001	Quadratic	-0.638	0.010	Quadratic	-0.651	0.007	Quadratic	-0.948	0.010
3	-	-	NS	-	-	NS	Linear	0.749	< 0.001	-	-	NS	Quadratic	-0.822	0.001
4	Quadratic	-0.520	0.010	-	-	NS	-	-	NS	-	-	NS	Quadratic	-0.631	< 0.001
5	-	-	NS	Quadratic	-0.503	0.003	Linear	-0.685	< 0.001	-	-	NS	Quadratic	-0.816	< 0.001
6	Linear	-0.908	< 0.001	Linear	-0.696	< 0.001	-	-	NS	Linear	-0.501	0.025	Linear	-0.976	< 0.001
7	Linear	-0.665	< 0.001	Linear	-0.857	< 0.001	-	-	NS	-	-	NS	Linear	-0.959	< 0.001
8	Quadratic	-0.561	0.038	Linear	0.480	0.032	-	-	NS	-	-	NS	Quadratic	-0.782	< 0.001
9	Linear	-0.797	< 0.001	-	-	NS	-	-	NS	Quadratic	-0.622	0.040	Quadratic	-0.812	< 0.001
Composite	Linear	-0.909	< 0.001	Quadratic	-0.716	< 0.001	-	-	NS	Linear	-0.636	0.003	Quadratic	-0.894	< 0.001

Table 4. Polynomial regression model, Correlation (Corr.), p - value for normalized EMG AMP, EMG MPF, MMG AMP, MMG MPF, and Torque vs. Time during the sustained, isometric forearm flexion fatiguing task anchored to RPE = 8 at a joint angle of 125°

Subjects	EMG AMP			EMG MPF			MMG AMP			MMG MPF			Torque		
	Model	Corr.	*p* - value	Model	Corr.	*p* - value	Model	Corr.	*p* - value	Model	Corr.	*p* - value	Model	Corr.	*p* - value
1	Quadratic	-0.562	< 0.001	Linear	-0.793	< 0.001	-	-	NS	-	-	NS	Quadratic	-0.909	0.013
2	Quadratic	-0.764	< 0.001	Quadratic	-0.637	< 0.001	Quadratic	-0.638	0.010	Quadratic	-0.651	0.007	Quadratic	-0.948	0.010
3	-	-	NS	-	-	NS	Linear	0.749	< 0.001	-	-	NS	Quadratic	-0.822	0.001
4	Quadratic	-0.520	0.010	-	-	NS	-	-	NS	-	-	NS	Quadratic	-0.631	< 0.001
5	-	-	NS	Quadratic	-0.503	0.003	Linear	-0.685	< 0.001	-	-	NS	Quadratic	-0.816	< 0.001
6	Linear	-0.908	< 0.001	Linear	-0.696	< 0.001	-	-	NS	Linear	-0.501	0.025	Linear	-0.976	< 0.001
7	Linear	-0.665	< 0.001	Linear	-0.857	< 0.001	-	-	NS	-	-	NS	Linear	-0.959	< 0.001
8	Quadratic	-0.561	0.038	Linear	0.480	0.032	-	-	NS	-	-	NS	Quadratic	-0.782	< 0.001
9	Linear	-0.797	< 0.001	-	-	NS	-	-	NS	Quadratic	-0.622	0.040	Quadratic	-0.812	< 0.001
Composite	Linear	-0.909	< 0.001	Quadratic	-0.716	< 0.001	-	-	NS	Linear	-0.636	0.003	Quadratic	-0.894	< 0.001

4.3. Electromyographic Amplitude Responses

During the sustained task at JA75, the normalized individual and composite EMG AMP responses indicated that there were significant negative linear relationships for EMG AMP vs. time ($r = -0.665$ to -0.908) for 3 of the 9 subjects, negative quadratic relationships ($R = -0.520$ to -0.764) for 4 of the 9 subjects, no significant relationships for 2 of the 9 subjects, and a negative linear relationship ($r = -0.909$) for the composite data (Table 3).

During the sustained task at JA125, the normalized individual and composite EMG AMP responses indicated that there were significant negative linear relationships for EMG AMP vs. time ($r = -0.496$ to -0.822) for 4 of the 9 subjects, negative quadratic relationships ($R = -0.647$ and -0.727) for 2 of the 9 subjects, no significant relationships for 3 of the 9 subjects, and a negative quadratic relationship ($R = -0.820$) for the composite data (Table 4).

The results of the repeated measures ANOVA for EMG AMP indicated no significant 2-way interaction ($p = 0.734$, $\eta_p^2 = 0.015$) or main effects for Joint Angle ($p = 0.643$, $\eta_p^2 = 0.028$) or Time ($p = 0.597$, $\eta_p^2 = 0.036$).

4.4. Electromyographic Mean Power Frequency Responses

During the sustained task at JA75, the normalized individual and composite EMG MPF responses indicated that there were significant negative linear relationships for EMG MPF vs. time (r = -0.696 to -0.857) for 3 of the 9 subjects, a positive linear relationship (r = 0.480) for 1 of the 9 subjects, negative quadratic relationships (R = -0.503 and -0.637) for 2 of the 9 subjects, no significant relationships for 3 of the 9 subjects, and a negative quadratic relationship (R = -0.716) for the composite data (Table 3).

During the sustained task at JA125, the normalized individual and composite EMG MPF responses indicated that there were significant negative linear relationships for EMG MPF vs. time (r = -0.551 to -0.875) for 7 of the 9 subjects, negative quadratic relationships (R = -0.449 and -0.680) for 2 of the 9 subjects, and a negative linear relationship (r = -0.934) for the composite data (Table 4).

The results of the repeated measures ANOVA for EMG MPF indicated there was a significant 2-way interaction for Joint Angle x Time ($p = 0.006$, $\eta_p^2 = 0.633$). Follow-up pairwise comparisons (decomposed by Joint Angle) indicated that at JA75, the initial EMG MPF value (101.8 ± 7.5% MVIC) was significantly greater ($p < 0.001$, $d = 2.369$; Bonferroni corrected alpha = 0.025) than the EMG MPF value at 5% TTF (78.6 ± 11.6% MVIC). At JA125, however, there was no significant difference ($p = 0.380$, $d = 0.165$) between the initial EMG MPF value (92.4 ± 17.7% MVIC) and the EMG MPF value at 5% TTF (89.9 ± 12.0% MVIC) (Figure 1).

4.5. Mechanomyographic Amplitude Responses

During the sustained task at JA75, the normalized individual and composite MMG AMP responses indicated that there was a significant negative linear relationship for MMG AMP vs. time (r = -0.685) for 1 of the 9 subjects, a positive linear relationship (r = 0.749) for 1 of the 9 subjects, a negative quadratic relationship (R = -0.638) for 1 of the 9 subjects, no significant relationships for 6 of the 9 subjects, and no significant relationships for the composite data (Table 3).

During the sustained task at JA125, the normalized individual and composite MMG AMP responses indicated that there were significant negative linear relationships for MMG AMP vs. time (r = -0.525 to -0.784) for 3 of the 9 subjects, a negative quadratic relationship (R = -0.575) for 1 of the 9 subjects, a positive quadratic relationship (R = 0.666) for 1 of the 9 subjects, no significant relationships for 4 of the 9 subjects, and no significant relationships for the composite data (Table 4).

The results of the repeated measures ANOVA for MMG AMP indicated no significant 2-way interaction ($p = 0.818$, $\eta_p^2 = 0.007$) or main effects for Joint Angle ($p = 0.070$, $\eta_p^2 = 0.353$) or Time ($p = 0.420$, $\eta_p^2 = 0.083$).

4.6. Mechanomyographic Mean Power Frequency Responses

During the sustained task at JA75, the normalized individual and composite MMG MPF responses indicated that there was a significant negative linear relationship for MMG MPF vs. time (r = -0.501) for 1 of the 9 subjects, negative quadratic relationships (R = -0.622 and -0.651) for 2 of the 9 subjects, no significant relationships for 6 of the 9 subjects, and a negative linear relationship (r = -0.636) for the composite data (Table 3).

During the sustained task at JA125, the normalized individual and composite MMG MPF responses indicated that there were significant negative linear relationships for MMG MPF vs. time (r = -0.472 and -0.506) for 2 of the 9 subjects, no significant relationships for 7 of the 9 subjects, and a negative linear relationship (r = -0.580) for the composite data (Table 4).

The results of the repeated measures ANOVA for MMG MPF indicated that there was no significant 2-way interaction ($p = 0.104$, $\eta_p^2 = 0.296$) or main effect for Time ($p = 0.173$, $\eta_p^2 = 0.219$). There was, however, a significant main effect for Joint Angle ($p = 0.049$, $\eta_p^2 = 0.403$). The follow-up pairwise comparison for the main effect for Joint Angle (collapsed across Time) indicated that the MMG MPF at JA75 (122.0 ± 20.0% MVIC) was significantly greater ($p = 0.049$, $d = 1.005$) than the MMG MPF at JA125 (99.8 ± 23.9% MVIC) (Figure 1).

4.7. Neuromuscular Efficiency Responses

During the sustained task at JA75, the normalized individual and composite NME responses indicated that there were significant negative linear relationships for NME vs. time (r = -0.717 to -0.941) for 6 of the 9 subjects, negative quadratic relationships (R = -0.808 to -0.916) for 3 of the 9 subjects, and a negative linear relationship (r = -0.979) for the composite data (Table 5).

During the sustained task at JA125, the normalized individual and composite NME responses indicated that there were significant negative linear relationships for NME vs. time (r = -0.791 to -0.962) for 6 of the 9 subjects, negative quadratic relationships (R = -0.828 to -0.911) for 3 of the 9 subjects, and a negative linear relationship (r = -0.985) for the composite data (Table 5).

The results of the repeated measures ANOVA for NME indicated that there was no significant 2-way interaction ($p = 0.723$, $\eta_p^2 = 0.017$) or main effect for Joint Angle ($p = 0.051$, $\eta_p^2 = 0.398$). There was, however, a significant main effect for Time ($p = 0.003$, $\eta_p^2 = 0.699$). The follow-up pairwise comparison for the main effect for Time (collapsed across Joint Angle) indicated that the initial NME value (1.27 ± 0.24) was significantly greater ($p = 0.003$, $d = 1.828$) than the NME value at 5% TTF (0.85 ± 0.23) (Figure 1).

Table 5. Polynomial regression model, Correlation (Corr.), *p* - value for Neuromuscular Efficiency (NME) vs. Time during the sustained, isometric forearm flexion fatiguing tasks anchored to RPE = 8 at joint angles of 75° and 125°

Subjects	NME_{75}			NME_{125}		
	Model	Corr.	*p* - value	Model	Corr.	*p* - value
1	Linear	-0.923	< 0.001	Quadratic	-0.911	0.002
2	Linear	-0.887	< 0.001	Linear	-0.962	< 0.001
3	Linear	-0.842	< 0.001	Linear	-0.935	< 0.001
4	Linear	-0.717	< 0.001	Quadratic	-0.847	0.017
5	Quadratic	-0.870	0.034	Linear	-0.912	< 0.001
6	Quadratic	-0.916	0.005	Linear	-0.791	< 0.001
7	Linear	-0.923	< 0.001	Linear	-0.946	< 0.001
8	Linear	-0.941	< 0.001	Quadratic	-0.828	< 0.001
9	Quadratic	-0.808	0.017	Linear	-0.922	< 0.001
Composite	Linear	-0.979	< 0.001	Linear	-0.985	< 0.001

Table 6. Pre-test maximal voluntary isometric contraction (MVIC) (Nm), initial torque (Nm), normalized initial torque (% of MVIC), torque at 5% time to task failure (TTF) (% of MVIC), and percent decrease (%) in torque from the initial torque value to 5% TTF during the sustained, isometric forearm flexion tasks anchored to RPE = 8 at an elbow joint angle of 75° (JA75) and 125° (JA125)

Joint Angle	Subjects	Pre-test MVIC	Initial Torque	% MVIC	Torque at 5% TTF	% Decrease*
JA75	1	26.8	13.2	49.3	44.8	9.2
	2	23.7	12.4	52.1	55.4	-6.2
	3	23.9	13.1	54.9	29.8	45.7
	4	30.1	27.5	91.4	61.4	32.9
	5	24.0	22.1	91.8	87.4	4.9
	6	27.8	17.1	61.3	41.9	31.7
	7	18.4	7.2	39.1	32.6	16.7
	8	35.5	21.3	59.8	40.7	32.0
	9	30.2	27.9	92.5	41.4	55.3
	Mean ± SD	26.7 ± 4.9	18.0 ± 7.2	65.8 ± 20.6	48.4 ± 17.7	24.7 ± 20.0
JA125	1	33.0	6.3	19.1	28.4	-48.4
	2	23.6	13.6	57.5	51.4	10.6
	3	24.4	14.5	59.4	32.7	44.9
	4	28.0	19.8	70.6	44.2	37.4
	5	22.4	14.0	62.5	48.7	22.1
	6	26.6	8.5	32.1	17.4	45.8
	7	11.3	5.5	48.5	32.0	34.0
	8	27.8	21.6	77.6	67.0	13.6
	9	27.3	20.6	75.3	24.2	67.8
	Mean ± SD	24.9 ± 6.0	13.8 ± 6.1	55.8 ± 19.7	38.4 ± 15.6	25.3 ± 32.8

*Percent decrease calculated as [(Initial % MVIC – 5% TTF) / Initial % MVIC] x 100.

5. Discussion

5.1. Reliability

The test-retest reliability analyses in the present study indicated that there were no significant mean differences for MVIC values at JA75 and JA125 and the ICCs were 0.831 and 0.882, respectively (Table 2). These ICCs reflected excellent reliability [40], but were lower (ICC = 0.982) than previously reported by Hill et al. [41] for isometric forearm flexion MVICs at an elbow joint angle of 45°. The differences in ICCs between the present study and that of Hill et al. [41] may be due to the differences in the elbow joint angles at which the MVICs were performed. In addition, there were no significant mean differences for the test and retest reliability at JA75 and JA125 for the neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) recorded from the BB during the forearm flexion MVICs (Table 2). The ICCs ranged from R = 0.171 – 0.780 and reflected poor to excellent reliability [40], and were lower (ICC = 0.863 – 0.975) than previously reported by Hill et al. [41] for neuromuscular parameters during isometric forearm flexion MVICs at an elbow joint angle of 45°. Koo and Li [42] previously stated that, “A low ICC could not only reflect the low degree of rater or measure agreement but also relate to the lack of variability among the sampled subjects…” (p. 158).

5.2. Underestimation of Torque and Initial Decreases in Torque, Neuromuscular Parameters, and Neuromuscular Efficiency

Theoretically, there is a proportional relationship between RPE (from the OMNI-RES Scale) and % MVIC torque, or force, where the expected torque value that corresponds to RPE = 8 should be equivalent to approximately 80% MVIC [43]. Previous studies, however, have reported that torque or force values based on RPE tend to underestimate the expected % MVIC [31,44]. For example, Smith et al. [15] reported that during isometric forearm flexion tasks anchored to RPE = 7 at elbow joint angles of 75° and 125°, women self-selected an initial intensity of 64.7 ± 12.3% MVIC (JA75) and 56.1 ± 12.3% MVIC (JA125) instead of the expected 70% MVIC. In addition, Keller et al. [10] found that the perceived torque at RPE = 8 during an isometric leg extension coincided with 58.5% MVIC instead of the expected 80% MVIC. Pincivero et al. [44] reported that for both men and women, the average % MVIC was 66.0 ± 12.3% at a perceptual intensity of 8. In the present study, the initial torque values from the first 1 s of the isometric, fatiguing task anchored to RPE = 8 were 65.8 ± 20.6% MVIC (range = 39.1% – 92.5%) at JA75 (Table 6) and 55.8 ± 19.7% MVIC (range = 19.1% – 77.6%) at JA125 (Table 6). These findings were consistent with Keller et al. [10] who reported that at RPE = 8, women self-selected an initial force value that was approximately 26.9% (58.5% MVIC) less than the expected 80% MVIC, as well as Smith et al. [12] who reported similar initial torque values at elbow joint angles of 75° (64.7% MVIC) and 125° (56.1% MVIC) for women at RPE = 7. Tucker [17] suggested that when a task is anchored to RPE, there is an anticipatory component that may be determined by the task modality, previous experiences, and physiological and psychological inputs that are processed in the brain to set an initial intensity that is perceived to match the required RPE. Thus, the results of the present study as well as others [10,15,44] indicated that the anticipatory mechanism described by Tucker [17] tends to underestimate the expected % MVIC for forearm flexion and leg extension at high perceptual intensities in both men and women.

Previous studies [12,14,15] have reported precipitous decreases in torque and neuromuscular parameters from the initial values during sustained, isometric forearm flexion tasks anchored to an RPE of 7. Smith et al. [15] reported that from the initial value to the value at 5% TTF there were rapid decreases in torque, EMG AMP, and MMG MPF at elbow joint angles of 75° and 125° for women. Smith et al. [12], however, reported that for men there were decreases in torque, but not EMG AMP, EMG MPF, MMG AMP, or MMG MPF from the initial value to 5% TTF at elbow joint angles of 75° and 125°. In the present study, the results indicated that there were similar decreases in torque from the initial value to 5% TTF at JA75 (65.8 ± 20.6% to 48.4 ± 17.7% MVIC) and JA125 (55.8 ± 19.7% to 38.4 ± 15.6% MVIC) with a concurrent decrease in EMG MPF (101.8 ± 7.5% to 78.6 ± 11.6% MVIC) at JA75 (Figure 1). There were, however, no differences between the initial and 5% TTF values for EMG AMP, MMG AMP, and MMG MPF for either joint angle. It has previously been hypothesized [12,15,16] that the initial decreases in torque were likely due to decreases in central drive and the de-recruitment of motor units. Specifically, the conscious decision to initially decrease torque to match the prescribed RPE = 8 may have been due to feedback from group III afferent neurons that can be sensitive to mechanical changes within the muscle [45], in addition to corollary discharge from premotor and primary motor areas of the brain [17,46,47] to the supplementary motor area [48] of the brain. In addition, the results of the present study indicated there was a decrease in NME from the initial value (1.27 ± 0.24) to 5% TTF (0.85 ± 0.23) with no differences between the two joint angles (75° and 125°) (Figure 1). Smith et al. [16] reported similar decreases in NME from the initial value (1.42 ± 0.26) to 5% TTF (0.94 ± 0.19). The authors [16] hypothesized that this decrease in NME was likely due to peripheral fatigue that occurred during the first few seconds (12.8 ± 3.7s) of the fatiguing task. Peripheral fatigue occurs distal to the myoneural junction and involves processes that affect excitation-contraction coupling failure. This includes metabolic perturbations within active muscle fibers such as increases in inorganic phosphate and ammonia, in addition to decreased intracellular pH, calcium release and reuptake kinetics, actin-myosin binding, and troponin-calcium binding [49,50], which can lead to excitation-contraction coupling failure and decreases in NME. Therefore, it is suggested that the precipitous decrease in torque from the initial value to 5% TTF was due to afferent feedback from group III neurons that caused subjects to perceive the torque as too high to maintain RPE = 8 and peripheral fatigue that diminished torque production capabilities (through excitation-contraction coupling failure) as reflected by the decreased NME.

5.3. Composite, Inter-individual, and Intra-individual Responses for Torque

During fatiguing isometric forearm flexion and leg extension tasks anchored to RPE, it is necessary to consciously reduce torque or force to maintain the prescribed RPE [9,11,13]. This was demonstrated in the present study by the negative, quadratic composite torque versus time relationships at both JA75 (Figure 2) and JA125 (Figure 3). These findings were consistent with those of Keller et al. [11] who reported a negative, quadratic composite force versus time relationship in women during isometric leg extension tasks anchored to RPE = 5. Smith et al. [13], however, found a negative, linear composite torque versus time relationship in women during isometric forearm flexion tasks at an elbow joint angle of 100°, anchored to RPE = 7. Thus, there are differences in the composite patterns (linear or quadratic) for the decreases in torque versus time during isometric tasks anchored to RPE that may be associated with the muscle group involved, as well as the joint angle at which the fatiguing task is performed. Furthermore, the individual subject responses in the present study indicated that 7 of the 9 subjects (77.8%) at JA75 and 5 of the 9 subjects (55.6%) at JA125 exhibited quadratic decreases for their torque versus time relationships which matched the negative, quadratic models of the composite data (Table 4 and Table 5). The percentage of subjects whose individual patterns of responses matched the composite patterns (55.6 – 77.8%) in the present study were substantially greater than that reported (9.1%) by Smith et al. [13]. Keller et al. [11], however, reported that during isometric leg extension tasks anchored to RPE = 5, all subjects (n = 10) exhibited individual force versus time relationships that matched the negative, quadratic relationship of the composite data. In addition, 7 of the 9 subjects in the present study had the same torque versus time relationships (linear or quadratic) at JA75 and JA125, while 2 of the 9 subjects (22.2%) exhibited different patterns of responses at each joint angle (Table 4 and Table 5). Thus, the current findings indicated that in most cases, but not all, the joint angle at which the fatiguing task was performed did not affect the patterns (linear or quadratic) or direction (negative) of the torque versus time relationship. Furthermore, the results of the present study indicated variability in the individual pattern of responses for the torque versus time relationships when compared to the composite data at both JA75 and JA125, however, both joint angles exhibited negative, quadratic relationships for the composite data. Therefore, composite responses are not applicable to all subjects, and responses for torque (or force) versus time relationships should also be reported on a subject-by-subject basis to give further insight into fatigue-induced torque responses during isometric forearm flexion tasks anchored to RPE, at various joint angles.

5.4. Composite Responses for the Neuromuscular Parameters and Neuromuscular Efficiency

During submaximal fatiguing isometric tasks anchored to force or torque, neuromuscular responses are typically characterized by increases in EMG AMP (muscle activation) and MMG AMP (motor unit recruitment) with decreases in EMG MPF (muscle fiber action potential conduction velocity) and MMG MPF (global firing rate of the activated, unfused motor units), as well as decreases in NME (peripheral fatigue and excitation-contraction coupling failure) [18,51,52]. When anchored to RPE, however, the responses of these neuromuscular parameters have been less consistent and it has been hypothesized that the neuromuscular responses are "…reflective of the fatigue-related physiological mechanisms that underly the perception of effort and not submaximal force production or MVIC" [11; p. 2505]. Furthermore, it has been reported that when anchored to force, NME decreases due to an increase in EMG AMP to maintain the required force [52]. When anchored to RPE = 8, however, Smith et al. [15] reported decreases in NME from 5% to 90% TTF during a sustained, isometric forearm flexion task at an elbow joint angle of 100° that were due to disproportionate decreases in torque versus EMG AMP. Previous studies that have examined neuromuscular responses during sustained, isometric leg extension tasks anchored to RPE = 5 [9,11] and forearm flexion tasks anchored to RPE = 7 [13] have reported no changes in EMG MPF or MMG MPF, increases or no change in MMG AMP, and decreases or no change in EMG AMP for the composite responses in men and women. Specifically, in men, Keller et al. [9] reported a quadratic decrease in EMG AMP, but no changes in EMG MPF, MMG AMP, and MMG MPF. In women, Keller et al. [11] reported a quadratic increase in MMG AMP, but no changes in EMG AMP, EMG MPF, and MMG MPF. In addition, Smith et al. [13] reported a quadratic decrease in EMG AMP and a quadratic increase in MMG AMP, but no changes in EMG MPF and MMG MPF for women at an elbow joint angle of 100°. In the present study, the results for the composite responses indicated linear or quadratic decreases in EMG AMP, EMG MPF, and MMG MPF, with no changes in MMG AMP during the sustained, isometric forearm flexion tasks anchored to RPE = 8 at JA75 (Figure 2) and JA125 (Figure 3). For both joint angles, the decreases in EMG AMP and EMG MPF were consistent with the conscious decisions by the subjects to reduce torque by derecruiting motor units throughout the tasks to maintain RPE = 8. In theory, however, derecruitment of motor units should result in decreases in MMG AMP across the fatiguing task. Like the current findings, however, Keller et al. [9] reported no change in MMG AMP with decreases in EMG AMP for men during isometric leg extensions anchored to RPE = 5. It was suggested [9] that the lack of fatigue-induced changes in MMG AMP were due to the competing influences associated with increases in muscle compliance, which results from decreases in force output and should increase MMG AMP, versus the derecruitment of motor units, which should decrease MMG AMP. Furthermore, theoretically, based on the Onion Skin Scheme [53], the conscious decision to derecruit motor units and reduce torque should have led to an increase in MMG MPF and the global firing rate of the unfused, activated motor units. This was not the case in the present study, however, perhaps suggesting that anchoring to RPE has a different effect on fatigue-induced changes in motor unit firing rate than when the task is anchored to torque (or force). In addition, Taylor et al. [54] stated that for isometric contractions anchored to torque or force, fatigue-induced decreases in motor unit firing rates "…are due to one or a combination of a decline in neural drive, local intrinsic adaptations of the motoneuron [55], or peripheral inhibitory feedback mechanisms" (p. 2297). Thus, the fatigue-induced neuromuscular responses in the present study were consistent with the expectations associated with a combination of peripheral and central mechanisms of fatigue. It has been suggested [50,56] that decreases in NME are driven by the fatigue-induced increases in intracellular hydrogen ions and inorganic phosphate associated with peripheral fatigue and lead to excitation-contraction coupling failure. Central fatigue, on the other hand, is primarily associated with the interstitial accumulation of H^+ which stimulates group III/IV afferent neuron feedback and results in a reduction in central motor drive [57]. Furthermore, Tucker [17] suggested that the exercise-induced metabolic perturbations within the primary and synergistic muscles involved in the task increases group III/IV afferent feedback, likely to the supplementary motor area of the brain [48], which affects the subject's perception of exertion. Thus, the increased afferent feedback and altered perception of exertion result in continuous torque adjustments to match the prescribed RPE = 8 [15,16]. In addition, the composite responses for NME indicated linear decreases at JA75 and JA125 (Figure 4). These decreases in NME throughout the fatiguing tasks suggested an increase in peripheral fatigue that resulted in excitation-contraction coupling failure and decreased torque production [16]. Therefore, the neuromuscular responses for the composite data likely reflected the subjects' conscious decisions to decrease torque, possibly due to the development of peripheral fatigue and decreases in neural drive that were mediated by mechanisms related to the perceived exertion needed to maintain the prescribed RPE = 8. The results of the present study, in conjunction with previous studies [9,11,13], indicated that when anchoring to RPE there is variability in both the direction (negative, positive, or no change) and pattern (linear or quadratic) of the neuromuscular responses that may be dependent on the joint angle of the task, level of intensity, type of muscle action, and sex of the subjects. Therefore, future studies should continue to examine the neuromuscular responses during sustained, isometric fatiguing tasks anchored to high and low perceptual intensities, as well as various joint angles, for both leg extension and forearm flexion tasks in men and women. In addition, future research should use the interpolated twitch technique and resting, potentiated twitch amplitude to determine the contributions of peripheral and central mechanisms to joint angle-specific neuromuscular and torque responses during tasks anchored to various RPE values.

5.5. Inter- and Intra-individual Responses for the Neuromuscular Parameters and Neuromuscular Efficiency

Previous studies [9,11,13,21,58] have reported fatigue-induced neuromuscular responses for individual subjects and composite data (averaged across all subjects) during bilateral, isokinetic and isometric leg extensions, as well as, unilateral, isometric forearm flexion tasks. Anders et al. [21] recommended that neuromuscular responses be presented on a subject-by-subject basis in addition to composite data, due to differences in the neuromuscular responses between subjects that "…may be indicative of interindividual variations in fatigue-related changes in motor unit activation strategies" (p. 11). During sustained, isometric fatiguing tasks anchored to RPE = 5 [9,11] and RPE = 7 [13], substantial inter-individual variability has been observed for neuromuscular responses for both leg extension and forearm flexion in men and women. Specifically, Smith et al. [13] reported that during an isometric forearm flexion task anchored to RPE = 7 at an elbow joint angle of 100° in women, 36.4%, 54.5%, 54.5%, and 18.2% of the individual responses matched the composite data for EMG AMP, EMG MPF, MMG AMP, and MMG MPF, respectively. During an isometric leg extension task anchored to RPE = 5 in women, Keller et al. [11] reported that 45.5%, 80.0%, 50.0%, and 90.0% of the responses matched the composite data for EMG AMP, EMG MPF, MMG AMP, and MMG MPF, respectively. In addition, in men, Keller et al. [9] reported that 70.0%, 70.0%, 70.0%, and 100.0% of the individual responses matched the composite data for EMG AMP, EMG MPF, MMG AMP, and MMG MPF, respectively, during an isometric leg extension task anchored to RPE = 5. The results of the present study for forearm flexion tasks anchored to RPE = 8 indicated that for EMG AMP, 7 of the 9 subjects at JA75 (77.8%) and 6 of the 9 subjects at JA125 (66.6%) exhibited the same direction (decrease), but not pattern (linear or quadratic) of responses as the composite data, while the remaining subjects at each joint angle exhibited no change in EMG AMP across the fatiguing task (Table 4 and Table 5). These findings suggested that for 2 subjects at JA75 and 3 subjects at JA125, there were similar levels of muscle activation (EMG AMP) throughout the fatiguing tasks that were not consistent with the decreases in torque and reflected decreases in NME. For EMG MPF at JA125, all subjects (n = 9) exhibited the same directional (decrease) responses as the composite data, but not the same pattern (linear or quadratic) of responses (Table 5). At JA75, however, only 5 of the 9 subjects had EMG MPF responses that matched the direction (negative) of the composite data, while 3 subjects exhibited no change in EMG MPF and one subject demonstrated a linear increase in EMG MPF (Table 4). For the individual MMG AMP responses at JA75, 6 of the 9 subjects matched the composite data response (no change), 2 subjects exhibited a decrease (linear or quadratic) in MMG AMP, and one subject exhibited a linear increase in MMG AMP (Table 4). At JA125, 4 of the 9 subjects exhibited MMG AMP responses (no change) that matched the composite response, while 4 subjects exhibited linear or quadratic decreases and one subject exhibited a quadratic increase in MMG AMP (Table 5). These decreases in MMG AMP tracked the decrease in torque and may have been due to the derecruitment of motor units as torque was consciously decreased to maintain the required RPE, while the increase in MMG AMP may have been due to an increase in muscle compliance that allowed for greater muscle fiber oscillations [11,51]. For MMG MPF at JA75, only 3 of the 9 subjects exhibited the same directional (decrease) responses as the composite data, while the remaining 6 subjects exhibited no change in MMG MPF (Table 4). Similarly, at JA125, only 2 subjects exhibited a MMG MPF response (linear decrease) that matched the composite data, while the remaining 7 subjects exhibited no change in MMG MPF (Table 5). For NME, all subjects had the same directional (decrease) responses as the composite data at both joint angles, while 33.3% of the subjects had a pattern of response (quadratic) that differed from the composite data at both joint angles (Table 6). Furthermore, when comparing the individual responses at each joint angle, the current findings indicated that 55.6% (EMG AMP), 44.4% (EMG MPF), 66.7% (MMG AMP), 55.6% (MMG MPF), and 66.7% (NME) of the individual responses varied between JA75 and JA125. Thus, the joint angle at which the fatiguing task was performed affected the neuromuscular responses and suggested that there were a variety of motor unit activation strategies employed by the individual subjects to maintain the prescribed RPE.

6. Limitations

The findings of the present study are limited to women during a forearm flexion task anchored to a high perceptual intensity (RPE = 8) at elbow joint angles of 75° and 125°, as well as neuromuscular responses from the BB only. It has previously been suggested [59] that men and women can exhibit different responses to fatiguing tasks and, therefore, the current study should be replicated in men. In addition, future studies should examine the neuromuscular responses from all three forearm flexor muscles.

7. Conclusions

In summary, the findings of the present study indicated that for women during a sustained, isometric forearm flexion fatiguing task anchored to RPE = 8 at elbow joint angles of 75° and 125°, the composite responses for torque, EMG AMP, EMG MPF, MMG MPF, and NME decreased, while MMG AMP remained unchanged. When comparing the torque responses during the fatiguing tasks at JA75 and JA125, there was no effect on the direction of responses for both the individual and composite data. The joint angle of the fatiguing task, however, affected the pattern of the torque responses for the individual subjects, but not the composite data. In addition, the individual responses, in conjunction with composite responses, further indicated that the variability in neuromuscular responses may be influenced by the muscle action of the task, the intensity of the task, and the joint angle at which the task is performed. Thus, due to the variability in the direction and pattern of responses within and between subjects during fatiguing, isometric forearm flexion tasks anchored to RPE, it is recommended that future studies continue to report individual torque and neuromuscular responses in addition to composite responses as motor unit activation strategies used to maintain the prescribed RPE are likely to differ from subject to subject.

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Author Contributions

JEA was primarily responsible for data collection, analyses, manuscript writing, and accepts responsibility for the integrity of the data analysis. JPVA, TJN, DGO, and RWS assisted with data collection and data analyses. TJH, RWS, RJS, and GOJ conceived and designed the study. RJS and GOJ provided administrative oversight of the study. All authors contributed to the final drafting and approved the final submission of this manuscript. There was no external funding for this project.

Conflict of Interest

Authors declare no conflict of interest.

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