For correspondence:
trisha.scribbans@umanitoba.ca

Exploring the Acute Muscle Fatigue Response in Resistance Trained Individuals During Eccentric Quasi-Isometric Elbow Extensions— A Cross-Sectional Comparison of Angular Kinetics, Kinematics, Surface Electromyography, and Sex

Zachariah J. Henderson[1], Shizhen Wang[2], Stephen M. Cornish[2], Trisha D. Scribbans[2]

[1]Applied Health Sciences, University of Manitoba, Winnipeg, Manitoba, Canada

[2]Faculty of Kinesiology and Recreation Management, University of Manitoba, Winnipeg, Manitoba, Canada

Please cite as: Henderson, Z. J., Wang, S., Cornish, S. M., Scribbans, T. D., (2003). Exploring the Acute Muscle Fatigue Response in Resistance Trained Individuals During Eccentric Quasi-Isometric Elbow Extensions— A Cross-Sectional Comparison of Angular Kinetics, Kinematics, Surface Electromyography, and Sex (Pre-print). *SportRχiv*.

All authors have read and approved this version of the manuscript. This article was last modified June, 2023 and has been submitted for peer review.

ABSTRACT

Eccentric quasi-isometrics (EQIs) are a novel, low-velocity resistance exercise technique with increasing notoriety, yet limited research. As females are typically more fatigue resistant than males during isometric and low-velocity dynamic muscle actions, this study explored sex-differences in the muscle fatigue response to an EQI protocol. Twenty-five (n = 12 female) participants completed 4 unilateral EQI elbow extensions. Absolute and relative surface electromyography (sEMG) amplitude (iEMG, LE Peak), mean power frequency (MPF), angular impulse (aIMP), and elbow kinematics were compared across repetitions and between sexes using discrete values and statistical parametric/non-parametric mapping. There were significant (p < .001 to .032) and substantial (η_p^2 = .15 to .55) sex and repetition differences in absolute iEMG, MPF, and aIMP, with males and earlier repetitions generally having larger values than females and later repetitions. When expressed relatively, there were no significant sex-differences, but significant decreases in iEMG, aIMP, and elbow angle (p < .001 to .007) with an increasing number of repetitions. The current study suggests that sex-differences in EQI induced muscle fatigue are diminished when expressed relatively, and consecutive repetitions leads to significant decreases in sEMG, kinematic, and kinetic characteristics, with the largest differences between repetition 1 and 2.

Key Words: Resistance exercise, statistical parametric mapping, SPM, time under tension

INTRODUCTION

Eccentric quasi-isometrics (EQIs) are a novel form of resistance exercise, incorporating both isometric and eccentric muscle contractions (“muscle actions”; Oranchuk et al., 2019; Oranchuk et al., 2020; Oranchuk et al., 2021). An EQI is performed by holding a yielding isometric muscle action for as long as possible; eventually, the accumulation of fatigue results in isometric failure and the inability to maintain joint position (Oranchuk et al., 2020; Oranchuk et al., 2021). A low-velocity, involuntary eccentric muscle action then ensues, which is voluntarily resisted through the full and/or desired range of motion (ROM; Oranchuk et al., 2019; Verkhoshansky & Siff, 2009). In a theoretical review, Oranchuk et al. (2019) suggested that large amounts of mechanical tension, and time under tension (TUT) would be produced during EQIs relative to traditional resistance exercise practices, thus increasing training volume and promoting morphological musculotendinous adaptations (e.g., greater muscle thickness, fascicle length, tendon stiffness) through mechanotransduction. As such, it has been suggested (Oranchuk et al., 2019) that EQIs may be useful for stimulating muscle morphological changes when stress to the joint or high velocity muscle actions are not tolerated (i.e., injury), desirable (e.g., low load/volume macrocycles), and where EQIs may simulate sport specific requirements (i.e., grappling, speed skating, sailing).

The potential for greater TUT relative to traditional isotonic resistance exercise underlies many of the proposed adaptations to EQIs, although practitioners have also suggested the EQI concept results in substantial motor unit recruitment relevant to other resistance exercise modalities (Morrison, 2016; Seedman, n.d.; Sinicki, 2019). Greater exercise volume, associated TUT, and motor unit recruitment are suggested factors in the muscle hypertrophic response (Schoenfeld, 2010; Schoenfeld et al., 2013; Schoenfeld et al., 2017). Both factors, however, will be influenced by the development and time-course of muscle fatigue. During traditional isotonic resistance exercise, TUT and therefore training volume will significantly decrease with subsequent repetitions (Paz et al., 2017), while EMG amplitude — long considered a broad representation of motor unit recruitment, will generally increase across repetitions and time (Bazzucchi et al., 2004; Kamen & Gabriel, 2010; Paz et al., 2017; Staudenmann et al., 2014). Relevant to these factors, females are generally more fatigue resistant than males, although differences are task, muscle, and intensity specific (Hunter, 2014; Hunter, 2016; Hunter, 2016b). Additionally, males and females may also exhibit different motor unit recruitment strategies during submaximal isometric exercise (Lulic-Kuryllo & Inglis, 2022). While theoretically promising, studies of EQIs to date (Oranchuk et al., 2020; Oranchuk et al. 2021) are limited to male participants, an acute knee extension model, and have yet to use electromyography to explore the myoelectrical manifestation of muscle fatigue during EQI resistance exercise. Given potential sex-differences in muscle fatiguability (Hunter, 2014; Hunter, 2016), motor unit behaviour (Lulic-Kuryllo & Inglis, 2022; Nishikawa et al., 2017; Pradhan et al., 2020) and the potential role that exercise volume, mechanical tension, and motor unit behaviour have on muscle hypertrophy and strength outcomes (Lim et al., 2022; Schoenfeld et al., 2017), it is plausible that sex-differences in muscle fatiguability during an EQI resistance exercise intervention would manifest in differing long-term strength, neurological and morphological adaptations. To support this hypothesis, however, it is first necessary to establish whether sex-differences exist in the muscle fatigue response during an acute bout of EQI resistance exercise.

The purpose of the current study was to define the fatigue response of the biceps brachii during elbow extension EQIs between resistance trained males and females. Specifically, surface electromyography (sEMG) was used to examine absolute (integrated EMG[$iEMG_{ABS}$], linear envelope peak [LE $Peak_{ABS}$], mean power frequency [MPF]), and relative

[$iEMG_{\%MVIC}$, LE $Peak_{\%MVIC}$] sEMG variables, while isokinetic dynamometry was used to examine kinematics (elbow angle), absolute ($aIMP_{ABS}$) and relative ($aIMP_{\%MVIT}$) angular impulse, and TUT across 4 EQI elbow extension repetitions. Further, exploratory analysis using statistical parametric (SPM) and non-parametric (SnPM) mapping was performed to see if the time course of sEMG amplitude and elbow angle changes differ between sexes within each EQI repetition, and across repetitions regardless of sex. For the primary analysis, the null hypothesis (H0) was that there would be no differences between repetitions, sex, or interaction of repetition and sex on any of the dependent variables. Based on consistent observations of lower MPF, sEMG, and torque amplitude in females (Farina et al., 2004; Freilich et al., 1995; Kotte et al., 2018), as well as their greater fatigue resistance during sustained isometric muscle actions for the elbow flexors (Hunter, 2016), the primary alternative hypothesis (H1) was that females would have lower absolute sEMG values and aIMP for all EQI repetitions. It was expected, however, that females would have greater relative aIMP values due to greater fatigue resistance (Avin et al., 2010), while absolute and relative iEMG and aIMP would decrease across all repetitions regardless of sex.

METHOD

Experimental Overview

Participants reported to a temperature-controlled lab (20 C°) at the same time of day (± 2-hours) for one familiarization (~1.5-hours), and one experimental session (~3-hours), with at least 1-week between sessions. A cross-sectional, between-subjects design was used to compare the onset of muscle fatigue between males and females, and across 4-repetitions of unilateral EQI elbow extension at 50% of maximum voluntary isometric torque (MVIT). sEMG of the biceps brachii and isokinetic dynamometry data were collected for all repetitions. Data were collected from August 2021 until December 2022.

Participants

As an exploratory study, and to our knowledge the first study to investigate EQIs between males and females in the upper extremity, a-priori sample size was informed by previous research, power calculations, and feasibility. Using a similar research design for a sample of 14 resistance trained males, Oranchuk et al. (2021) observed a medium-large effect size ($\omega^2 = 0.11$) for total angular impulse across 4-repetitions of EQI knee extension. However, given large (> 20%) sex-differences in fatiguability during isometric tasks using similar contraction intensities of the proposed study (Hunter, 2014), we elected to calculate power for a large effect size. Our a-priori power calculations (G*Power V. 3.1.9.2) for a 2 (between factor; sex)*4 (within factor; repetition) mixed factorial ANOVA indicated a sample of 30 participants were required to detect a significant (p < .05) sex*repetition interaction and large effect size ($\eta_p^2 = 0.14$) for angular impulse, with an achieved a power of 0.80 (1-β error probability) and non-sphericity correction of 0.80.

All participants were recruited from the University community via convenience sampling and the study protocol (HS24806) was approved by the University of Manitoba Research Ethics Board (REB 1). Written and verbal informed consent was obtained from all participants prior to participating in the study. Potential participants were eligible if they were: 1) 18-35 years of age, and 2) considered themselves resistance trained, which was defined as a minimum of 6 exercises (regardless of muscle group), 2x per week, for 6 months. Potential participants were excluded if they answered “yes” to any questions on the Get-Active Questionnaire (Canadian Society for Exercise Physiology, 2017), or experienced an acute musculoskeletal injury in the last 6 months that affected their ability to perform upper-body resistance exercise. Prior to each session, participants were asked to refrain from upper-body resistance exercise, alcohol and cannabis, general exercise, caffeine and a large meal for 48-hours, 24-hours, 12-hours, and 3-hours, respectively.

Familiarization Session

Prior to participating in any physical components of the study, participants had their blood pressure measured with an automatic blood pressure monitor and cuff (BP761CAN and HEM RML31, OMRON Healthcare Co., Ltd, Lake Forest, IL, USA), and body composition assessed via bio-electrical impedance (InBody270; InBody Co.; Seoul, South Korea) according to manufacturer recommendations. Participants then performed a 5-minute general warm-up on a stationary bike (UBK 835, Precor, Woodinville, WA, USA), at a self-selected “moderate” intensity (Oranchuk et al., 2020).

Isokinetic Dynamometry. Participants were pseudo-randomized to complete the protocol with either the dominant or non-dominant limb, based on the Edinburgh Handedness Inventory (Oldfield, 1971). In cases where participants were classified as ambidextrous, the side that they skewed towards was considered the dominant limb. One participant scored “0,” and thus a coin was flipped to assign limb dominance. Participants were then set-up in an isokinetic dynamometer (Biodex Multi-Joint System Pro; Biodex Medical Systems, Inc., Shirley, New York, USA) for unilateral elbow flexion/extension of the assigned limb. Participants were seated up-right with the backrest at 85°, dynamometer arm rotated laterally 30°, and the arm supported at ~45 ° to the shoulder. The handle of the dynamometer was positioned horizontally such that the forearm was supinated. In this position, participants were tightly secured to the dynamometer with 2 straps across the torso, and 1 strap across the lap. Flexion/extension range of motion (ROM) was set anatomically at 130° (0° = full extension, 130 ° = full flexion). Due to attachment limitations, some participant's arm position was > 45° relative to the shoulder, although anatomical and elbow ROM remained fixed. Positions for all adjustable dynamometer components and attachments were recorded for the subsequent session.

Maximum Voluntary Isometric Contractions. Once set-up in the dynamometer, participants completed a subjective warm-up involving single 5-second isometric muscle actions at 25%, 50% and 75% of their perceived maximum voluntary isometric torque (MVIT; Oranchuk et al., 2020, 2021). These warm-up repetitions were spaced 30-seconds apart and performed at 90° of elbow flexion. After 3-minutes of rest, participants completed two, 5-second maximum voluntary isometric contractions (MVICs) at 120°, followed by two MVICs at 90° and 60° of elbow flexion, respectively. Each MVIC was followed by 2-minutes of rest. During all MVICs, participants were given real time visual feedback of their torque output, and participants were given strong verbal encouragement to push the visual feedback bar "as high as you can." For MVICs, participants were also instructed to a) contract as "hard and fast" as possible (Maffiuletti et al., 2016) without pushing into the footrest, b) to keep the non-involved hand in their lap, and c) be as relaxed as possible prior to each MVIC. Participants were presented with a countdown timer for rest and each MVIC.

Eccentric Quasi-Isometric Contractions. Following completion of all MVICs, participants were given 5-minutes rest. Using their estimated 50% MVIT at 90° of elbow flexion, participants completed 2 EQI repetitions to familiarize themselves with the EQI protocol.

For EQIs, the dynamometer was set to isotonic mode (Oranchuk et al., 2020; Oranchuk et al., 2021), with the lever arm ROM anatomically set at 130° and velocity set at 60°/s. Applied torque was set at 50% of participant's MVIT, according to the highest torque value obtained during the 90° MVICs. Based on pilot testing, 50% MVIT was selected so that participants would have an extended period of near 0 movement velocity (Oranchuk et al., 2020). As the applied torque of the dynamometer was limited to intervals of 2- 5 N m, applied torque values were rounded up to the closest interval available in the dynamometer software (Biodex Advantage Software V.4; Biodex Medical Systems, Inc., Shirley, New York, U.S.A). Actual torque values during each EQI as a percentage of the MVIC (%MVIC) at 90° are presented in Table 1.

To start the protocol, participants slowly brought the dynamometer arm to full elbow flexion. In this position, participants were given a countdown of “3-2-1-go!”. On “go,” participants were instructed to slowly apply force to the handle, which resulted in the dynamometer applying eccentric torque. Rather than allowing a controlled eccentric muscle action, participants were instructed to brace and to resist the applied torque, with the goal of maintaining joint position, but not causing a concentric muscle action (Oranchuk et al., 2020; Oranchuk et al., 2021). Visual feedback of the real-time torque was provided to assist participants (OT Biolab V. 1.2, OT Bioelettronica, Torino, Italy). As participants fatigued and reached isometric/positional failure, they resisted the resulting eccentric muscle action until the dynamometer arm reached full extension (Oranchuk et al., 2020, 2021). Participants were then given 3-minutes rest, before completing one or two more repetitions, depending on their subjective comfort with the protocol. Following completion of the EQIs and as part of another study, participants then completed MVICs and eccentric muscle actions with the contralateral limb.

Experimental Session

The experimental session mirrored the familiarization session, however, participants performed 4 EQI repetitions (Oranchuk et al., 2020; Oranchuk et al., 2021) while surface electromyography data were collected over the skin of the biceps brachii.

Surface Electromyography. Prior to performing the general warm-up, participant’s skin was prepared for sEMG by shaving (if necessary), lightly abrading (Nuprep, Weaver and Company, Aurora, Colorado, USA), and wiping clean with water (Lulic-Kuryllo et al., 2021; Piervirgili et al., 2014). A 2-dimensional, rectangular array of 32-electrodes (8-rows x 4-columns; GR10MM0804; 10 mm interelectrode distance, gold coated; OT Bioelettronica, Torino, Italy) and foam pad (KIT10MM0804; OT Bioelettronica, Torino, Italy) filled with conductive paste (AC Cream, Spes Medica, Genova, Italy) was applied and affixed with tape (Hypafix; BSN Medical, Hamburg, Germany) to the muscle belly of the biceps brachii, such that the 4 electrode columns were parallel to the muscle fibre orientation. Specific placement was just proximal of 62% (measured proximal to distal) on an imaginary line from the acromion process to the distal biceps brachii tendon insertion (Barbero et al., 2012). Additionally, the electrode array was oriented so that the distal biceps tendon (palpated and marked) formed a line bisecting the array vertically. A damp ground strap was placed on the contralateral arm, and, to further reduce common-mode interference, a driven right leg circuit was implemented using straps attached to participants’ contralateral ankle (OT Bioelettronica, 2021).

Data Collection and Processing

All electronics were turned on 1-hour prior to calibration. Dynamometer position and torque were calibrated daily with a level and torque verification fixture (67.8 N m +/- 0.68 N m) as per manufacturer instructions (Biodex Medical Systems, Inc, 2014).

A 400-channel bioelectrical signal amplifier (Quattrocento; OT Bioelettronica, Torino, Italy ; +/- 5 V total input range, common-mode rejection ratio > 95 dB, 150V/V fixed-gain, 16-bit analogue to digital converter) was used to collect analogue data (V; volts) at 2048 Hz. Raw sEMG data were acquired in differential configuration (within columns, proximal to distal) via an AD32 electrode adapter (OT Bioelettronica, Torino, Italy), using a hardware bandpass filter of 10–500 Hz (II order Butterworth, -3 dB bandwidth). Full-scale analogue dynamometer data (kinematic and kinetic) were synchronously fed to the Quattrocento auxiliary input interface (fixed gain 0.5 V/V) without filtering (rated noise 15-35 mV). All analogue data were collected, visualized, and recorded using OT BioLab+ (V 1.2) software, and saved to a secure personal computer (Latitude 5500, Dell, Inc., Round Rock, Texas, U.S.).

Preliminary data processing and visualization were performed in OT BioLab+ (V.1.5). sEMG data were first visually inspected for any movement artifact, excessive signal noise, saturation, and poor electrode-skin contact. After visual inspection, and to mimic a traditional bipolar approach, the differential waveform from the most distal electrodes in the center-lateral column, along with raw kinematic and kinetic data were exported as a .csv and imported into Labchart 8 (ADInstruments Inc., Colorado Springs, USA) for further analysis. Similarly, the corresponding differential signal from a 10-second sEMG baseline (quiet sitting) was exported for the purposes of calculating the signal-to-noise ratio (SNR).

In LabChart 8, custom macros were used to perform additional bandpass filtering of the sEMG waveform (20-500 Hz, zero-phase-lag Finite Impulse Response [FIR]). MPF was calculated based on a 1024-point Fast Fourier Transform (cosine-bell) and 50% overlap. For all sEMG amplitude measures, the sEMG waveform was full-wave rectified and lowpass filtered at 8 Hz (zero-phase-lag FIR) to create a linear envelope, with the lowpass cut-off based on recommendations by Winter (2005). Initial raw values recorded during calibration and two-point conversion were then used to remove baseline noise and convert unfiltered analogue kinematic data to their respective units. For torque data, each 0.0072 V was equivalent to 1 N m (Biodex Medical Systems Inc, 2011). For velocity data, each 0.0098 V was equivalent to 1 deg/s^{-1} (Biodex Medical Systems Inc, 2011). For position, the minimum raw data value was equal to anatomical 0° (full elbow extension), and each 0.0287 V was equivalent to 1° of elbow flexion thereafter (Biodex Medical Systems Inc, 2011). For normalization purposes, the filtered EMG linear envelope and torque-time trace were also normalized to the linear envelope peak (%MVIC) and MVIT (%MVIT) from the 90° MVICs, respectively.

Data extraction and normalization. The start of each EQI was determined using the peak linear envelope value obtained during EQI repetition 1 (EQI 1). With no direct studies for reference, a 20% sEMG amplitude threshold, confirmed with visual inspection (Kamen & Gabriel, 2010), was used to define the start and end of each repetition. The absolute sEMG linear envelope peak (LE $Peak_{ABS}$), relative sEMG linear envelope peak (LE $Peak_{\%MVIC}$), absolute integrated sEMG linear envelope ($iEMG_{ABS}$; V/s), relative integrated sEMG linear envelope ($iEMG_{\%MVIC}$; %MVIC/s), bandpass filtered sEMG mean power frequency (MPF; Hz), absolute angular impulse ($aIMP_{ABS}$; V/s), relative angular impulse ($aIMP_{\%MVIT}$; MVIT/s), TUT (s), and angular velocity (°/s) were then extracted for all EQI repetitions. Both iEMG and aIMP variables were integrated using the rectangular rule. For the purposes of SPM, the normalized LE and absolute elbow angle traces were linearly interpolated in Labchart 8 to 100 data points (0-100% repetition time) using node-based sampling, and iteratively smoothed with a 5-sample width Guassian filter (Matlab R2021a; The Mathworks Inc., Natick, MA, USA) to produce LE-time and elbow angle-time continua.

General Statistical Procedures

All traditional frequentist statistical analyses were conducted in open-source Jamovi software (v 2.3.21), while all one-dimensional statistical parametric mapping (SPM; Penny et al., 2007) and subsequent statistical procedures were completed within the open-source package (SPM1D v. 0.4; http://www.spm1d.org) for Matlab (R2021a; Matlab R2021a; The Mathworks Inc., Natick, MA, USA).

Primary analysis. To determine if there were sex-differences in absolute and relative sEMG and angular impulse variables, multiple 2 (sex)* 4 (repetition) mixed-factorial ANOVAs with repeated measures on repetition were conducted. Additionally, two-sample t-tests were used to compare sex-differences in descriptive variables. For all ANOVAs, normality, homogeneity of variances, and sphericity were assessed with Shapiro-Wilk's, Levene's and Mauchly's tests, using an alpha of $p < .05$ (Field, 2009; Levene, 1960), respectively. In cases where sphericity was violated, Greenhouse-Geisser corrected values were interpreted (Greenhouse & Geisser, 1959). Outliers were defined as data points outside 1.5x the interquartile range.

Due to participant drop-out, a compromise power analysis (G*Power V. 3.1.9.2), which computes α and power based on effect size, sample size, and β/α error probability ratio (Faul et al., 2007) was calculated. Assuming a β/α = 1 and a non-sphericity correction of 0.8, a power of 86.7% (1- β error probability) was achieved for a large effect size (η_p^2 = 0.14) when α = .132 for a 2(sex)*4(repetition) interaction. As such, ANOVAs were considered significant at $p \leq .132$, with small, medium, and large effect sizes (η_p^2) considered to be .01, .06, and .14, respectively (University of Cambridge, 2021). Significant ANOVAs were followed up with post-hoc pairwise comparisons using conventional Bonferroni corrected *p*-values (.132/6 tests = .022; Field, 2009). For post-hoc pairwise comparisons, 99% confidence intervals (CI) for the mean differences and the effect sizes (Cohen's d) are reported in text for independent and paired-sample t-tests. Cohen's d values of 0.2, 0.5, and 0.8, were used to define small, medium, and large effect sizes, respectively (Cohen, 1988). Variability was expressed as ± standard error (SE) unless otherwise indicated.

Secondary Analysis. One-dimensional SPM (Pataky, 2012) and SnPM (Nichols & Holmes, 2001; Trama et al., 2021) were used to quantify regional specific effects between males and females within LE-time and angle-time continua (i.e., data plotted over time). One-dimensional SPM is a methodology that allows for statistical inferences to be made regarding the spatiotemporal characteristics of data, while minimizing the post-hoc regional focus bias and increased family wise error rate otherwise associated with conducting repeated statistical tests (Pataky, 2012; Pataky et al., 2013). Briefly, one-dimensional SPM calculates a test-statistic (e.g., *t*) at each data point (i.e., time), which forms a test-statistic continuum SPM{t}. For parametric statistical inference, a random field theory (RFT; Adler & Taylor, 2007) based *t*-distribution is used to calculate the critical threshold (t^*) for the continua at a given α (Pataky, 2012; Pataky et al., 2015; Robinson et al., 2015). Traditional parametric statistical inference is then then used to determine the probability (*p*) that the SPM{t} would cross t^* and produce a supra threshold region as wide as that which might be observed in an equally smoothed residual (random) continua (Pataky, 2012). For non-parametric statistical inference, permutations, rather than RFT, are used to create a test statistic distribution (Holmes et al., 1996; Nichols & Holmes, 2001; Trama et al., 2021). Both parametric and non-parametric inferences from SPM have been validated for 1D kinematic and EMG data (Pataky et al., 2015, 2019; Penny et al., 2007; Robinson et al., 2015). Current post-hoc procedures in SPM1D, however, have yet to be validated.

As post-hoc procedures in SPM1D have not been shown to be valid, multiple t-tests (between-subjects, two-tailed) were conducted within each EQI repetition to compare LE-time and angle-time continua between males and females. The critical threshold for all tests was determined for a Bonferroni corrected *p*-value of .008 (.05/6 tests). The null hypothesis was rejected if the SPM{t} value crossed the critical threshold at any point, and *p*-values for supra-threshold clusters were calculated and interpreted as described above. Furthermore, as SPM uses frequentist statistics, the traditional assumptions of parametric statistical inference applied. The assumption of normality was tested within SPM1D using the D'agostino-Pearson K^2 test (D'agostino & Belanger, 1990). Given the unequal group sizes, lack of explicit equality of variance test within SPM1D, and exploratory nature of the work, non-parametric inference (two-tailed, 1000 iterations) was also conducted using procedures based on Nichols and Holmes (2001), and compared with parametric results. As a follow-up analysis, data were then collapsed between sexes and compared repetition-by- repetition (paired-samples; two-tailed) as per Oranchuk et al. (2021). It should be noted, however, that this approach has yet to be validated.

Results

Descriptive Characteristics

In total, 32 participants were recruited and/or completed the protocol; one participant was screened out of the study based on their Get-Active Questionnaire responses, while 6 did not complete the protocol due to reasons unrelated to the study (injury, drop-out). Due to technical difficulties, one male participant's data was completely excluded, and in two instances, data were replaced with the average value from the EQI repetition before and after. For repetition-by-repetition SPM and SnPM analysis, these participants were removed from all comparisons. Subsequently, 13 males (sex assigned at birth; age: 25.1 ± 1.2 years, height 178.2 ± 1.8 cm, weight 83 ± 3.5 kg, skeletal muscle mass: 40.5 ± 1.4 kg, %bodyfat 16.8 ± 1.7%) and 12 females (sex assigned at birth; age: 24.7 ± 1.1 years, height 165.3 ± 1.8 cm, weight 66.4 ± 2.6 kg, skeletal muscle mass: 27.5 ± 0.8 kg, %bodyfat 25.1 ± 1.4%) were included in the statistical analysis. sEMG SNR (20log;Delsys, 2020) for each participant ranged from 1.25-2.17. Absolute kinetic and kinematic characteristics of the EQI protocol, and between sex differences are presented in Table 1.

Table 1. MVIC and EQI Protocol Characteristics.

	Mean ± SE		Range		Mean Difference
Sex (13 M, 12 F)	M	F	M	F	M - F
MVIT (Nm)	81.3 (4.76)	38.3 (2.38)	58.7-107	22.8-50.5	43*
Load (Nm)	42.2 (2.28)	20.5 (1.23)	31.7-55.3	13.4-26.5	21.64*
Velocity (°/s)	3.81 (0.85)	2.79 (0.58)	1.02-13.5	0.92-6.65	1.01
TUT EQI 1 (sec)	54.68 (6.57)	64.55 (9.99)	13.53-93.1	16.86-128.3	-9.87
TUT EQI 2 (sec)	40.8 (3.90)	51.35 (8.23)	8.79-57.66	19.1-98.72	-10.55
TUT EQI 3 (sec)	33.64 (3.28)	44.34 (5.73)	7.38-47.45	20.23-76.5	-10.7
TUT EQI 4 (sec)	29.31 (3.30)	40.36 (6.20)	8.23-47.94	10.23-82.94	-11.06

MVIT = maximum voluntary isometric torque during the 90° MVICs. Load = absolute eccentric load during EQI repetitions. TUT = time under tension. Load and velocity data are the average of all 4 EQI repetitions. * Significant ($p < .001$) difference between males and females (independent t-tests).

As expected, male participants displayed greater absolute strength (MVIT) than female participants (81.3 vs. 38.3 Nm), $t(23) = 7.87$, $p < .001$, Cohen's d = 3.15, 99% CI : 27.67 to 58.33. As a result, males performed the EQIs with a greater (42.2 vs. 20.5 Nm) absolute load. On average, EQIs were performed with a relative load of 52.1 ± 0.5 %MVIT for males, and 53.8 ± 0.6 %MVIT for females, which represents a small, but statistically significant difference between groups $t(23) = -2.15$, $p = .042$, Cohen's d = -0.86, 99% CI: -3.96 to 0.526) at $\alpha = .05$.

ANOVAS

There was a significant main effect of sex ($p < .001$ to $p = .015$) for all absolute variables (LE $Peak_{ABS}$, MPF, $iEMG_{ABS}$, $aIMP_{ABS}$) with large effect sizes ($\eta_p^2 = .23$ to $\eta_p^2 = .41$). However, there was no main effect of sex for any relative variables (LE $Peak_{\%MVIC}$, $iEMG_{\%MVIC}$, and $aIMP_{\%MVIT}$). There was also a significant ($p < .132$) main effect of repetition ($p < .001$) for MPF, $iEMG_{ABS}$, $aIMP_{ABS}$, $iEMG_{\%MVIC}$, and $aIMP_{\%MVIT}$ with large effect sizes (η_p^2 .32 to .58). Furthermore, there was a significant ($p < .132$) repetition*sex interaction effect ($p = .015$) for aIMP$_{ABS}$ with a large effect size ($\eta_p^2 = 0.15$). Two-way ANOVA results are presented in Supplementary Table 1.

Post-hoc Comparisons

Absolute Variables. Mean differences, effect sizes, and 99% confidence intervals are presented in Supplementary Table 2.

Across repetitions, LE Peak$_{ABS}$ was 0.43 V ± 0.11 (99% CI: 0.13 to 0.73; ES = 1.59, 99% CI: 0.26 to 2.91) higher in males compared to females; however, there was no main effect of repetition or interaction effect ($p > .132$; Figure 1a.).

With medium-large effect sizes, MPF during EQI 1 was significantly less than MPF during EQI 2 ($p < .001$, Cohen's d = -0.78), EQI 3 ($p = .001$, Cohen's d = -0.75), and EQI 4 ($p < .001$, Cohen's d = -1.55). Additionally, during EQI 2, MPF was significantly less than EQI 4 ($p = .013$, Cohen's d = -0.53) (Figure 1b.). Across all repetitions, MPF for males was 26.78 ± 7.82 Hz (99% CI: 4.83 to 48.73, $p = .002$; Cohen's d = 1.37, 99% CI: 0.11 to 2.61) higher than females (Figure 1b.).

iEMG$_{ABS}$ during EQI 1 was significantly, and with a medium-large effect sizes greater than EQI 2 ($p = .012$, Cohen's d = 0.55), EQI 3 ($p = .001$, Cohen's d = 0.75) and EQI 4 ($p < .001$, Cohen's d = 0.77). iEMG$_{ABS}$ for EQI 2 was also significantly greater than EQI 4 ($p = .005$; Cohen's d = 0.61). There was also a main effect of sex, with males displaying greater iEMG$_{ABS}$ across repetitions (7.13 ± 2.72 V/s, 99% CI: -0.51 to 14.78, $p = .015$; ES = 1.05, 99% CI: -0.13 to 2.20) (Figure 1c.).

For the aIMP$_{ABS}$ repetition*sex interaction, simple main effects analysis indicated that males and females were significantly ($p < .138$) different from each other during EQI 1 ($p = .012$), EQI 2 ($p = .007$), and EQI 3 ($p = .011$), but not EQI 4 ($p = .480$), with males having larger aIMP$_{ABS}$ values during EQI 1 (975.74 ± 357.26, 99% CI: -27.20 to 1978.69; Cohen's d = 1.09, 99% CI: -0.010 to 2.26), EQI 2 (676.84 ± 226.43, 99% CI: 41.17 to 1312.51; Cohen's d = 1.20, 99% CI: -0.02 to 2.39), and EQI 3 (501.45 ± 181.33, 99% CI: -7.61 to 1010.50; Cohen's d = 1.11, 99% CI: -0.09 to 2.28). For males, all pairwise comparisons between repetitions were significantly ($p < .022$) different from each other ($p = .006$ to $p < .001$). For females, however, significant ($p < .022$) and large differences were only present relative to EQI 1, which produced greater aIMP$_{ABS}$ than EQI 2 (279.56 ± 77.38, 99% CI: 39.21 to 519.90, $p = .004$; Cohen's d = 1.04, 99% CI: 0.01 to 1.97), EQI 3 (403.23 ± 123.76, 99% CI: 18.85 to 787.60, $p = .008$; Cohen's d = 0.94, 99% CI: 0.03 to 1.83), and EQI 4 (480.34 ± 132.83, 99% CI: 67.80 to 892.87, $p = .004$; Cohen's d = 1.04, 99% CI: 0.010 to 1.97) (Figure 1d.).

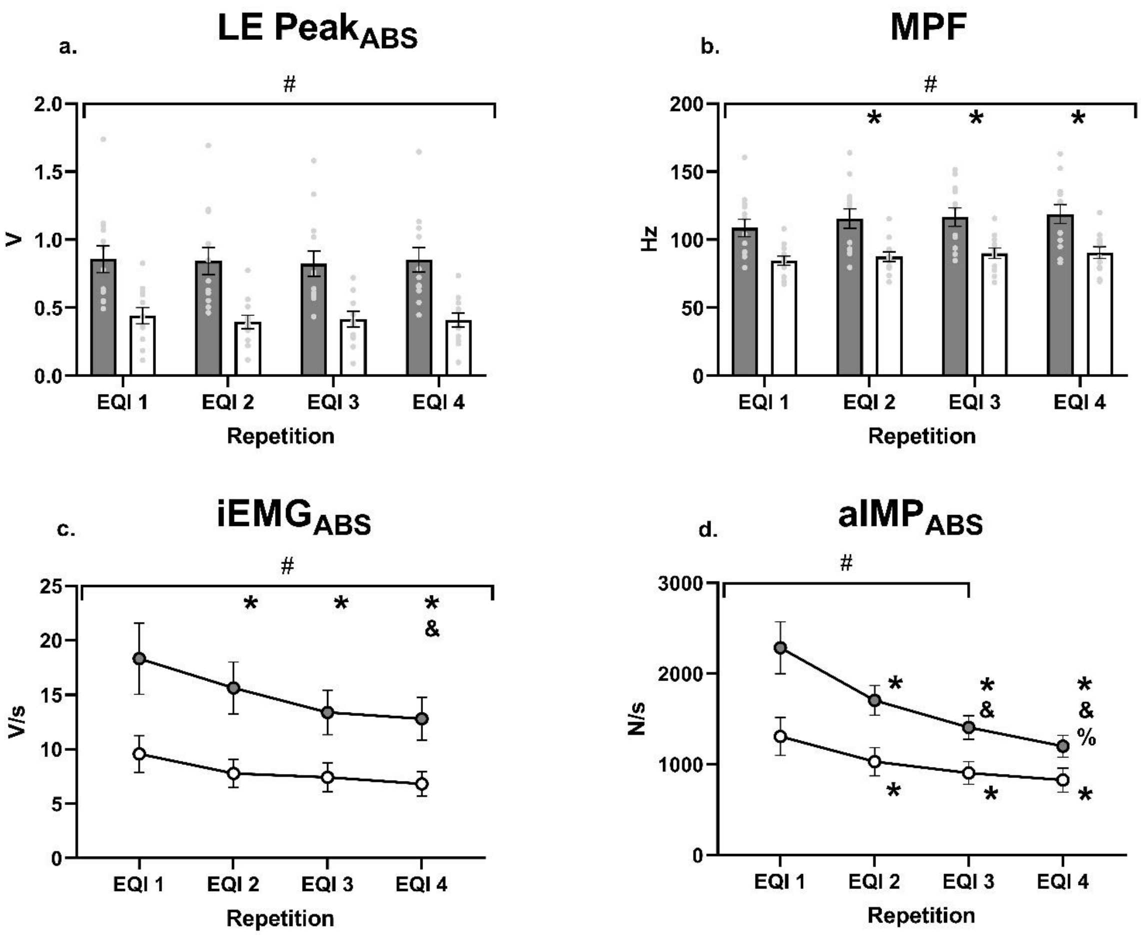

Figure 1. Group and Repetition Means for Absolute EMG and Kinetic Variables. Grey = males, white = females. Error bars denote standard error of the mean. Grey dots indicate individual data points. a.) absolute linear envelope peak (LE Peak$_{ABS}$), b.) Mean power frequency (MPF), c.) absolute integrated surface EMG (iEMG$_{ABS}$), d.) absolute angular impulse (aIMP$_{ABS}$) # = significant ($p < .132$) main effect of sex. ⋆ = significantly ($p < .022$) different from EQI 1. & = significantly ($p = .022$) different from EQI 2. % = significantly ($p < .022$) different from EQI 3. V = volts, Hz = hertz, V/s = volt-seconds, N/s = newton-seconds.

Relative Variables. Mean differences, effect sizes, and 99% confidence intervals are presented in Supplementary Table 2.

For LE$_{PEAK}$, there was no main effect for EQI repetition or sex, and there was no repetition*sex interaction ($p > .132$). With medium-large effect sizes, iEMG$_{\%MVIC}$ during EQI 1 was significantly greater than iEMG$_{\%MVIC}$ for EQI 2 ($p = .006$, Cohen's d = 0.61), EQI 3 ($p < .001$;

Cohen's d = 0.81), and EQI 4 (p < .001, Cohen's d = 0.78). Between repetition comparisons are presented in Figure 2.

With large effect sizes, $aIMP_{\%MVIT}$ during EQI 1 was significantly greater than EQI 2 (p < .001, Cohen's d = 1.08), EQI 3 (p <.001, Cohen's d = 1.20), and EQI 4 (p < .001, Cohen's d = 1.33). With medium-large effect sizes, $aIMP_{\%MVIT}$ was also significantly greater during EQI 2 than EQI 3 (p = .003, Cohen's d = 0.65), and EQI 4 (p < .001, Cohen's d = 0.93), while aIMP for EQI 3 was significantly and with a large effect size greater than EQI 4 (p < .001, Cohen's d = 0.91). Between repetition comparisons are presented in Figure 2b.

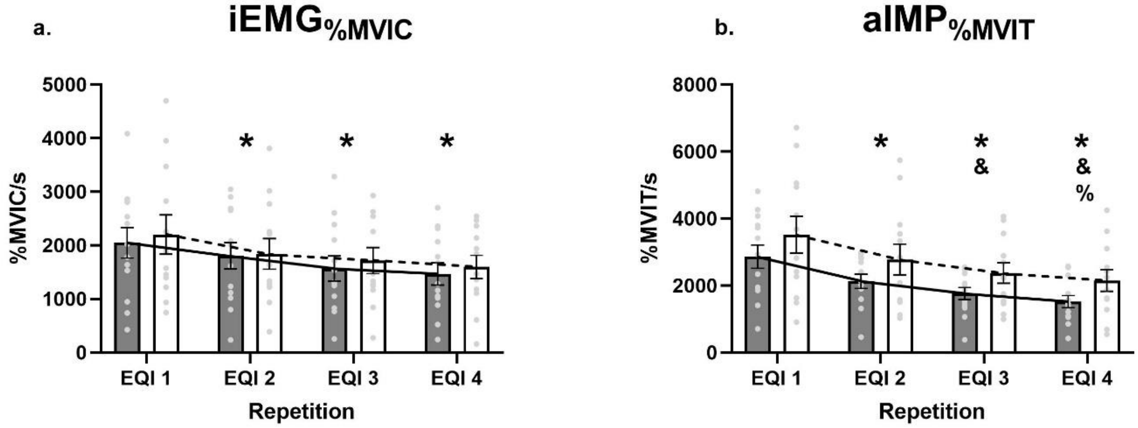

Figure 2. Group and Repetition Means for Relative EMG and Kinetic Variables. Grey = males, white = females. Error bars denote standard error of the mean. Grey dots indicate individual data points. a.) relative integrated surface EMG ($iEMG_{\%MVIC}$), b.) relative angular impulse ($aIMP_{\%MVIT}$). ⋆ = significantly (p < .022) different from EQI 1. & = significantly (p = .022) different from EQI 2. % = significantly (p < .022) different from EQI 3. %MVIC/s = percent of maximum voluntary isometric contraction-seconds. %MVIT = percent of maximum voluntary isometric torque-seconds.

Statistical Parametric and Non-Parametric Mapping

Sex-Differences. Data for LE-time were normally distributed for all repetitions. Angle-time data (df = 1,2) for EQI 2 was not normally distributed, forming one suprathreshold clusters that exceeded the critical threshold (X^2 = 10.013) from 48%-62% (p =. 023), as was angle-time data for EQI 3, forming 2 suprathreshold clusters that exceeded the critical threshold (X^2 = 10.107) from 4%-12% (p =. 037), and 44%-79% (p < .001) of repetition time. For both LE-time and angle-time, the critical threshold was not exceed at any point for EQI 1, EQI 2, EQI 3, or EQI

4, and both parametric and non-parametric inference were in agreement. Therefore, there were no significant differences at any time point between males and females for each EQI repetition.

Repetition Differences. When male and female data were collapsed for repetition-by-repetition comparisons, angle-time data were not normally distributed, except for EQI 2 vs. EQI 4. For LE-time data, EQI 2 vs EQI 3, EQI 2 vs. EQI 4, and EQI 3 vs. EQI 4 were normally distributed.

In multiple cases, parametric and non-parametric were not in agreement for angle-time data. Specifically, parametric inference revealed one suprathreshold cluster from 8%-11% of repetition time for EQI 1 vs. EQI 4. However, nonparametric inference resulted in 3 instances where the critical threshold was exceeded, creating suprathreshold clusters from 6%-31%, 61-72%, and 79%-84% of repetition time. Example SnPM comparisons are presented in Figure 3. Angle-time SPM and SnPM results are presented in Supplementary Table 3.

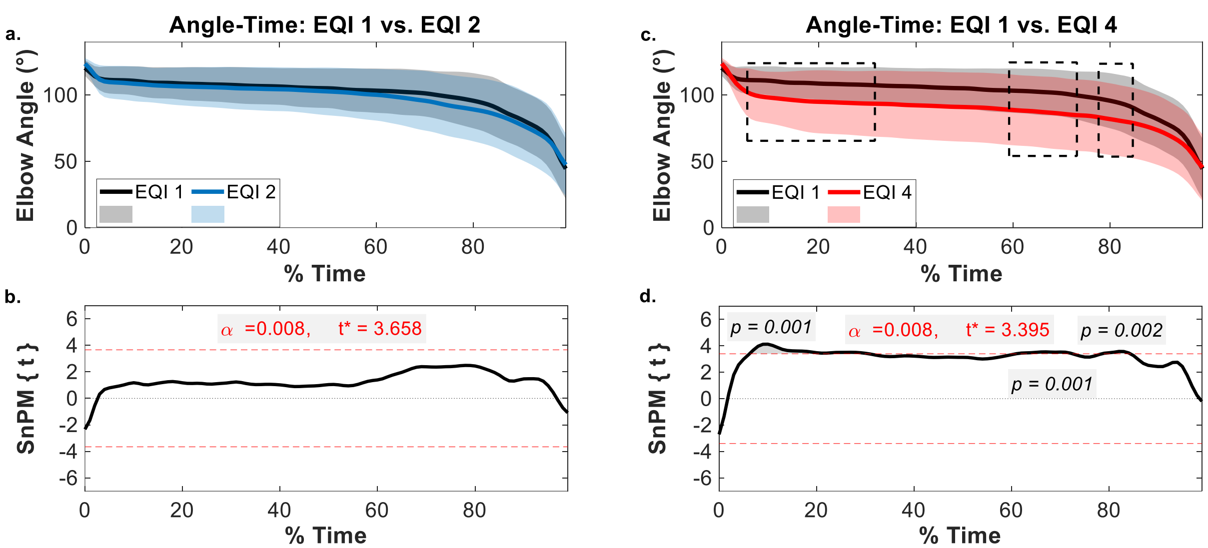

Figure 3. Time normalized elbow angle means, standard deviations, and statistical non-parametric maps (SnPM) for EQI 1 vs EQI 2 (a, b), and EQI 1 vs. EQI 4 (c, d). Top graphs display mean values (solid lines) and standard deviations (shaded areas) at a given time point. Perforated boxes represent suprathreshold clusters imposed on observed data. Bottom graphs display the test statistic (t) continuum ("map"). Perforated red line represents critical threshold (t*).

For LE-time data, EQI 1 vs. EQI 2, and EQI 1 vs. EQI 3 were significantly different using non-parametric inference only. Non-parametric inference resulted in a suprathreshold cluster from 60-61% for EQI 1 vs EQI 2 (Figure 4a, 4b.), and a suprathreshold cluster at 79% for EQI 1 vs. EQI 3. EQI 1 vs. EQI 4, and EQI 2 vs. EQI 4 were significantly different based on parametric and non-parametric inference. For EQI 1 vs. EQI 4, parametric inference resulted in a suprathreshold cluster from 51%-52% and 59%-62%, while non-parametric inference resulted in suprathreshold clusters at 8%, 33%, 47%-52%, and 59%-63% of repetition time (Figure 4c, 4d.). Parametric results for EQI 2 vs. EQI 4 indicated a suprathreshold cluster from 6%-9% and non-parametric inference produced suprathreshold clusters from 6% to 9% and at 29% of repetition time (Supplementary Table 3). All suprathreshold clusters were the result of later repetitions having a greater amplitude than earlier repetitions. Example LE-time SnPM maps are presented in Figure 4.

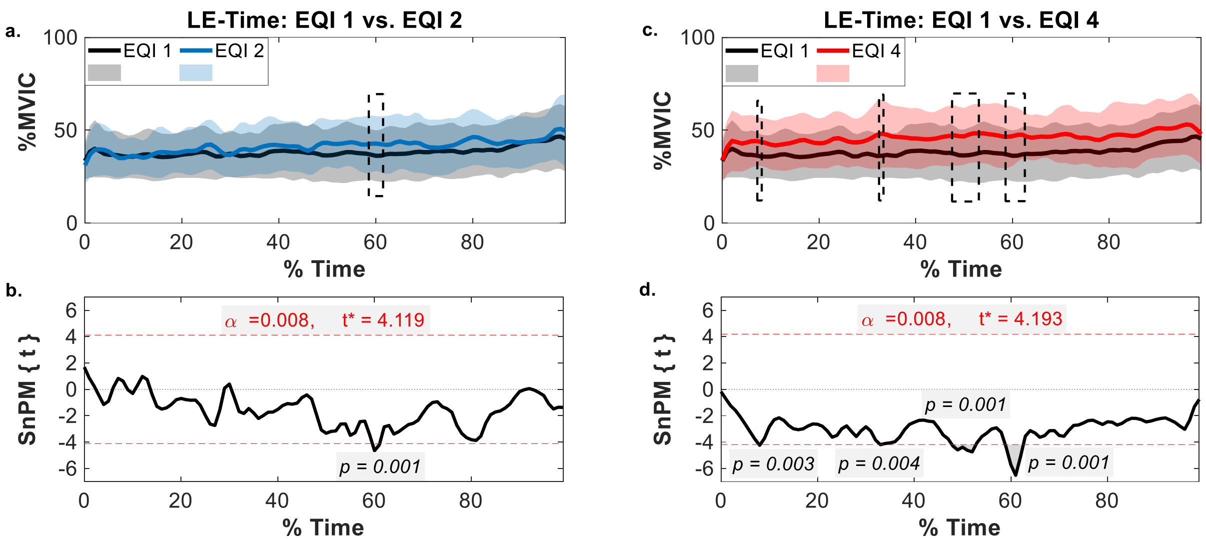

Figure 4. Time normalized linear envelope means, standard deviation, and statistical non-parametric maps (SnPM) for EQI 1 vs EQI 2 (a, b), and EQI 1 vs. EQI 4 (c, d). Top graphs display mean values (solid lines) and standard deviations (shaded areas) at a given time point. Perforated boxes represent suprathreshold clusters imposed on observed data. Bottom graphs display the test statistic (*t*) continuum ("map"). Perforated red line represents critical threshold (*t**).

Discussion

The primary purpose of the current study was to determine if sex-differences existed in the muscle fatigue response during a 4 repetition EQI elbow extension protocol. Specifically, whether differences existed in absolute (LE $Peak_{ABS}$, $iEMG_{ABS}$, MPF, $aIMP_{ABS}$) and relative (LE $Peak_{\%MVIC}$, $iEMG_{\%MVIC}$, and $aIMP_{\%MVIT}$) measures of biceps brachii sEMG and angular impulse between the sexes and across repetitions. There were significant differences with medium-large effects sizes between males and females for all absolute variables, with males having higher LE $Peak_{ABS}$, $iEMG_{ABS}$, MPF, and $aIMP_{ABS}$ than females. When expressed relatively, there were no significant sex differences, although females tended to have higher values for $iEMG_{\%MVIC}$ and $aIMP_{\%MVIT}$. Irrespective of sex, the accrued muscle activity ($iEMG_{ABS}$, $iEMG_{\%MVIC}$), mechanical impulse ($aIMP_{ABS}$, $aIMP_{\%MVIT}$), and MPF significantly decreased across repetitions with a large effect size. There was an interaction between repetition and sex for $aIMP_{ABS}$; males experienced a larger relative drop-off in $aIMP_{ABS}$ across repetitions, to the point where there were no sex-differences in $aIMP_{ABS}$ for the last EQI. When relative data was collapsed between males and females, SPM analysis indicated that both elbow angle-time kinematics and LE-time amplitude characteristics differed from the beginning to the end of the protocol, with EQI 4 generally having larger elbow angles and greater EMG amplitude at a given time than earlier repetitions. Conversely, within-repetition SPM analysis of angle-time kinematics and LE-time amplitude did not elucidate any sex-differences.

Although there are no upper-body EQI studies for comparison, as integrated variables are a product of time and amplitude, the linear decrease in iEMG and aIMP across repetitions is not unexpected, given the concurrent reduction in TUT across the protocol (see Table 1) and typical decreases in volume with isotonic resistance exercise as the number of sets increases (Paz et al., 2017). Similar to our findings, Oranchuk et al. (2021) observed a relatively linear and significant decrease in aIMP from EQI 1 to EQI 4 for an EQI knee-extension/flexion protocol, although the study only included resistance trained males. As the case in the current study, males typically have greater absolute strength, muscle mass, and less adipose tissue compared to females (Janssen et al., 2000), and therefore have greater EMG and torque amplitudes (Farina et al., 2004; Freilich et al., 1995; Kotte et al., 2018). As such, this likely explains the larger $iEMG_{ABS}$ and $aIMP_{ABS}$ values for males. Conversely, females are generally more fatigue resistant than males, and thus would theoretically be able to accrue more TUT. In studies of isometric elbow flexion, women typically exhibit significantly greater absolute times to task failure than men during low-moderate sustained submaximal contractions (Hunter, 2009; Hunter 2014; Hunter 2016b, Hunter 2016c). For example, using the same intensity of the current study (50% MVIT), Avin et al. (2010) observed that females had a significantly greater time to task failure compared to men (112.3 vs 80.3 sec), and generally produced greater relative EMG amplitude values in the elbow flexors and extensors for the entire task. Therefore, it was assumed for the current study that females would have greater TUT and relative EMG amplitude, which would result in larger integrated absolute and relative values for iEMG and aIMP. Indeed, the lack of significant sex-differences for $iEMG_{\%MVIC}$ and $aIMP_{\%MVIT}$ is surprising, given that TUT for females was between 18% (EQI 1) and 38% (EQI 4) longer than males. That being said, there was substantial variability in the female data relative to male participants for both $iEMG_{ABS}$ and $aIMP_{ABS}$, with the 99% CI of the difference crossing 0, which can be reflected in the lack of statistical significance.

Despite a lack of statistical significance, potential sex-differences in relative aIMP when performing EQIs is difficult to ignore. Cumulatively, total $aIMP_{MVIT}$ across the protocol was 31% less in male participants, which represents a meaningful difference in volume when considering that even small (<10%) relative increases in weekly set-volume are associated with significant increases in muscle size (Schoenfeld et al., 2017). Thus, given the importance of mechanical tension and exercise volume for stimulating muscle hypertrophy, it seems reasonable to suggest that if potential volume and TUT differences were compounded over the course of a training program, that detectable sex-differences in muscle hypertrophy may be elucidated. Even at higher intensities than the current study, females still maintain a performance advantage in time to task failure when examining the elbow flexors using sustained isometric muscle actions at higher intensities (Hunter, 2014), and therefore would still theoretically accrue more TUT. With that stated, proximity to volitional fatigue or task failure appears to be more relevant than intensity for stimulating muscle hypertrophy, while intensity is relevant for strength adaptations (Lixandrão et al., 2018; Schoenfeld, Grgic, et al., 2017). Given the proposed use of EQIs when high-velocity muscle actions are not tolerated (Oranchuk et al., 2019), further research may want to compare different intensities of EQIs with respect to muscle hypertrophy and strength adaptations.

The interaction effect for $aIMP_{ABS}$ poses some intriguing questions regarding the development of fatigue across multiple EQIs. For males, $aIMP_{ABS}$ was significantly less than the preceding repetition across the entire protocol, whereas in females, EQI 2, EQI 3, and EQI 4 were only significantly less than EQI 1. Coupled with the lack of significant sex-differences during EQI 4, this suggests that females better maintain performance across EQI elbow extension repetitions, while males experience a substantial decline in performance with successive repetitions, to the point where $aIMP_{ABS}$ is equal to females during EQI 4. When examining the LE $Peak_{ABS}$ and MPF data, however, males and females experienced similar effects across repetitions, which may suggest that mechanical or metabolic factors play a larger role than neuromuscular factors in the development of muscle fatigue during an EQI elbow extension protocol. Indeed, other researchers have attributed sex-differences in isometric and dynamic tasks to be more likely the result of metabolic and contractile differences between males and females (Hunter et al., 2006; Wüst et al., 2008). Given the lack of sex-differences in relative voluntary muscle excitation, the present study seems to support this assertation.

As there were no sex-differences for angle-time kinematics, and LE-time amplitude characteristics within each EQI repetition, data were collapsed across sexes for exploratory SPM and SnPM analysis, and compared repetition by repetition as per Oranchuk et al. (2021). Although Oranchuk et al. (2021) did not observe significant differences from EQI 1 to EQI 4, initial changes in knee angle tended to occur more quickly after successive repetitions, with EQI 4 generally exhibiting greater displacement (i.e., larger joint angles) at the beginning of the repetition than EQI 1. Using an almost identical protocol, Oranchuk et al. (2020) observed that the majority of eccentric angular impulse was accumulated in the first half of the EQI ROM across all 4 repetitions. When considering the angle-time kinematic data of the current study, the results suggest a similar pattern and accumulation of fatigue. While there were discrepancies between parametric and non-parametric results, both indicated that EQI 4 had significantly smaller elbow angles within the first one-third of repetition time. As with Oranchuk et al. (2021), this suggests that initial changes in muscle length and joint angle during EQI elbow extension also occur more quickly as fatigue accumulates. Visually, however, these differences appear to remain stable through the majority of the ROM. That being said, it should be noted that performing repeated statistical tests in this manner has not been validated for SPM, and thus the results of the repetition-by-repetition comparisons of Oranchuk et al., (2021) and the current study should be interpreted with caution.

In line with the aforementioned kinematic and kinetic data, the LE-time data from the current study supports a greater fatigue response in the first two-thirds of the EQI ROM as the number of EQI repetitions increases. Significant increases in EMG amplitude from EQI 1 to EQI 4 were only observed in the first two-thirds of repetition time and ROM. During sustained isometric muscle actions, EMG amplitude is known to increase, presumably due to increases in motor unit recruitment (Kamen & Gabriel, 2010). While the current methods are unable to elucidate specific motor unit behaviours or recruitment strategies, this observation suggests that motor unit recruitment is more relevant than mechanical factors for maintaining force output during EQIs at short-medium muscle lengths (i.e., greater elbow flexion). When considering the traditional isometric length-tension relationship, the passive structures of an elongated muscle will contribute more substantially than the active structures to muscular tension (Abbott & Wilkie, 1953; Hamill, 2015). Thus, at longer-muscle lengths (i.e., last third of the ROM), it is logical that EQIs would be less reliant on motor unit recruitment and resulting active tension to maintain force output, even in a non-fatigued state. Although the current study was not designed to compare EQI motor unit recruitment patterns relative to traditional resistance exercise, sEMG analysis would not seem to point to an inherent advantage of EQIs for increasing motor unit recruitment when considering studies of sustained isometric elbow flexion (Avin et al., 2010; Bazzucchi et al., 2004; Hunter et al., 2004; Rudroff et al., 2011), although this assumption needs to be tested with future experimental or quasi-experimental research.

Limitations of the current study that are relevant to its interpretation, and the direction of future studies must be considered. Namely, the use of the isokinetic dynamometer to perform the EQI protocol does not resemble real world applications, as the torque generated during an elbow flexion exercise will vary through the movement with the use of dumbbells, cables, or resistance bands, whereas constant torque is provided by the isokinetic dynamometer through the ROM. Additionally, the initial decrease in elbow angle may have been due to participants not producing enough "pre-activation" prior to the dynamometer applying torque, resulting in a larger and immediate change in elbow angle before participants were able to meet the applied torque, which would not be relevant in applied contexts Participants were aware that they would be performing 4 EQI repetitions, which may have resulted in participants pacing themselves and not performing all repetitions to volitional fatigue. With respect to sEMG, the innervation zone was not identified prior to placement of the electrode array. As such, when the biceps brachii lengthened, it is possible that the innervation zone would have moved underneath the electrode, which would have altered the EMG amplitude characteristics independent of physiological effects. As a result, we elected to take a more traditional bi-polar approach to sEMG, in line with SENIAM guidelines (www.seniam.org), which reduced the representative surface area of the sEMG data.

Application

Given recent reviews (Pallarés et al., 2021; Schoenfeld & Grgic, 2020) that suggest emphasizing longer muscle lengths during resistance exercise may have equivalent hypertrophic outcomes as resistance exercise using a full ROM, Oranchuk et al. (2021) proposed that EQIs could be performed with a smaller ROM, which would increase TUT at longer muscle lengths. Based on Oranchuk et al. (2021) and the current study, this would also be a logical suggestion, as results from both studies suggest muscle fatigue increases the relative time spent at longer muscle lengths due to fatigue at short muscle lengths, but decreases overall TUT. Despite females having discernably greater TUT and relative aIMP, the current study suggests that males and females have similar relative fatigue response to moderate intensity EQI elbow extensions. When designing or implementing training programs, practitioners and trainees should also consider the possibility that males may have substantial drop-off in performance following a single EQI, whereas females may be able to maintain performance with subsequent sets. Furthermore, although significant, changes in sEMG amplitude between repetitions and during repetitions appear to be unremarkable, suggesting that EQIs may require several repetitions to meaningfully increase motor unit recruitment. As such, practitioners and trainees should also strongly consider the specificity and relevance of EQIs to training goals, and whether these goals can be accomplished with more traditional resistance exercise methods.

Conclusion

The current study suggests that, while there are acute absolute sex-differences in sEMG and aIMP across 3 EQI elbow extension repetitions, there is no sex-difference in absolute aIMP during repetition 4. Furthermore, these differences are largely negated when expressed relatively. Although there were discernable differences in TUT and relative aIMP between males and females, these differences were not statistically significant. Exploratory analysis suggests that the accumulation of muscle fatigue predominately manifests at short-medium muscle lengths. It is unclear whether acute sex-differences would emerge in sEMG or aIMP with differing intensities, ROM, or tasks, and whether or not EQI resistant exercise results in unique neuromuscular responses relative to traditional resistance exercise.

Contributions

ZJH, TDS, and SMC contributed to conception and design. ZJH and SW contributed to acquisition of data. ZJH and TDS contributed to analysis and interpretation of data.
ZJH, TDS, SW, SMC drafted, evaluated, and revised the article.

Funding information

The work was funded in part by the University of Manitoba Research Grants Program (URGP). ZJH was supported by a National Sciences and Engineering Research Council of Canada Graduate Scholarship (CGS-D).

Conflict of interest:

The authors declare no competing interests.

Data and supplementary material accessibility

Data will be made available upon reasonable request and institutional ethics approval.

References

Abbott, B. C., & Wilkie, D. R. (1953). The relation between velocity of shortening and the tension-length curve of skeletal muscle. *The Journal of Physiology*, *120*(1–2), 214–223. https://doi.org/10.1113/jphysiol.1953.sp004886

Adler, R. J., & Taylor, J. E. (2007). *Random fields and geometry*. Springer Science + Business Media LLC.

Avin, K. G., Naughton, M. R., Ford, B. W., Moore, H. E., Monitto-Webber, M. N., Stark, A. M., Gentile, A. J., & Law, L. A. F. (2010). Sex differences in fatigue resistance are muscle group dependent. *Medicine and Science in Sports and Exercise*, *42*(10), 1943–1950. https://doi.org/10.1249/MSS.0b013e3181d8f8fa

Barbero, M., Merletti, R., & Rainoldi, A. (2012). *Atlas of Muscle Innervation Zones Understanding Surface Electromyography and Its Applications*. Springer.

Bazzucchi, I., Felici, F., Macaluso, A., & De Vito, G. (2004). Differences between young and older women in maximal force, force fluctuations, and surface EMG during isometric knee extension and elbow flexion. *Muscle and Nerve*, *30*(5), 626–635. https://doi.org/10.1002/mus.20151

Canadian Society for Exercise Physiology. (2017). *Pre-Screening for Physical Activity: Get Active Questionnaire*. https://csep.ca/2021/01/20/pre-screening-for-physical-activity/

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics*, *24*(4), 327–340. https://doi.org/10.1016/j.clinbiomech.2009.01.010

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Lawrence Erlbaum Associates.

D'agostino, R. B., & Belanger, A. (1990). A Suggestion for Using Powerful and Informative Tests of Normality. *The American Statistician* , *44*(4), 316–321.

Delsys. (2020). *How does one verify the quality of an EMG signal?* https://delsys.com/faq-items/how-does-one-verify-the-quality-of-an-emg-signal/#:~:text=The formal signal-to-noise,SNR %3D 65dB

Farina, D., Merletti, R., & Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, *96*, 1486–1495. https://doi.org/10.1152/japplphysiol.01070.2003.-This

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191.

Field, A. (2009). *Discovering Statistics Using SPSS* (3rd ed.).

Freilich, R. J., Kirsner, R. L. G., & Byrne, E. (1995). Isometric strength and thickness relationships in human quadriceps muscle. *Neuromuscular Disorders*, *5*(5), 415–422.

Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, *24*, 95–112.

Hamill, J. , K. K. M. , & D. T. R. (2015). *Biomechanical basis of human movement* (4th ed.). Wolters Kluwer.

Hicks, A. L., Kent-Braun, J., & Ditor, D. S. (2001). Sex differences in human skeletal muscle fatigue. *Exercise and Sport Sciences Reviews*, *29*(3), 109–112. https://doi.org/10.1097/00003677-200107000-00004

Holmes, A. P., Blair, R. C., Watson, H. D. G., & Ford, I. (1996). Nonparametric analysis of statistic images from functional mapping experiments. *Journal of Cerebral Blood Flow and Metabolism*, *16*, 7–22.

Hunter, S. K. (2009). Sex differences and mechanisms of task-specific muscle fatigue. *Exercise and Sport Sciences Reviews*, *37*(3), 113–122. https://doi.org/10.1097/JES.0b013e3181aa63e2.Sex

Hunter, S. K. (2014). Sex differences in human fatigability: Mechanisms and insight to physiological responses. *Acta Physiologica*, *210*(4), 768–789. https://doi.org/10.1111/apha.12234

Hunter, S. K. (2016a). Sex differences in fatigability of dynamic contractions. *Experimental Physiology*, *101*(2), 250–255. https://doi.org/10.1113/EP085370

Hunter, S. K. (2016b). The relevance of sex differences in performance fatigability. *Medicine and Science in Sports and Exercise*, *48*(11), 2247–2256. https://doi.org/10.1249/MSS.0000000000000928

Hunter, S. K. (2016c). The relevance of sex differences in performance fatigability. *Physiology & Behavior*, *48*(11), 2247–2256. https://doi.org/10.1249/MSS.0000000000000928.The

Hunter, S. K., Butler, J. E., Todd, G., Gandevia, S. C., & Taylor, J. L. (2006). Supraspinal fatigue does not explain the sex difference in muscle fatigue of maximal contractions. *Journal of*

Applied Physiology, *101*, 1036–1044. https://doi.org/10.1152/japplphysiol.00103.2006.-Young

Hunter, S. K., Critchlow, A., Shin, I.-S., & Enoka, R. M. (2004). Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength. *Journal of Applied Physiology*, *96*(1), 195–202. https://doi.org/10.1152/japplphysiol.00893.2003

Janssen, I., Heymsfield, S. B., Wang, Z., & Ross, R. (2000). Skeletal muscle mass and distribution in 468 men and women aged 18-88 yr. *Journal of Applied Physiology*, *89*, 81–88. http://www.jap.org

Kamen, G., & Gabriel, D. A. (2010). *Essentials of Electromyography*. Human Kinetics.

Kotte, S. H. P., Viveen, J., Koenraadt, K. L. M., The, B., & Eygendaal, D. (2018). Normative values of isometric elbow strength in healthy adults: a systematic review. *Shoulder and Elbow*, *10*(3), 207–215. https://doi.org/10.1177/1758573217748643

Levene, H. (1960). Robust tests for equality of variances. In I. Olkin, S. G. Ghurye, W. Hoeffding, W. G. Madow, & H. B. Mann (Eds.), *Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*.

Lim, C., Nunes, E. A., Currier, B. S., McLeod, J. C., Thomas, A. C. Q., & Phillips, S. M. (2022). An evidence-based narrative review of mechanisms of resistance exercise-induced human skeletal muscle hypertrophy. *Medicine and Science in Sports and Exercise*, *54*(9), 1546–1559. https://doi.org/10.1249/MSS.0000000000002929

Lixandrão, M. E., Ugrinowitsch, C., Berton, R., Vechin, F. C., Conceição, M. S., Damas, F., Libardi, C. A., & Roschel, H. (2018). Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: A systematic review and meta-analysis. *Sports Medicine*, *48*(2), 361–378. https://doi.org/10.1007/s40279-017-0795-y

Lulic-Kuryllo, T., & Inglis, J. G. (2022). Sex differences in motor unit behaviour: A review. *Journal of Electromyography and Kinesiology*, *66*. https://doi.org/10.1016/j.jelekin.2022.102689

Lulic-Kuryllo, T., Thompson, C. K., Jiang, N., Negro, F., & Dickerson, C. R. (2021). Neural control of the healthy pectoralis major from low-to-moderate isometric contractions. *Journal of Neurophysiology*, *126*(1), 213–226. https://doi.org/10.1152/jn.00046.2021

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology*, *116*(6), 1091–1116. https://doi.org/10.1007/s00421-016-3346-6

Morrison, N. (2016). *The Russian Training Secret*. https://www.t-nation.com/training/qi-the-russian-training-secret/

Nichols, T. E., & Holmes, A. P. (2001). *Nonparametric Permutation Tests For Functional Neuroimaging: A Primer with Examples*.

Nishikawa, Y., Watanabe, K., Takahashi, T., Hosomi, N., Orita, N., Mikami, Y., Maruyama, H., Kimura, H., & Matsumoto, M. (2017). Sex differences in variances of multi-channel surface electromyography distribution of the vastus lateralis muscle during isometric knee extension in young adults. *European Journal of Applied Physiology*, *117*(3), 583–589. https://doi.org/10.1007/s00421-017-3559-3

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(97–113).

Oranchuk, D. J., Diewald, S. N., McGrath, J. W., Nelson, A. R., Storey, A. G., & Cronin, J. B. (2021). Kinetic and kinematic profile of eccentric quasi-isometric loading. *Sports Biomechanics*, *00*(00), 1–14. https://doi.org/10.1080/14763141.2021.1890198

Oranchuk, D. J., Nelson, A. R., Storey, A. G., Diewald, S. N., & Cronin, J. B. (2020). Short-term neuromuscular, morphological, and architectural responses to eccentric quasi-isometric muscle actions. *European Journal of Applied Physiology*, *121*, 141–158. https://doi.org/10.1007/s00421-020-04512-4

Oranchuk, D. J., Storey, A. G., Nelson, A. R., & Cronin, J. B. (2019). Scientific basis for eccentric quasi-isometric resistance training: A narrative review. *Journal of Strength and Conditioning Research*, *33*(10), 2846–2859. https://doi.org/10.1519/JSC.0000000000003291

OT Bioelettronica. (2021). *Quattrocento bioelectrical signal amplifier user manual v1.7*.

Pallarés, J. G., Hernández-Belmonte, A., Martínez-Cava, A., Vetrovsky, T., Steffl, M., & Courel-Ibáñez, J. (2021). Effects of range of motion on resistance training adaptations: A systematic review and meta-analysis. *Scandinavian Journal of Medicine and Science in Sports*, *31*(10), 1866–1881. https://doi.org/10.1111/sms.14006

Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(3), 295–301. https://doi.org/10.1080/10255842.2010.527837

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, *46*(14), 2394–2401. https://doi.org/10.1016/j.jbiomech.2013.07.031

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*, *48*(7), 1277–1285. https://doi.org/10.1016/j.jbiomech.2015.02.051

Pataky, T. C., Vanrenterghem, J., Robinson, M. A., & Liebl, D. (2019). On the validity of statistical parametric mapping for nonuniformly and heterogeneously smooth one-dimensional biomechanical data. *Journal of Biomechanics*, *91*, 114–123. https://doi.org/10.1016/j.jbiomech.2019.05.018

Paz, G. A., Robbins, D. W., De Oliveira, C. G., Bottaro, M., & Miranda, H. (2017). Volume load and neuromuscular fatigue during an acute bout of agonist-antagonist paired-set vs. traditional-set training. *Journal of Strength and Conditioning Research*, *31*(10), 2777–2784. www.nsca.com

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2007). *Statistical parametric mapping: The analysis of functional brain images* (1st ed.). Academic Press.

Piervirgili, G., Petracca, F., & Merletti, R. (2014). A new method to assess skin treatments for lowering the impedance and noise of individual gelled Ag-AgCl electrodes. *Physiological Measurement*, *35*(10), 2101–2118. https://doi.org/10.1088/0967-3334/35/10/2101

Pradhan, A., Malagon, G., Lagacy, R., Chester, V., & Kuruganti, U. (2020). Effect of age and sex on strength and spatial electromyography during knee extension. *Journal of Physiological Anthropology*, *39*(1). https://doi.org/10.1186/s40101-020-00219-9

Robinson, M. A., Vanrenterghem, J., & Pataky, T. C. (2015). Statistical Parametric Mapping (SPM) for alpha-based statistical analyses of multi-muscle EMG time-series. *Journal of Electromyography and Kinesiology*, *25*(1), 14–19. https://doi.org/10.1016/j.jelekin.2014.10.018

Rudroff, T., Justice, J. N., Holmes, M. R., Matthews, S. D., & Enoka, R. M. (2011). Muscle activity and time to task failure differ with load compliance and target force for elbow flexor muscles. *J Appl Physiol*, *110*, 125–136. https://doi.org/10.1152/japplphysiol.00605.2010.-The

Schoenfeld, B. J. (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *Journal of Strength and Conditioning Research*, *24*, 2857–2872. www.nsca-jscr.org

Schoenfeld, B. J. (2013). Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Medicine*, *43*(3), 179–194. https://doi.org/10.1007/s40279-013-0017-1

Schoenfeld, B. J., & Grgic, J. (2020). Effects of range of motion on muscle development during resistance training interventions: A systematic review. *SAGE Open Medicine*, *8*. https://doi.org/10.1177/2050312120901559

Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and hypertophy adaptations between low- vs high-load resistance training: A systematic review and meta-analysis. *Journal of Strength and Conditioning Research*, *31*(12), 3508–3523.

Schoenfeld, B. J., Ogborn, D., & Krieger, J. W. (2017). Dose-response relationship between weekly resistance training volume and increases in muscle mass: A systematic review and meta-analysis. *Journal of Sports Sciences*, *35*(11), 1073–1082. https://doi.org/10.1080/02640414.2016.1210197

Seedman, J. (n.d.). *Eccentric Isometrics: The Ultimate Way to Strength Train Part 1*. Retrieved February 14, 2021, from https://www.advancedhumanperformance.com/eccentric-isometrics-the-ultimate-way-to-strength-train-part-1

Sinicki, A. (2019). *Advanced Isometric Training: Ballistic and Quasi Isometrics*. https://www.thebioneer.com/advanced-isometric-training-ballistic-quasi-isometrics/

Staudenmann, D., van Dieën, J. H., Stegeman, D. F., & Enoka, R. M. (2014). Increase in heterogeneity of biceps brachii activation during isometric submaximal fatiguing contractions: A multichannel surface EMG study. *Journal of Neurophysiology*, *111*(5), 984–990. https://doi.org/10.1152/jn.00354.2013

Trama, R., Hautier, C., & Blache, Y. (2021). fctSnPM: Factorial ANOVA and post-hoc tests for Statistical nonParametric Mapping in MATLAB. *Journal of Open Source Software*, *6*(63), 3159. https://doi.org/10.21105/joss.03159

University of Cambridge. (2021, November 30). *Rules of thumb on magnitudes of effect sizes*.

Verkhoshansky, Y. v, & Siff, M. C. (2009). *Supertraining* (6th ed.). Ultimate Athlete Concepts.

Wüst, R. C. I., Morse, C. I., De Haan, A., Jones, D. A., & Degens, H. (2008). Sex differences in contractile properties and fatigue resistance of human skeletal muscle. *Experimental Physiology*, *93*(7), 843–850. https://doi.org/10.1113/expphysiol.2007.041764

Supplementary Tables

Table 1. Two-way Mixed ANOVA Results for Absolute and Relative EMG and Kinetic Variables.

LE $Peak_{ABS}$ = absolute linear envelope peak. MPF = mean power frequency. $iEMG_{ABS}$ = absolute integrated surface EMG., $aIMP_{ABS}$ = absolute angular impulse. LE $Peak_{\%MVIC}$ = relative linear envelope peak. $iEMG_{\%MVIC}$ = relative integrated surface EMG., $aIMP_{\%MVIT}$ = relative angular impulse. df = degrees of freedom. η_p^2 = partial eta squared. Significant *p*-values ($p < .132$) are bolded. # = assumption of sphericity not met, and

Dependent Variable	Comparison	df	*F*	*p*	η_p^2
LE $Peak_{ABS}$#	Repetition	2.28, 52.34	0.58	.586	.02
	Sex	1, 23	15.82	**< .001**	.41
	Repetition ✻ Sex	2.28, 52.34	0.29	.775	.01
MPF	Repetition	3, 69	11.71	**< .001**	.34
	Sex	1, 23	11.73	**.002**	.34
	Repetition ✻ Sex	3, 69	0.93	.429	.04
$iEMG_{ABS}$#	Repetition	1.82, 41.93	10.86	**< .001**	.32
	Sex	1, 23	6.86	**.015**	.23
	Repetition ✻ Sex	1.82, 41.93	1.57	.221	.06
$aIMP_{ABS\#}$	Repetition	1.42, 32.74	28.34	**< .001**	.55
	Sex	1, 23	8.21	**.009**	.26
	Repetition ✻ Sex	1.42, 32.74	4.16	**.037**	.15
LE $Peak_{\%MVIC}$	Repetition	3, 69	0.38	.7695	.02
	Sex	1, 23	0	.9612	0
	Repetition ✻ Sex	3, 69	0.15	.9281	.01
$iEMG_{\%MVIC}$#	Repetition	1.84, 42.28	10.92	**< .001**	.32
	Sex	1, 23	0.11	.738	0
	Repetition ✻ Sex	1.84, 42.28	0.12	.8673	.01
$aIMP_{\%MVIT}$#	Repetition	1.51, 34.66	31.38	**< .001**	.58
	Sex	1, 23	2.1	.161	.08
	Repetition ✻ Sex	1.51, 34.66	0.01	.9734	0

Greenhouse-Geisser degrees of freedom reported.

Table 2. Significant Pairwise Comparisons of Repetition Main Effect.

Dependent Variable	Comparison	Mean Difference (± SE)	Mean Difference 99% CI	*p*	Cohen's d	Effect Size 99% CI
MPF	EQI 1 vs. EQI 2	-4.96 (1.27)	-8.51 to -1.41	< .001	-0.78	-1.37 to -0.19
	EQI 1 vs. EQI 3	-6.75 (1.79)	-11.77 to -1.73	.001	-0.75	-1.33 to -0.16
	EQI 1 vs. EQI 4	-8.13 (1.74)	-13 to -3.26	< .001	-0.93	-1.55 to -0.31
	EQI 2 vs. EQI 4	-3.17 (1.19)	-6.49 to 0.15	.013	-0.53	-1.08 to 0.02
$iEMG_{ABS}$	EQI 1 vs. EQI 2	2.26 (0.83)	-0.06 to 4.58	.012	0.55	-0.01 to 1.09
	EQI 1 vs. EQI 3	3.6 (0.96)	0.9 to 6.291	.001	0.75	0.16 to 1.33
	EQI 1 vs. EQI 4	4.2 (1.1)	1.13 to 7.26	< .001	0.77	0.17 to 1.35
	EQI 2 vs. EQI 4	1.94 (0.63)	0.16 to 3.71	.006	0.61	0.04 to 1.17
$iEMG_{MVIC}$	EQI 1 vs. EQI 2	298.66 (98.34)	23.6 to 573.71	.006	0.61	0.04 to 1.17
	EQI 1 vs. EQI 3	480.75 (118.24)	150.03 to 811.46	< .001	0.81	0.21 to 1.41
	EQI 1 vs. EQI 4	590.29 (151.59)	166.3 to 1014.28	< .001	0.78	0.18 to 1.36
	EQI 2 vs. EQI 4	291.64 (107.09)	-7.9 to 591.17	.012	0.54	-0.01 to 1.09
$aIMP_{MVIT}$	EQI 1 vs. EQI 2	736.97 (136.61)	354.87 to 1119.06	< .001	1.08	0.42 to 1.73
	EQI 1 vs. EQI 3	1120.1 (186.17)	599.38 to 1640.81	< .001	1.2	0.52 to 1.88
	EQI 1 vs. EQI 4	1353.16 (203.55)	783.84 to 1922.48	< .001	1.33	0.62 to 2.04
	EQI 2 vs. EQI 3	383.13 (117.26)	55.16 to 711.11	.003	0.65	0.08 to 1.22
	EQI 2 vs. EQI 4	616.19 (132)	246.98 to 985.4	< .001	0.93	0.31 to 1.55
	EQI 3 vs. EQI 4	233.06 (51.06)	90.25 to 375.87	< .001	0.91	0.29 to 1.52

MPF = mean power frequency. $iEMG_{ABS}$ = Absolute integrated surface EMG. $iEMG_{MVIC}$ = Absolute integrated surface EMG. $aIMP_{MVIT}$ = Relative angular impulse. Significance based on Bonferroni corrected α of .018.

Table 3. Repetition by Repetition SPM vs. SnPM Results.

ANGLE-TIME		Parametric		Non-Parametric	
Comparison	df	t*	Suprathreshold Clusters	t*	Suprathreshold Clusters
EQI 1 vs. EQI 2	1, 23	4.039	*n/a*	3.658	*n/a*
EQI 1 vs. EQI 3	1, 23	4.012	*n/a*	3.697	*n/a*
EQI 1 vs. EQI 4	**1, 23**	**3.997**	**8-11% ($p = .007$)**	**3.395**	**6%-31% ($p < .001$)** **61%-72% ($p < .001$)** **79%-84% ($p = .002$)**
EQI 2 vs. EQI 3	1, 23	4.014	*n/a*	3.598	*n/a*
EQI 2 vs. EQI 4	**1, 23**	**4.017**	***n/a***	**3.625**	**12%-14% ($p = .004$)**
EQI 3 vs. EQI 4	1, 23	4.075	*n/a*	3.728	*n/a*

LE-TIME		Parametric		Non-Parametric	
Comparison	df	t*	Suprathreshold Clusters	t*	Suprathreshold Clusters
EQI 1 vs. EQI 2	**1, 22**	**4.701**	***n/a***	**4.119**	**60%-61% ($p < .001$)**
EQI 1 vs. EQI 3	**1, 22**	**4.611**	***n/a***	**4.02**	**79% ($p = .004$)**
EQI 1 vs. EQI 4	**1, 22**	**4.607**	**51%-52% ($p = .005$)** **59%-62% ($p < .001$)**	**4.193**	**8% ($p = .003$)** **33% ($p = .004$)** **47%-52% ($p < .001$)** **59%-63% ($p < .001$)**
EQI 2 vs. EQI 3	1, 22	4.661	*n/a*	4.345	*n/a*
EQI 2 vs. EQI 4	**1, 22**	**4.662**	**6%-9% ($p < .001$)**	**4.364**	**6%-9% ($p < .001$)** **29% ($p = .003$)**
EQI 3 vs. EQI 4	1, 22	4.699	*n/a*	4.331	*n/a*

Discrepancies between parametric and non-parametric inference are bolded. df = degrees of freedom, t* = critical threshold, n/a = no suprathreshold clusters. Discrepancies between parametric and non-parametric inference are bolded. Significance based on a Bonferroni corrected α of .008.