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The Effects of Joint Angle and Anchoring Scheme on Performance Fatigability and Neuromuscular Responses Following Isometric Forearm Flexion Tasks to Failure

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Abstract

Purpose: The purpose of this study was to examine the effects of joint angle on MVIC and neuromuscular responses at task failure following sustained, isometric forearm flexion tasks anchored to a rating of perceived exertion (RPE) of 8 (RPE = 8) and anchored to the initial torque that corresponded to RPE = 8 (TRQ). Methods: Ten women (age: 21.0 ± 2.8 yrs; height: 168.5 ± 7.2 cm; body mass: 68.0 ± 7.2 kg) performed 2, 3 s MVICs at joint angles (JA) of 75°, 100°, and 125° (randomized order) before and after sustained, isometric forearm flexion tasks to failure at fatiguing joint angles (FJA) of 75° and 125° (dominant arm), anchored to RPE = 8 and TRQ, while electromyographic (EMG) signals were recorded from the biceps brachii (BB). Results: The pre-test MVIC values at JA100 were significantly greater than both JA75 (p = 0.001) and JA125 (p = 0.002). There was no significant (p = 0.369) mean difference in time to task failure (TTF) for FJA75 versus FJA125 when anchored to TRQ, but when anchored to RPE = 8, FJA75 was significantly greater (p = 0.009) than FJA125. For performance fatigability (percent decline in MVIC), JA125 was significantly greater (p < 0.001) than JA75, but not JA100 (p = 0.038). During the fatiguing tasks at FJA75, EMG amplitude (AMP) decreased for JA100 and JA125, and JA100 had a significantly greater (p = 0.004) percent change than JA75. For EMG mean power frequency (MPF), there were decreases for both anchor schemes, but TRQ had a significantly greater (p = 0.003) percent change than RPE = 8. Conclusion: Following the fatiguing tasks at FJA75 (RPE = 8 and TRQ), the decreases in EMG AMP and MVIC at MVIC JA100 and MVIC JA125 suggested that both central and peripheral fatigue contributed to performance fatigability, but for MVIC JA75, the MVIC decrease and increase in EMG AMP were due to peripheral fatigue.

Keywords

Ratings of Perceived Exertion, Forearm Flexion, Fatigue, Electromyography, Joint Angle, Women

Cover Page Footnote

Acknowledgments: 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.

Introduction

Based on the model of Kluger et al. (2013) and the taxonomy of Enoka and Duchateau (2016), fatigue is derived from two interdependent domains: 1) perceived fatigability, which assesses the changes in sensations associated with the performance of a fatiguing task; and 2) performance fatigability, which examines fatigue-induced changes in objective measures of performance. Perceived fatigability can be influenced by modulating factors associated with homeostasis including blood glucose, core temperature, hydration, neurotransmitters, metabolites, oxygenation, and wakefulness, as well as the individual's psychological state such as arousal, executive function, expectations, mood, motivation, pain, and performance feedback (Enoka & Duchateau, 2016). Performance fatigability, however, is modulated by factors associated with contractile function including calcium kinetics, force capacity, blood flow, and metabolism, as well as muscle activation parameters such as voluntary activation, activation patterns, motor neurons, afferent feedback, and neuromuscular propagation (Enoka & Duchateau, 2016). In addition, neuromuscular fatigue (Hureau et al., 2014) is an aspect of fatigue that is typically characterized by a decline in maximal force production during or after a muscular performance-based task and is often assessed from changes in the maximal voluntary isometric contraction (MVIC) (Enoka & Duchateau, 2008).

The separate domains of perceived fatigability and performance fatigability can influence each other (Kluger et al., 2013). For example, Enoka and Duchateau (2016) stated that to understand the task-dependent causes of fatigue, it is necessary to consider the interactions of perceived fatigability and performance fatigability "…as most voluntary actions performed by humans involve significant interactions between the two domains" (Enoka & Duchateau, 2016, p. 2230). St Clair Gibson et al. (2018) also hypothesized that competition between psychological (perceived) and physiological (performance) homeostatic factors influence the process of fatigue.

Previous studies (Keller et al., 2020, 2021; Place et al., 2005) have assessed time-dependent changes in the time (amplitude; AMP) and frequency (mean power frequency; MPF) domain parameters of the electromyographic (EMG) signals as well as ratings of perceived exertion (RPE) during sustained, isometric tasks anchored to force to investigate the interactions of perceived fatigability and performance fatigability. Fatigue-induced neuromuscular and perceptual responses provide insight into the mechanisms and motor unit activation strategies that are employed to maintain the parameters used to anchor the exercise intensity, such as force or RPE (Keller et al., 2020; Keller et al., 2022, 2018; Smith et al., 2016; Smith et al., 2022a; Smith et al., 2022b). Typically, during sustained, submaximal isometric tasks anchored to force, RPE and EMG AMP increase while EMG MPF decreases at rates that are dependent on the intensity of the task (Farina et al., 2014; Smith et al., 2016). During sustained, submaximal isometric tasks anchored to RPE, however, there are usually no changes in EMG MPF, but force and EMG AMP decrease due to the conscious reductions in force to maintain the RPE (Keller et al., 2019, 2018). Thus, fatigue-induced changes in neuromuscular responses and motor unit activation strategies when anchored to force can differ from those when anchored to RPE.

Ratings of perceived exertion (RPE) are used during exercise to quantify the sensations of how hard, heavy, and/or strenuous a task is (Marcora & Staiano, 2010), and are influenced by the discomfort, strain, or fatigue experienced by the primary and synergistic muscles, cardiovascular system, respiratory system, and the central nervous system during a task (Robertson & Noble, 1997). Recent studies (Arnett et al., 2022; Keller et al., 2019, 2020, 2022; Keller et al., 2018) have utilized the RPE Clamp Model of Tucker (2009) to examine the interactions between perceived fatigability and performance fatigability. The RPE Clamp Model (Tucker, 2009) uses RPE values to anchor exercise intensity as opposed to performance-related anchors like force or power output (Cochrane-Snyman et al., 2016). When anchored to RPE, intensity can be consciously decreased to maintain a constant perceived exertion, and the force and neuromuscular responses reflect the changes needed to maintain the RPE as well as how performance-related modulating factors respond to perceived fatigability. Previous studies (Arnett et al., 2022; Cochrane-Snyman et al., 2019; Keller et al., 2019, 2020, 2022; Smith et al., 2022a; Smith et al., 2022b) have utilized RPE to anchor intensity during isometric and dynamic tasks while examining the physiological effects of fatigue. For example, Keller et al. (2020) and Arnett et al. (2022) have recently examined the effects of anchoring to an RPE of 8 (RPE = 8) or the initial torque that corresponded to RPE = 8 (TRQ) on performance fatigability and neuromuscular responses following sustained isometric leg extension and forearm flexion tasks in men and found no performance fatigability differences between anchors (Keller et al., 2020), while Arnett et al. (2022) found that performance fatigability was not joint angle specific.

The overlap of actin and myosin cross-bridges is influenced by joint angle (JA) and muscle length which can affect MVIC (Huijing, 1992; Petrofsky, 1980), time to task failure (TTF) (Petrofsky, 1980), and the neuromuscular responses to a fatiguing task (Weir et al., 2000). Petrofsky and Phillips (1980) reported that the TTF for sustained, isometric forearm flexion tasks was the greatest at an elbow joint angle of 120° compared to 30, 60, 90, and 150°, and suggested this was likely due to "…the number of cross bridges which form between actin and myosin at the onset of a contraction relative to the total number which can form during an MVC" (p. 130). For isometric leg extension tasks, however, it was reported that TTF was greatest at 30 and 35° leg flexion compared to 60, 75, and 90° leg flexion (Pethick et al., 2021; Place et al., 2005). Thus, joint angle, and subsequently, muscle length can affect performance-related outcomes during a fatiguing task. It is, however, unclear whether these responses are similar when anchored to a constant perceptual intensity. Therefore, this study utilized the RPE Clamp Model of Tucker (2009) to examine the effects of joint angle on MVIC and neuromuscular responses at task failure following sustained, isometric forearm flexion tasks anchored to RPE = 8 and anchored to TRQ. Based on the results of previous studies (Downer, 1953; Knapik et al., 1983; Kulig et al., 1984; Sato & Sakai, 1968; Singh & Karpovich, 1968; Tsunoda et al., 1993), it was hypothesized that there would be joint angle-specific differences in MVIC values, as well as differences between joint angles and anchoring schemes for performance fatigability (percent decline in MVIC) and the neuromuscular responses.

Methods

Subjects

Ten women (age: 21.0 ± 2.8 yrs; height: 168.5 ± 7.2 cm; body mass: 68.0 ± 7.2 kg) volunteered to participate in this study. The subjects were university students and recreationally active (McKay et al., 2022), 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 of Keller et al. (2020), 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.

Time Course of Procedures

Table 1 includes the time course of the procedures used in the current study. The subjects visited the laboratory on five occasions (orientation session and four testing visits) separated by 24 – 96 hours. The initial visit was an orientation session, and the first two testing visits (RPE = 8 testing visits) included the standardized warm-up, pre-test and post-test MVIC measurements, and a sustained, isometric forearm flexion task anchored to RPE = 8 to task failure at a fatiguing joint angle (FJA) of 75° and 125°. The third and fourth testing visits (TRQ testing visits) included the standardized warm-up, pre-test and post-test MVIC measurements, and a sustained, isometric forearm flexion task anchored to the torque that corresponded to the subjects' initial torque values at RPE = 8 to task failure at FJA75 and FJA125. The RPE = 8 testing visits preceded the TRQ testing visits to establish the initial torque value at an RPE of 8, which was used to anchor the sustained, isometric tasks anchored to TRQ. Furthermore, during all sustained forearm flexion tasks, EMG signals were recorded from the biceps brachii (BB) muscle of the dominant arm based on throwing preference.

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. (2001) as a standardized method to gauge training intensity during lower body tasks. The instructions were modified for use during isometric forearm flexion tasks (Smith et al., 2021a). 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 a 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."

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 (Robertson et al., 2003) and read the standardized OMNI-RES instructions that were used during the testing visits (Keller et al., 2018; Robertson et al., 2003). 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 (Robertson et al., 2003). The subjects then completed the standardized warm-up (Table 1) 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 task anchored to RPE = 8 to become familiarized with the testing and anchoring procedures.

Table 1. The time course of procedures.

Orientation Session	Testing Visits 1 and 2	Testing Visits 3 and 4
1. Informed Consent. 2. Health History Questionnaire. 3. Age, height, and body mass recorded. 4. Familiarized to testing procedures. 5. Read the standardized anchoring instructions (OMNI-RES scale). 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. 8. Brief (~ 1 min) sustained isometric task anchored to RPE = 8.	1. Standardized warm-up. 2. Read the standardized anchoring instructions (OMNI-RES scale). 3. Pre-test: 2, 3 s MVICs at joint angles of 75°, 100°, and 125°, in randomized order. 4. Sustained, isometric forearm flexion task anchored to RPE = 8 (OMNI-RES scale) performed at fatiguing joint angles of 75° or 125° until task failure, in randomized order. 5. Post-test: 2, 3 s MVICs at joint angles of 75°, 100°, and 125°, in randomized order.	1. Standardized warm-up. 2. Pre-test: 2, 3 s MVICs at joint angles of 75°, 100°, and 125°, in randomized order. 3. Sustained, isometric forearm flexion task anchored to the initial torque value that corresponded to RPE = 8 at fatiguing joint angles of 75° or 125° until task failure. 4. Post-test: 2, 3 s MVICs at joint angles of 75°, 100°, and 125°, in randomized order.

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 (Table 1), 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, JA100, 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 JAs of 75°, 100°, and 125° for the MVIC measurements were selected to reflect a range of isometric torque production (Kulig et al., 1984). Following the pre-test MVIC trials, the sustained, isometric forearm flexion task anchored to RPE = 8 (OMNI-RES scale) was performed at either FJA75 or FJA125. During the sustained isometric tasks at RPE = 8, the subjects were unaware of torque and elapsed time to avoid pacing strategies (Albertus et al., 2005; Keller et al., 2020). The RPE = 8 trial was sustained until task failure, which was defined as a torque that would require RPE > 8, or the torque was 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 task, 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 (Keller et al., 2018; Robertson & Noble, 1997). 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 task, 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 in a manner identical to the pre-test MVIC trials.

For the TRQ testing visits, the setup and protocol were identical to the RPE = 8 visits. For the fatiguing task at either FJA75 or FJA125, however, the subjects were required to maintain the torque value that corresponded to their initial torque from the RPE = 8 testing visit for as long as possible. The initial torque values from the RPE tasks used to anchor the TRQ tasks were the average values from the first one second of their RPE = 8 tasks at each joint angle. In addition, the subjects were asked about their RPE every 10 s. The criterion for task failure during the TRQ tasks was the inability to maintain the prescribed torque despite strong verbal encouragement. Upon task failure, the TTF was recorded. Immediately after task failure, the post-test MVIC trials were performed in a manner identical to the pre-test MVIC trials.

Electromyographic 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 (Hermens et al., 2000). 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.

The raw EMG were digitized at 2000 samples per 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: $\times 1000$) using differential amplifiers (EMG2-R Bionomadix, Biopac Systems, Inc. Goleta, CA, USA; bandwidth—10-500 Hz). The EMG signals were digitally bandpass filtered (fourth-order Butterworth) at 10-500 Hz. Signal processing was performed using custom programs written with LabVIEW programming software (version 20.0f1, National Instruments, Austin, TX, USA). A 1 second epoch from the center of the highest 3 s forearm flexion MVIC was used to calculate the amplitude (AMP in µVrms) and mean power frequency (MPF in Hz) for the EMG signals. The MPF was selected to represent the power density spectrum and was calculated as described by Kwatny et al. (1970). 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) with the highest torque value used for analyses.

Statistical Analysis

The test-retest reliability for the MVICs, EMG AMP, and EMG MPF at MVIC JA75, MVIC JA100, and MVIC 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) (Weir, 2005). The mean differences for performance fatigability (percent decline in MVIC = [(pre-test MVIC – post-test MVIC) / pre-test MVIC] x 100) and the percent changes in EMG AMP (percent change = [(pre-test EMG AMP – post-test EMG AMP) / pre-test EMG AMP] x 100) and EMG MPF (percent change = [(pre-test EMG MPF – post-test EMG MPF) / pre-test EMG MPF] x 100) were determined using three, separate 2 (Anchoring Scheme: RPE = 8 and TRQ) x 2 (Fatiguing Joint Angle: 75° and 125°) x 3 (MVIC Joint Angle: 75°, 100°, and 125°) repeated measures ANOVAs. The mean differences for TTF were determined using a 2 (Anchoring Scheme: RPE = 8 and TRQ) x 2 (Fatiguing Joint Angle: 75° and 125°) repeated measures ANOVA. The mean differences for pre-test MVIC values were determined using a 1 x 3 (MVIC Joint Angle: 75°, 100°, and 125°) repeated measures ANOVA. An alpha value of $p \leq 0.05$ was used for all ANOVAs. Significant interactions were decomposed with follow-up ANOVAs and post-hoc, Bonferroni corrected, paired t-tests (Weir, 2005; Wickens & Keppel, 2004). Effect sizes were reported as partial eta squared (η_p^2) and Cohen's *d* for the ANOVAs and pairwise comparisons, respectively. All statistical analyses were completed in IBM SPSS v. 28 (Armonk, NY, USA).

Results

Descriptive values for performance fatigability for MVIC, EMG AMP, and EMG MPF by Anchoring Scheme, Fatiguing Joint Angle, and MVIC Joint Angle for each subject are presented in Tables 2 – 7.

Table 2. Performance fatigability (% decline) for Torque anchored to RPE = 8.

	Fatiguing Joint Angle (75°)			Fatiguing Joint Angle (125°)		
Subjects	75°	100°	125°	75°	100°	125°
1	0.44	24.80	30.16	4.11	24.88	10.11
2	-0.75	4.91	12.41	-0.54	5.79	17.81
3	20.48	21.82	31.81	25.93	17.07	46.53
4	5.60	10.89	14.04	28.27	25.73	14.90
5	-2.59	12.20	34.46	8.95	30.77	14.28
6	12.14	26.81	23.37	-2.11	25.45	15.95
7	20.23	23.85	38.31	18.82	10.26	17.13
8	10.38	24.00	33.27	18.08	26.99	1.76
9	18.35	21.72	39.73	28.66	31.33	17.26
10	12.18	12.34	13.65	17.58	21.07	28.17
Mean ± SD	9.65 ± 8.67	18.33 ± 7.52	27.12 ± 10.49	14.78 ± 11.56	21.93 ± 8.49	18.39 ± 11.88

Calculated as [((Pre-test MVIC – Post-test MVIC) / Pre-test MVIC) x 100]. Positive values demonstrate a greater Pre-test than Post-test value, while negative values demonstrate a greater Post-test than Pre-test value.

Table 3. Performance fatigability (% change) for Torque anchored to TRQ.

	Fatiguing Joint Angle (75°)			Fatiguing Joint Angle (125°)		
Subjects	75°	100°	125°	75°	100°	125°
1	20.48	11.20	16.74	15.25	17.45	17.15
2	9.20	2.87	10.19	8.00	15.02	21.11
3	18.27	25.86	34.75	36.19	30.70	35.64
4	10.20	22.68	45.72	11.76	18.19	22.87
5	11.09	16.97	17.21	17.34	26.17	32.67
6	-1.54	20.03	17.13	22.66	5.65	21.65
7	18.78	11.66	19.12	16.80	14.39	27.11
8	24.01	28.86	31.71	31.29	19.97	29.72
9	26.97	14.30	-1.13	30.08	35.35	35.92
10	29.41	17.57	25.44	12.30	24.59	31.76
Mean ± SD	16.69 ± 9.45	17.20 ± 7.67	21.69 ± 13.28	20.17 ± 9.48	20.75 ± 8.66	27.56 ± 6.59

Calculated as [((Pre-test MVIC – Post-test MVIC) / Pre-test MVIC) x 100]. Positive values demonstrate a greater Pre-test than Post-test value, while negative values demonstrate a greater Post-test than Pre-test value.

Table 4. Performance fatigability (% change) for EMG AMP anchored to RPE = 8.

	Fatiguing Joint Angle (75°)			Fatiguing Joint Angle (125°)		
Subjects	75°	100°	125°	75°	100°	125°
1	-25.15	15.65	24.23	-1.66	-4.01	-44.57
2	16.97	31.22	-18.42	20.34	17.42	-13.40
3	9.49	12.31	5.03	43.92	10.65	-10.45
4	10.65	24.43	16.73	6.22	5.42	2.07
5	1.31	39.80	0.70	17.90	22.83	28.25
6	8.86	-3.97	17.74	-9.04	-5.93	-9.57
7	-23.52	27.82	4.54	24.27	18.52	-2.26
8	5.96	58.56	45.70	32.75	27.86	37.85
9	17.80	5.87	22.02	5.93	16.81	23.15
10	4.10	9.37	32.14	18.77	1.22	-8.71
Mean ± SD	2.65 ± 15.12	22.11 ± 18.27	15.04 ± 17.99	15.94 ± 15.97	11.08 ± 11.52	0.23 ± 24.08

Calculated as [((Pre-test EMG AMP – Post-test EMG AMP) / Pre-test EMG AMP) x 100]. Positive values demonstrate a greater Pre-test than Post-test value, while negative values demonstrate a greater Post-test than Pre-test value.

Table 5. Performance fatigability (% change) for EMG AMP anchored to TRQ.

	Fatiguing Joint Angle (75°)			Fatiguing Joint Angle (125°)		
Subjects	75°	100°	125°	75°	100°	125°
1	-0.66	19.49	24.91	5.41	-7.28	-5.93
2	-36.75	-18.84	-18.83	-11.66	-8.31	-36.26
3	18.01	14.75	8.47	34.56	9.27	-2.05
4	15.78	34.00	46.99	31.18	32.45	34.03
5	-15.70	2.66	-11.84	-19.45	-9.94	-24.24
6	-25.54	-5.97	8.28	2.62	12.83	-7.96
7	9.52	12.95	29.07	-8.43	-2.02	-19.62
8	-17.59	23.07	51.10	-19.68	-5.31	32.24
9	-23.26	-2.03	38.29	-10.44	7.51	3.88
10	20.32	33.17	-1.27	26.29	-16.23	5.69
Mean ± SD	-5.59 ± 20.72	11.33 ± 17.23	17.52 ± 24.31	3.04 ± 20.77	1.30 ± 14.37	-2.02 ± 22.59

Calculated as [((Pre-test EMG AMP – Post-test EMG AMP) / Pre-test EMG AMP) x 100]. Positive values demonstrate a greater Pre-test than Post-test value, while negative values demonstrate a greater Post-test than Pre-test value.

Table 6. Performance fatigability (% change) for EMG MPF anchored to RPE = 8.

	Fatiguing Joint Angle (75°)			Fatiguing Joint Angle (125°)		
Subjects	75°	100°	125°	75°	100°	125°
1	32.57	22.11	-11.12	13.60	2.51	10.49
2	24.46	19.14	14.17	15.58	4.24	4.85
3	13.71	-1.64	9.14	-9.03	0.50	1.16
4	-2.99	11.24	16.31	2.62	-4.53	0.91
5	3.98	6.64	12.27	0.37	9.33	-8.72
6	20.19	-14.05	-2.86	13.94	4.86	6.51
7	25.42	16.43	11.60	-6.28	16.68	5.09
8	-0.20	-3.37	-11.96	-12.16	7.92	-16.82
9	9.30	12.22	-17.00	-10.75	11.88	4.68
10	-7.36	2.96	-7.66	-2.53	9.15	3.60
Mean ± SD	11.91 ± 13.53	7.17 ± 11.31	1.29 ± 12.65	0.54 ± 10.63	6.25 ± 6.06	1.17 ± 8.06

Calculated as [((Pre-test EMG MPF – Post-test EMG MPF) / Pre-test EMG MPF) x 100]. Positive values demonstrate a greater Pre-test than Post-test value, while negative values demonstrate a greater Post-test than Pre-test value.

Table 7. Performance fatigability (% change) for EMG MPF anchored to TRQ.

	Fatiguing Joint Angle (75°)			Fatiguing Joint Angle (125°)		
Subjects	75°	100°	125°	75°	100°	125°
1	25.62	5.37	6.43	5.16	15.86	2.50
2	37.47	-5.91	11.93	22.26	16.89	14.21
3	13.68	14.83	7.56	-1.08	15.31	20.83
4	13.61	26.14	8.61	12.40	16.59	8.32
5	10.45	15.25	8.45	14.09	8.70	15.66
6	1.32	3.78	3.82	2.39	7.75	7.21
7	19.30	5.54	-1.37	8.46	2.94	9.18
8	17.43	0.78	13.11	22.57	-14.78	25.22
9	-6.77	7.41	-6.47	9.34	13.23	19.42
10	18.44	7.69	8.47	6.98	20.35	17.19
Mean ± SD	15.05 ± 12.20	8.09 ± 8.85	6.05 ± 5.98	10.26 ± 7.79	10.28 ± 10.22	13.97 ± 7.06

Calculated as [((Pre-test EMG MPF – Post-test EMG MPF) / Pre-test EMG MPF) x 100]. Positive values demonstrate a greater Pre-test than Post-test value, while negative values demonstrate a greater Post-test than Pre-test value.

Reliability

Table 8 includes the test-retest reliability parameters (*P*-value (systematic error), ICC, $ICC_{95\%}$, and SEM) for MVIC, EMG AMP, and EMG 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 0.406 (EMG MPF at 125°) to 0.865 (MVIC Forearm Flexion at 100°).

Pre-test Maximal Voluntary Isometric Contractions

The results of the repeated measures ANOVA for the pre-test MVICs (collapsed across Anchoring Scheme and Fatiguing Joint Angle) indicated that there were significant ($p < 0.001$, $\eta_p^2 = 0.551$) mean differences between the MVIC Joint Angles. The follow-up pairwise comparisons indicated that the MVIC at JA100 (29.1 ± 4.3 Nm) was significantly greater ($p = 0.001$, $d = 0.694$; Bonferroni corrected alpha = 0.0167) than the MVIC at JA75 (25.9 ± 4.7 Nm) and JA125 (23.5 ± 5.0 Nm; $p = 0.002$, $d = 1.181$).

Table 8. Reliability data for maximal voluntary isometric contraction (MVIC) torque and neuromuscular parameters (EMG AMP and EMG MPF) during the pre-test forearm flexions at elbow joint angles (JA) of 75°, 100°, and 125°.

MVIC (mean ± SD)	**Visit 1**	**Visit 2**	**Visit 3**	**Visit 4**	***P***	**ICC**	**ICC95%**
Forearm Flexion at JA75 (Nm)	26.1 ± 4.2	25.7 ± 5.8	26.2 ± 5.7	27.9 ± 4.9	0.168	0.789	0.578 – 0.928
Forearm Flexion at JA100 (Nm)	30.3 ± 4.9	29.9 ± 4.0	29.4± 5.2	29.1 ± 5.1	0.417	0.865	0.710 – 0.956
Forearm Flexion at JA125 (Nm)	25.2 ± 5.7	24.0 ± 6.1	23.2 ± 5.1	23.4 ± 4.7	0.214	0.805	0.604 – 0.934
Neuromuscular Parameters (mean ± SD)							
EMG AMP at JA75 (µVrms)	672.7 ± 181.6	631.1 ± 165.4	632.8 ± 313.7	675.8 ± 313.7	0.767	0.743	0.502 – 0.910
EMG AMP at JA100 (µVrms)	622.7 ± 160.8	689.0 ± 234.2	619.1 ± 256.9	623.4 ± 243.4	0.521	0.691	0.430 – 0.888
EMG AMP at JA125 (µVrms)	637.4 ± 212.8	681.4 ± 244.0	713.3 ± 205.3	746.5 ± 245.5	0.376	0.570	0.280 – 0.831
EMG MPF at JA75 (Hz)	75.2 ± 7.8	78.0 ± 11.6	75.8 ± 11.4	77.1 ± 9.3	0.588	0.740	0.500 – 0.909
EMG MPF at JA100 (Hz)	70.9 ± 9.6	71.1 ± 10.5	72.7 ± 10.2	72.1 ± 11.1	0.898	0.648	0.365 – 0.870
EMG MPF at JA125 (Hz)	63.2 ± 6.6	67.7 ± 8.2	65.9 ± 10.7	65.7 ± 6.4	0.416	0.406	0.113 – 0.738

P = Alpha from the ANOVA (2,1 model) for systematic error; ICC = intraclass correlation coefficient; $ICC_{95\%}$ = ICC 95% confidence interval; EMG AMP = electromyographic amplitude; EMG MPF = electromyographic mean power frequency.

Time to Task Failure

The results of the repeated measures ANOVA for TTF indicated a significant 2-way (p = 0.011, η_p^2 = 0.530) interaction for Anchoring Scheme x Fatiguing Joint Angle. The follow-up pairwise comparisons indicated that for RPE = 8, FJA75 had a significantly (p = 0.018, d = 1.076; Bonferroni corrected alpha = 0.025) greater TTF (361.7 ± 256.0 s) than FJA125 (152.3 ± 90.4 s). For TRQ, however, there was no significant (p = 0.738, d = 0.114) difference in TTF between FJA75 (73.9 ± 38.4 s) and FJA125 (80.8 ± 76.5 s) (Table 9).

Table 9. Time to Task Failure (seconds) for Anchoring Scheme (RPE = 8 and TRQ) and Fatiguing Joint Angle (75° and 125°).

	Fatiguing Joint Angle (75°)		Fatiguing Joint Angle (125°)	
Subjects	RPE = 8	TRQ	RPE = 8	TRQ
1	130.8	56.6	92.7	43.9
2	318.0	115.8	298.8	270.0
3	154.2	103.2	74.0	41.3
4	267.0	60.2	228.0	22.0
5	723.6	58.7	250.8	49.3
6	331.8	17.3	127.2	21.8
7	229.2	20.5	54.1	78.5
8	228.0	81.4	31.1	108.0
9	298.2	133.2	174.0	138.0
10	936.0	92.3	192.0	35.5
Mean ± SD	361.7 ± 260.0*	73.9 ± 38.4	152.3 ± 90.4	80.8 ± 76.5

*TTF for the FJA75 significantly (p < 0.05) greater than FJA125 when anchored to RPE = 8.

Performance Fatigability

The results of the repeated measures ANOVA for MVIC indicated no significant 3-way (p = 0.113, η_p^2 = 0.215) or 2-way (p = 0.134 to p = 0.299, η_p^2 = 0.161 to η_p^2 = 0.200) interactions. There was, however, a significant main effect for MVIC Joint Angle (p < 0.001, η_p^2 = 0.567). The follow-up pairwise comparisons for the main effect for MVIC Joint Angle (collapsed across Anchoring Scheme and Fatiguing Joint Angle) indicated that the MVIC at JA125 (23.7 ± 5.8 %) had a significantly (p < 0.001, d = 1.239; Bonferroni corrected alpha = 0.0167) greater performance fatigability than the MVIC at JA75 (15.3 ± 7.6 %) (Figure 1).

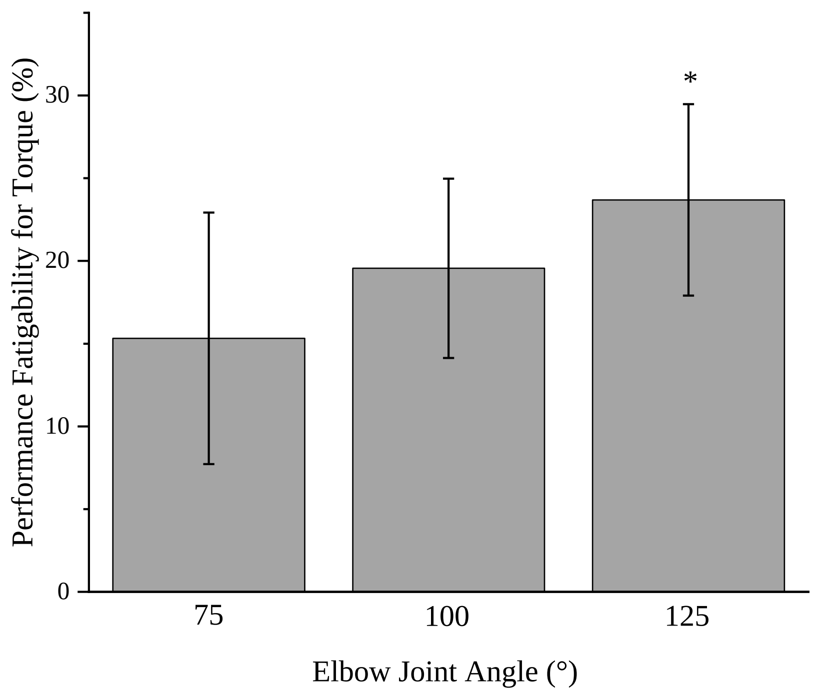

Figure 1. Performance fatigability (mean ± SD) for Torque [((Pre-test MVIC – Post-test MVIC) / Pre-test MVIC) x 100] at elbow joint angles (JA) of 75°, 100°, and 125°, collapsed across Anchoring Scheme (RPE = 8 and TRQ) and Fatiguing Joint Angle (75° and 125°).

*JA125 significantly ($p < 0.001$) greater than JA75.

Electromyographic Amplitude

The results of the repeated measures ANOVA for EMG AMP indicated no significant 3-way interaction (p = 0.864, η_p^2 = 0.016) and no significant 2-way interactions for Anchoring Scheme x MVIC Joint Angle (p = 0.073, η_p^2 = 0.252) or Anchoring Scheme x Fatiguing Joint Angle (p = 0.629, η_p^2 = 0.027). There was, however, a significant 2-way interaction for Fatiguing Joint Angle x MVIC Joint Angle (p = 0.000, η_p^2 = 0.599). A one-way follow-up repeated measures ANOVA, with post-hoc, pairwise comparisons for MVIC Joint Angle (75°, 100°, and 125°) was performed for each fatiguing joint angle (collapsed across Anchoring Scheme). As a result of the fatiguing task at FJA75, there was a significantly (p = 0.004, d =

1.522) greater percent change in EMG AMP for the MVIC at JA100 (16.7 ± 13.3 %) than the MVIC at JA75 (-1.5 ± 10.4 %) (Figure 2). For FJA125, however, there were no differences between MVIC joint angles for percent change in EMG AMP (p = 0.206, η_p^2 = 0.161). Follow-up pairwise comparisons (collapsed across Anchoring Scheme) also indicated that the MVIC at JA75 for FJA125 had a significantly (p = 0.001, d = 0.911) greater percent change in EMG AMP than the MVIC at JA75 for FJA75 and the MVIC at JA125 for FJA75 had a significantly (p = 0.005, d = 0.900) greater percent change in EMG AMP than the MVIC at JA125 for FJA125 (Figure 2).

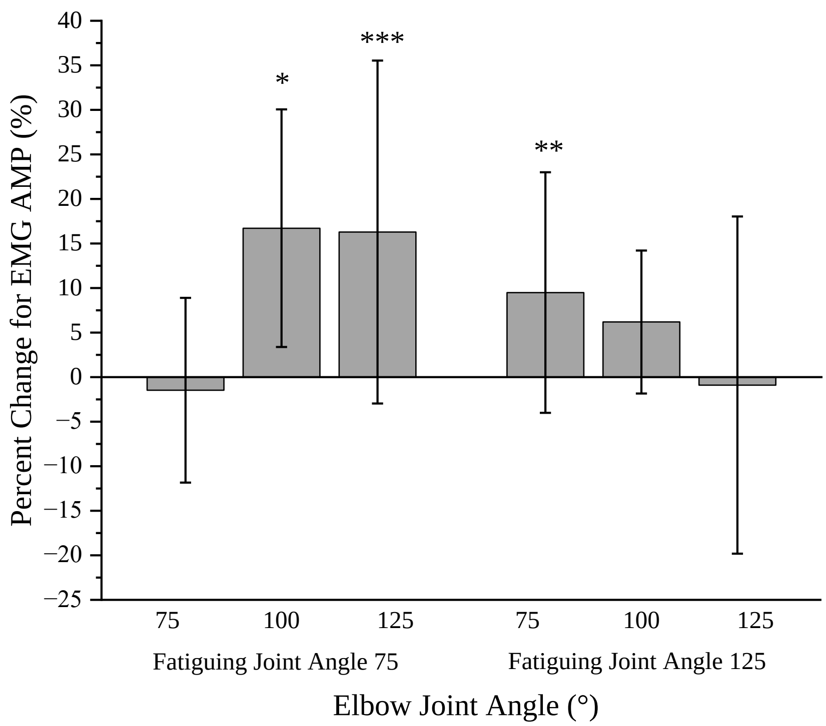

Figure 2. Percent change (mean ± SD) for EMG AMP [((Pre-test EMG AMP – Post-test EMG AMP) / Pre-test EMG AMP) x 100], collapsed across Anchor (RPE and Torque).

* Joint angle (JA) 100 significantly (p = 0.004) greater than JA75.

**JA75 at the fatiguing joint angle (FTJA) 125° significantly (p < 0.001) greater than JA75 at the FTJA 75°.

***JA125 at the FTJA75 (p = 0.005) greater than JA125 at the FTJA125.

Electromyographic Mean Power Frequency

The results of the repeated measures ANOVA for EMG MPF indicated no significant 3-way interaction (p = 0.837, η_p^2 = 0.020). There was, however, significant 2-way interactions for Muscle Length x Joint Angle (p = 0.009, η_p^2 = 0.404) and Muscle Length x Anchor (p = 0.028, η_p^2 = 0.430). The follow-up repeated measures ANOVAs (decomposed by Muscle Length) indicated, for the short muscle length, no significant Anchor x Joint Angle interaction (p = 0.826, η_p^2 = 0.021), but a significant main effect for Joint Angle (p = 0.032, η_p^2 = 0.319). Follow-up pairwise comparisons (collapsed across Anchor) for the short muscle length indicated there were no significant differences (p = 0.020 to p = 0.202, d = 0.538 to d = 1.069; Bonferroni corrected alpha = 0.0167) between joint angles (Figure 3A). The follow-up repeated measures ANOVAs (decomposed by Muscle Length) indicated, for the long muscle length, no significant Anchor x Joint Angle interaction (p = 0.361, η_p^2 = 0.097), but a significant main effect for Anchor (p = 0.003, η_p^2 = 0.641). Follow-up pairwise comparisons (collapsed across Joint Angle) for the long muscle length indicated that TRQ had a significantly (p = 0.003, d = 1.947; Bonferroni corrected alpha = 0.025) greater percent change than RPE (Figure 3B).

Discussion

The test-retest reliability analyses for the MVIC and neuromuscular (EMG AMP and EMG MPF) parameters in the present study are presented in Table 8. For forearm flexion MVIC, there were no significant mean differences for the test versus retest and the ICCs ranged from R = 0.789 – 0.865. These ICCs reflected excellent reliability (Cicchetti, 1994), but were somewhat lower (ICC = 0.982) than those previously reported by Hill et al. (2020) for isometric forearm flexion MVIC values. There were also no significant mean differences between the test and retest reliability for the neuromuscular parameters (EMG AMP and EMG MPF) from the BB during the forearm flexion MVICs. These findings were consistent with Smith et al. (2021b) and Hill et al. (2020) who have previously reported no systematic error for the test versus retest reliability of isometric forearm flexion MVIC, EMG AMP, and EMG MPF. The ICCs for the neuromuscular parameters ranged from R = 0.406 – 0.743. These ICCs reflected fair to good reliability (Cicchetti 1994) but were lower (ICC = 0.863 – 0.975) than previously reported by Hill et al. (2020) for neuromuscular parameters during isometric forearm flexion MVICs. Koo and Li (2016) have 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).

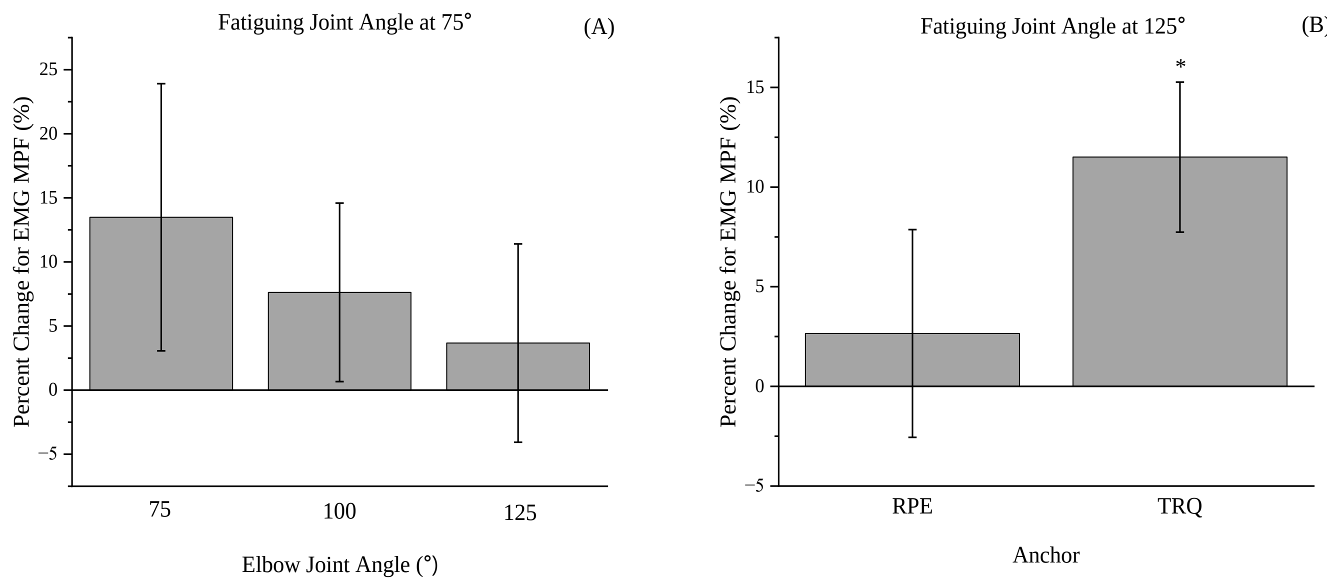

Figure 3. A) Percent change (mean ± SD) for EMG MPF [((Pre-test EMG MPF – Post-test EMG MPF) / Pre-test EMG MPF) x 100], collapsed across Anchoring Scheme (RPE = 8 and TRQ). B) Percent change (mean ± SD) for EMG MPF [((Pre-test EMG MPF – Post-test EMG MPF) / Pre-test EMG MPF) x 100], collapsed across MVIC Joint Angle (75°, 100°, 125°).

A) No significant (Bonferroni corrected $p > 0.0167$) differences between MVIC joint angles ($p = 0.020$ to $p = 0.202$).

*B) TRQ significantly ($p = 0.003$) greater than RPE = 8 following the fatiguing task at a fatiguing joint angle of 125°.

The current study indicated joint angle-specific differences in pre-test MVIC values, where MVIC JA100 (29.1 ± 4.3 Nm) was greater than MVIC JA75 (25.9 ± 4.7 Nm) and MVIC JA125 (23.5 ± 5.0 Nm). It has been reported that for forearm flexion muscle actions (Downer, 1953; Knapik et al., 1983; Kulig et al., 1984; Sato & Sakai, 1968; Singh & Karpovich, 1968; Tsunoda et al., 1993) MVIC values are typically the greatest between joint angles of 90° and 120° and decrease at both ends of the range of motion. In theory (Fitch & McComas, 1985; Huijing, 1992; Petrofsky & Phillips, 1980), the optimal overlap of actin-myosin for cross-bridge attachment occurs in the middle of a range of motion, while larger and smaller joint angles are characterized by inefficient force production capabilities due to less actin-myosin overlap and excessive, disadvantageous actin-myosin overlap, respectively. Thus, these theories are consistent with the findings of the current study as MVIC JA100 resulted in greater force production than MVIC JA75 and MVIC JA125.

The TTF values for the sustained, isometric forearm flexion tasks anchored to RPE = 8 were greater than those anchored to TRQ for both FJA75 and FJA125 (Table 9), which were likely due to the ability to consciously reduce torque during the RPE = 8 trials (Keller et al., 2019). Previously, Keller et al. (2020) examined the effects of anchoring scheme (RPE versus TRQ) on TTF in men during bilateral, isometric leg extensions anchored to RPE values of 1, 5, and 8, as well as anchored to the force values that corresponded to each RPE trial. Unlike the current study, however, Keller et al. (2020) found no significant ($p = 0.058$) differences in the TTF values between anchoring schemes. Additional research is needed to determine if these differences between studies were due to sex differences in the fatigue characteristics of women (Hunter, 2016) subjects in the present study versus men subjects in Keller et al. (2020), and/or muscle-specific responses for forearm flexion versus leg extension muscle actions. Previously it has been suggested (Hunter, 2016; Keller et al., 2022) that during fatiguing, isometric tasks, women exhibit less metabolite build-up and an enhanced ability for metabolic byproduct clearance (likely due to differences in blood flow) compared to men. In addition, Enoka and Duchateau (2016) proposed that while performance fatigability and perceived fatigability are separate domains of fatigue, voluntary actions in humans involve significant interactions between the two. Thus, based on the suggestions of Hunter (2016) and Enoka and Duchateau (2016), it is possible that women experience perceived fatigability differently than men. If so, this may have contributed to the longer TTF when anchored to RPE = 8 than when anchored to TRQ for the women in the present study, but not the men studied by Keller et al. (2020).

The current study indicated that when anchored to TRQ, there were no significant ($p = 0.369$) differences in TTF between FJA75 and FJA125. These findings were consistent with previous studies (Baker et al., 1992; Sacco et al.,

1994) who reported no differences in TTF for short and long muscle lengths of the ankle dorsiflexor muscles and the tibialis anterior. These results, however, were not inconsistent with those of Petrofsky and Phillips (1980) who examined isometric forearm flexion endurance at various elbow joint angles (30, 60, 90, 120, and 150°) and force values (25, 40, 55, 70, or 90% of MVIC) and reported that for all loads the endurance time was significantly greater at 120° than at other elbow joint angles. Kooistra et al. (2005), however, reported that the TTF was greater at shorter joint angles than longer joint angles during intermittent, isometric leg extension tasks, perhaps due to a lower ATP consumption rate per cross-bridge cycle at shorter joint angles. Furthermore, previous studies (Fitch & McComas, 1985; Weir et al., 2000) have suggested that differences in TTF between muscle lengths may be due to disadvantageous actin-myosin interaction, ATP costs, and/or motor unit recruitment rates. Petrofsky and Phillips (1980) further suggested that "…the main criteria in determining endurance is the number of cross bridges which form between actin and myosin at the onset of the contraction relative to the total number which can form during an MVC" (p. 130). While these previous studies (Baker et al., 1992; Fitch & McComas, 1985; Kooistra et al., 2005; Petrofsky & Phillips, 1980; Sacco et al., 1994; Weir et al., 2000) have examined the effect of muscle length and joint angle on TTF for tasks anchored to force, no previous studies have examined joint angle-specific differences in endurance while anchored to a constant RPE.

When anchored to RPE = 8, the current results indicated that the TTF for FJA75 was greater than FJA125 (Table 9). Tasks anchored to RPE typically result in a longer TTF compared to tasks anchored by TRQ or force due to the ability to consciously decrease force to maintain the prescribed RPE (Keller et al., 2019, 2018). This combined with the disadvantageous actin-myosin interaction that may occur at larger joint angles (Fitch & McComas, 1985) could explain why, when anchored to RPE = 8, the TTF for FJA75 was 2.4 times longer than FJA125. Future studies should continue to examine how joint angle affects TTF during fatiguing isometric tasks anchored to RPE for various muscle groups, joint angles, and RPE intensities for both women and men.

The results of the current study indicated that performance fatigability for forearm flexion MVIC was not influenced by the anchoring scheme (RPE = 8 or TRQ) or the FJA (75° or 125°) of the fatiguing task. Previous studies have reported performance fatigability for MVIC values that were similar to the current study and ranged from 9.9 - 29% for unilateral forearm flexion, unilateral leg extension, and bilateral leg extension in women (Keller et al., 2022, 2018) and men (Keller et al., 2022, 2020; Arnett et al., 2022) following sustained, isometric tasks anchored to RPE = 5 and RPE = 8. These decreases in MVIC values (Keller et al., 2022, 2020, 2018; Arnett et al., 2022) for forearm flexion and leg extension were similar to that of the current study, where decreases in MVIC values ranged from 15.3 to 23.7%

following a sustained, isometric forearm flexion task anchored to RPE = 8. This suggests that similar decreases in MVIC values occur following a sustained, isometric task regardless of muscle action, perceptual intensity, or sex.

Thomas et al. (2018) hypothesized that the magnitude of performance fatigability is determined by the amount of muscle mass engaged and that "…muscle mass recruited during exercise is dependent on the intensity and mode of the task," (p. 241) which together will determine the magnitude of performance fatigability. While the current study and that of Arnett et al. (2022) utilized forearm flexion muscle actions and Keller et al. (2022, 2020, 2018) utilized leg extensions, both studies used isometric tasks. Therefore, the similarities in performance fatigability among studies may be due to the mode of exercise. Future studies should also examine the effects of dynamic fatiguing tasks anchored to various perceptual intensities on performance fatigability and perceived fatigability.

Anchoring to RPE is typically characterized by decreases in force and EMG AMP, while tasks anchored to absolute force or a percent of MVIC are characterized by the maintenance of force with increases in EMG AMP (Beck et al., 2004; Farina et al. 2014; Keller et al., 2019, 2018). Thus, the amount of activated muscle mass during tasks anchored to RPE can decrease with force to maintain the required perception of exertion, whereas the amount of activated muscle mass during tasks anchored to submaximal force increases to maintain the intensity. Therefore, based on the hypothesis of Thomas et al. (2018), Keller et al. (2020) suggested that there would be greater performance fatigability following a task anchored to RPE than when anchored to the corresponding force. Similar to the current study for forearm flexion, however, Keller et al. (2020) found that the anchoring scheme (RPE or TRQ) had no effect on performance fatigability following bilateral, isometric leg extensions. Perhaps the findings of the present study and Keller et al. (2020) differ from the hypothesis of Thomas et al. (2018) due to the use of fatigue-induced decreases in MVIC to define performance fatigability, while Thomas et al. (2018) used evoked twitch responses. Future studies should compare the responses from tasks anchored to RPE and TRQ using MVIC, voluntary activation, and potentiated twitch amplitude as indicators of performance fatigability.

Although performance fatigability for MVIC was not affected by the anchoring scheme (RPE = 8 versus TRQ) or the joint angle at which the fatiguing tasks were performed (fatiguing joint angle of 75° versus 125°) there was a significant main effect for MVIC Joint Angle where performance fatigability for the MVIC at JA125 (23.7%) was significantly greater than the MVIC at JA75 (15.3%), but not the MVIC at JA100 (19.6%). There is conflicting evidence from previous studies (Fitch & McComas, 1985; Pethick et al., 2021; Place et al., 2005; Weir et al., 2000) regarding the effects of joint angle and muscle length on performance fatigability, perhaps due to the muscle group involved (Fitch &

McComas, 1985; Pethick et al., 2021; Place et al., 2005; Weir et al., 2000), the mode of fatiguing task (Fitch & McComas, 1985; Pethick et al., 2021), or how performance fatigability was determined (Fitch & McComas, 1985). For example, Fitch and McComas (1985) found that following both an evoked tetanic fatiguing task and voluntary MVIC fatiguing task of the dorsiflexor muscles, there was greater performance fatigability at the "optimal" muscle length (15° plantarflexion) than the shorter muscle length (25° dorsiflexion). Fitch and McComas (1985) defined the "optimal" muscle length as the one where "optimum tension was produced" (p. 206). In the current study for forearm flexion, MVIC JA100 exhibited greater pre-test MVIC torque than MVIC JA75 and MVIC JA125, but performance fatigability was not different for MVIC JA100 versus MVIC JA75 or MVIC JA125. In addition, Weir et al. (2000) found no significant (p = 0.084) difference in performance fatigability for MVICs of the dorsiflexor muscles between long (40° plantarflexion) and short (5° dorsiflexion) muscle lengths following isometric, dorsiflexion fatiguing tasks at 50% MVIC for 60s. For leg extension, Pethick et al. (2021) found that following intermittent, isometric fatiguing tasks at 50% MVIC, there was less performance fatigability at the short joint angle (30° leg flexion) than at the medium (60° leg flexion) and long (90° leg flexion) joint angles. Place et al. (2005), however, found similar performance fatigability for both the short (35° leg flexion) and long (75° leg flexion) joint angles following isometric, leg extension fatiguing tasks at 20% MVIC. While the underlying mechanisms of joint angle-specific performance fatigability have not been fully defined, previous studies (Balnave & Allen, 1996; Fitch & McComas, 1985; Pethick et al., 2021; Place et al., 2005; Weir et al., 2000) have suggested that neuromuscular, metabolic, and biochemical processes may contribute to joint angle-specific differences in performance fatigability. For example, Weir et al. (2000) assessed fatigue-induced EMG and mechanomyographic (MMG) responses to sustained, isometric dorsiflexion tasks and reported greater increases in motor unit recruitment across time for the long versus short muscle length. It was suggested (Weir et al., 2000) that differences in performance fatigability associated with muscle length "… are driven by motor control processes and not necessarily by cellular metabolic factors." (p. 358). Pethick et al. (2021), however, examined the effects of joint angle on muscle oxygen consumption rate ($m\dot{V}O_2$) following fatiguing, intermittent, isometric leg extensions and found that performance fatigability, as well as the rate of change in $m\dot{V}O_2$, were less at 30° than 60° and 90° leg flexion. Furthermore, Fitch and McComas (1985) suggested that performance fatigability is related to the number of cross-bridge attachments that form during a muscle contraction and Balnave and Allen (1996) indicated that the number of attached cross-bridges affects calcium-troponin C binding sensitivity. In addition, Place et al. (2004) reported greater increases in twitch potentiation and doublet potentiation at the short (35° leg flexion) than the long (75° leg flexion) joint angle and suggested that excitation-contraction coupling was affected by the joint angle at which the fatiguing, isometric leg extension tasks were performed. Future studies are needed to examine the mechanisms responsible for joint angle-specific performance fatigability for various muscle groups and joint angles.

Peripheral and central mechanisms of fatigue can contribute to performance fatigability and are typically reflected in neuromuscular responses (Farina et al., 2004). Peripheral fatigue involves processes distal to the myoneural junction that affect excitation-contraction coupling, including metabolic perturbations within the active muscle fibers such as increases in inorganic phosphate and ammonia, as well as decreases in intracellular pH, calcium release and reuptake kinetics, actin-myosin binding, and troponin-calcium binding (Bigland-Ritchie et al., 1995; Maclaren et al., 1989). Central fatigue involves group III/IV afferent neural feedback from the intracellular metabolic perturbations to the motor areas of the brain and leads to fatigue-induced decreases in central motor command and force production (Hureau et al., 2022). Fatigue-induced decreases in EMG MPF reflect decreases in muscle fiber action potential conduction velocity (Farina et al., 2004, 2014). In the present study, the decreases in EMG MPF and MVIC at the three joint angles indicated that the sustained, isometric tasks were fatiguing for both anchoring schemes and fatiguing joint angles at which the tasks were performed. Following the fatiguing tasks at FJA75 in the present study, there were decreases in EMG AMP at MVIC JA100 and MVIC JA125, but an increase at MVIC JA75. These findings suggested joint angle-specific contributions to performance fatigability from peripheral and central mechanisms. It is possible that the decreases in EMG AMP and MVIC at MVIC JA100 and MVIC JA125, as the result of FJA75, may have been due to a combination of peripheral and central fatigue. That is, the magnitude of performance fatigability was due to peripheral and central mechanisms, while the decreases in EMG AMP reflected reduced central command associated with central fatigue. The performance fatigability for the MVIC at JA75 was less than at the MVIC at JA100 and the MVIC at JA125 and was associated with a slight (1.5%) increase in EMG AMP, possibly due to increased synchronization (Farina et al., 2004; Yao et al., 2000). These findings suggested that the fatigue-induced decrease in MVIC was due to peripheral mechanisms because a decrease in central command from central fatigue would likely have resulted in decreased motor unit recruitment and a decrease in EMG AMP. The potential for joint angle-specific differences in the contributions of peripheral and central mechanisms that underly performance fatigability as the result of isometric, forearm flexion tasks should be further examined using evoked potentiated twitch amplitude and interpolated twitch procedures.

The findings of the current study are limited to women subjects, high intensity isometric, forearm flexion fatiguing tasks at joint angles of 75° and 125° (RPE = 8 and TRQ), and neuromuscular responses from the BB. Hunter (2016) has described sex differences in response to fatiguing tasks and, therefore, the current study should be replicated in men. Due to these limitations, future studies should examine the effects of anchoring scheme on fatigue responses for various intensities, joint angles, and muscle groups. Furthermore, additional research should examine the neuromuscular responses from all three muscles that contribute to forearm flexion.

In summary, the results of the current study indicated that the TTF was 46.5% greater for the tasks anchored to RPE = 8 than when anchored to TRQ, due to the ability to consciously reduce torque throughout the fatiguing task to maintain RPE = 8. There were no differences in TTF between fatiguing joint angles when anchored to TRQ, but when anchored to RPE = 8, the fatiguing joint angle of 75° resulted in greater TTF than 125°. Furthermore, for the MVIC at JA125, performance fatigability was greater than the MVIC at JA75 and the MVIC at JA100 regardless of the anchoring scheme or joint angle used for the fatiguing task. These findings suggested that there were joint angle-specific mechanisms that affected the magnitude of performance fatigability. For the MVIC at JA100 and the MVIC at JA125, there were decreases in EMG AMP and MVIC values following the fatiguing task performed at the fatiguing joint angle of 75°. These findings suggested that a combination of peripheral and central fatigue mechanisms contributed to performance fatigability. For the MVIC at JA75, however, decreases in MVIC, but increases in EMG AMP suggested that the performance fatigability was due to peripheral fatigue, but not central fatigue. There were decreases in EMG MPF for all three MVIC joint angles, as well as both joint angles of the fatiguing tasks and anchoring schemes which further characterized the fatiguing nature of the sustained, isometric tasks. Thus, the current findings indicated that TTF, performance fatigability, and the neuromuscular responses were affected by the joint angle at which the fatiguing tasks were performed, the anchoring scheme of the tasks, and the joint angle where the MVICs were assessed.

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