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Robert W. Smith

Terry J. Housh

Jocelyn E. Arnett

John Paul V. Anders

Tyler J. Neltner

*See next page for additional authors*

## Authors

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Robert W. Smith,[1,3] Terry J. Housh,[1] Jocelyn E. Arnett,[1] John Paul V. Anders,[2] Tyler J. Neltner,[1] Dolores G. Ortega,[1] Richard J. Schmidt,[1] and Glen O. Johnson[1]

1 Exercise Physiology Laboratory, Department of Nutrition and Health Sciences, University of Nebraska-Lincoln, Lincoln, NE 68510, USA
2 The Exercise Science Program, Department of Human Sciences, The Ohio State University, Columbus, OH 43017, USA
3 840 N 14th Street, Lincoln, NE 68508, USA

*Correspondence* — Robert W. Smith, bsmith80@huskers.unl.edu

**Abstract**

**Purpose** The purpose of the present study was to examine the interactions between perceived fatigability and performance fatigability in women and men by utilizing the RPE-Clamp model to assess the fatigue-induced effects of a sustained, isometric forearm flexion task anchored to RPE = 8 on time to task failure (TTF), torque, and neuromuscular responses.

**Methods** Twenty adults (10 men and 10 women) performed two, 3 s forearm flexion maximal voluntary isometric contractions (MVICs) followed by a sustained, isometric forearm flexion task anchored to RPE = 8 using the OMNI-RES (0–10) scale at an elbow joint angle of 100°. Electromyographic amplitude (EMG AMP)

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was recorded from the biceps brachii. Torque and EMG AMP values resulting from the sustained task were normalized to the pretest MVIC. Neuromuscular efficiency was defined as NME = normalized torque/normalized EMG AMP. Mixed factorial ANOVAs and Bonferroni corrected dependent t tests and independent t tests were used to examine differences across time and between sex for torque and neuromuscular parameters.

**Results** There were no differences between the women and men for the fatigue-induced decreases in torque, EMG AMP, or NME, and the mean decreases (collapsed across sex) were 50.3 ± 8.6 to 2.8 ± 2.9% MVIC, 54.7 ± 12.0 to 19.6 ± 5.3% MVIC, and 0.94 ± 0.19 to 0.34 ± 0.16, respectively. Furthermore, there were no differences between the women and men for TTF (251.8 ± 74.1 vs. 258.7 ± 77.9 s).

**Conclusion** The results suggested that the voluntary reductions in torque to maintain RPE and the decreases in NME were likely due to group III/IV afferent feedback from peripheral fatigue that resulted in excitation–contraction coupling failure.

**Keywords** Electromyography, Efficiency, Biceps brachii, Perceived exertion, Sex, Fatigue

**Abbreviations**

| | |
|---|---|
| AMP | Amplitude |
| ANOVA | Analysis of variance |
| EJ | Elbow joint angle |
| EMG | Electromyography |
| MVIC | Maximal voluntary isometric contraction |
| NME | Neuromuscular efficiency |
| OMNI-RES | Omnibus-resistance exercise scale |
| RPE | Ratings of perceived exertion |
| TTF | Time to task failure |

## Introduction

The ratings of perceived exertion (RPE) scale was originally developed to provide clinicians and researchers with a simple and reliable method to quantify the individual's perception of exercise intensity during aerobic exercise (Borg and Dahlstrom 1962). In recent decades, RPE have been applied to resistance training with multiple RPE scale adaptations such as the category ratio 0–10 (Borg CR10) scale (Buckley and Borg 2011), the 6–20 (Borg–15 category) scale (Cotter et al. 2017), and the omnibus resistance exercise 0–10 (OMNI–RES) scale (Lagally and Robertson 2006; Robertson et al. 2003). More recently, RPE has been used to prescribe intensity during resistance training (Dias et al. 2018; Helms et al.

2018), autoregulate resistance training intensity and volume (Helms et al. 2020; Shattock and Tee 2022), and assess the physiological and psychological responses when exercise intensity is anchored to a constant RPE value (Greenhouse–Tucknott et al. 2022; Keller et al. 2022; Smith et al. 2021, 2022a). While many definitions (Abbiss et al. 2015; Marcora and Staiano 2010; Pageaux 2016; Robertson and Noble 1997) and models (Marcora 2019; Noakes et al. 2004; Robertson and Noble 1997) have been used to define RPE, Hutchinson and Tenenbaum (2019) suggested that RPE is likely influenced by sensations such as strain, intensity, discomfort, and fatigue. Previous studies (Keller et al. 2022; Noboa et al. 2021; Smith et al. 2022a, b) have utilized the definition of Hutchinson and Tenenbaum (2019) during sustained, isometric tasks to quantify the sensations of strain, intensity, discomfort, and fatigue felt during exercise.

Over several decades, the collective understanding of the neurological, psychological, and performance-related effects of fatigue has grown exponentially. The interpretation of fatigue, however, has been confounded by the various methods and techniques used to study this phenomenon, as well as the many characteristics assigned to its definition (Enoka and Stuart 1992). Therefore, Kluger et al. (2013) proposed a unified taxonomy of fatigue that includes two main components: (1) performance fatigability; and (2) perceived fatigability. Specifically, Kluger et al. (2013) defined performance fatigability as "… the magnitude or rate of change in a performance criterion relative to a reference value over a given time of task performance or measure of mechanical output" (p. 411). Recently, however, Skau et al. (2021) suggested that this definition be updated to include the direction of change and to remove "measure of mechanical output" due to its redundancy. Thus, Skau et al. (2021) defined performance fatigability as "… the decrement in magnitude or rate of change in a performance criterion relative to a reference value over a given time of task performance" (p. 5). Furthermore, Enoka and Duchateau (2016) suggested that performance fatigability is modulated by factors associated with contractile function such as force capacity and blood flow, as well as muscle activation including activation patterns, motor neurons, afferent feedback, and neuromuscular propagation. Kluger et al. (2013) stated that perceived fatigability refers to "… subjective sensations of weariness, increases in sense of effort, mismatch between effort expended and actual performance, or exhaustion” (p. 411). Perceived fatigability is influenced by factors associated with the maintenance of homeostasis such as hydration, neurotransmitters, metabolites, and wakefulness, as well as the individual’s psychological state including arousal, executive function (i.e., higher-level cognitive skills involved with control and coordination of cognitive abilities and behaviors), expectations, mood, motivation, pain, and performance feedback (Enoka and Duchateau 2016).

Recent studies that have applied the RPE-Clamp model of Tucker (2009) have indicated there are interactions among the perception of fatigue and factors associated with performance fatigability during sustained, isometric forearm flexion (Smith et al. 2021, 2022a) and leg extension (Keller et al. 2020a, 2022) tasks anchored to a constant RPE value (Tucker 2009). For example, Smith et al. (2021) reported mean decreases in torque and amplitude of the electromyographic signal (EMG AMP) during a sustained, isometric forearm flexion task anchored to RPE = 7. It was hypothesized (Smith et al. 2021) that the decreases in torque were likely due to a combination of afferent feedback and peripheral fatigue, which led to excitation–contraction coupling failure, and that some of the participants may have voluntarily reduced torque due to perceived fatigability (i.e., a loss of motivation to continue). Thus, by applying the RPE-Clamp model (Tucker 2009), the contractile and metabolic factors related to performance fatigability, as well as the homeostatic and psychological factors associated with perceived fatigability can be examined simultaneously during sustained, isometric tasks anchored to a constant RPE value.

Fatigue-induced neuromuscular changes are often assessed by examining the time and frequency domain parameters of the EMG signal. It has been suggested (Basmajian and De Luca 1985; Vigotsky et al. 2017), that EMG AMP represents muscle excitation attributed to motor unit recruitment, firing rate, and/or synchronization. For example, recent studies utilized neuromuscular parameters such as EMG AMP to make inferences regarding fatigue-induced adjustments in motor unit activation strategies during isometric forearm flexion (Smith et al. 2021, 2022a) and leg extensions tasks (Keller et al. 2018a), as well as cycle ergometry (Cochrane et al. 2015), with torque, force, and power output anchored to a constant RPE, respectively, using the OMNI-RES (0–10) scale (Keller et al. 2018a; Smith et al. 2021, 2022a) and Borg-15 category scale (Cochrane et al. 2015). In addition, previous studies (Jones et al. 2016; Miller et al. 1987; Milner-Brown et al. 1986) examined the ratio between normalized torque or force and normalized EMG AMP to estimate neuromuscular efficiency (NME), which has been proposed as a measure of the level of muscle excitation required to generate a given amount of torque or force (Miller et al. 1987; Milner-Brown et al. 1986, p.). Specifically, Miller et al. (1987) reported a 40% decrease in NME during a sustained, isometric task of the adductor pollicis muscle anchored to 50% of maximum force. The authors suggested that NME was reduced due to the effects of peripheral fatigue which was characterized by excitation– contraction coupling failure that was likely caused by a buildup of metabolites (Miller et al. 1987). Therefore, neuromuscular parameters such as EMG AMP and NME may be useful indicators of the mechanisms underlying fatigue during a sustained, isometric task.

It has been suggested (Hicks et al. 2001), that differences between women and men in muscle-mass, muscle morphology, substrate utilization, and neuromuscular activation can "... alter the rate and magnitude of fatigability that develops in the muscle and central nervous system" (Hunter 2016, p. 2247). In a previous review of sex differences between women and men during various modes of exercise, Hunter (2014) proposed several potential physiological mechanisms that may explain why women are generally less fatigable than men. Specifically, Hunter (2014) suggested that a greater composition of type I fibers, a higher rate of lipid metabolism, augmented vasodilation caused by greater sympathetic activation, and reduced metabolite accumulation via decreased mechanical compression of the blood vessels as a result of lower force production capabilities due to less muscle mass may explain the sex differences in fatigue resistance (Avin et al. 2010; Hunter and Enoka 2001; Wust et al. 2008; Yoon et al. 2007). In addition, previous studies have demonstrated sex differences in perception of exertion during fatiguing eccentric forearm flexion tasks (O'Connor et al. 2002), dynamic leg extensions (Pincivero et al. 2004), and force estimation across multiple RPE values (Keller et al. 2018b), as well as differences in perceptual responses such as pain during fatiguing tasks (Noboa et al. 2021; Otto et al. 2019). While recent studies have assessed sex differences in performance fatigability (Keller et al. 2020b, 2022), femoral artery blood flow (Keller et al. 2020b), and the patterns of neuromuscular responses (Keller et al. 2020b, 2022) following sustained, isometric leg extensions anchored to a low and high perceptual intensity (RPE = 2 and RPE = 8), no previous investigations have examined the potential sex differences in the time course of changes in torque, EMG AMP, or NME with regard to the interaction between perceived fatigability and performance fatigability. Therefore, the purpose of the present study was to examine the interactions between perceived fatigability and performance fatigability in women and men by utilizing the RPE-Clamp model (Tucker 2009) to assess the fatigue-induced effects of a sustained, isometric forearm flexion task anchored to RPE = 8 on time to task failure (TTF), torque, EMG AMP, and NME responses. Based on the findings of previous studies (Avin et al. 2010; Keller et al. 2022; Miller et al. 1987; Noboa et al. 2021; Yoon et al. 2007), it was hypothesized that women and men would exhibit different fatigue-related responses in task duration and neuromuscular parameters, as well as reductions in torque output during a sustained, isometric forearm flexion task anchored to RPE = 8.

## Methods

An a prior G*Power3 power analysis determined that a minimum of 4 participants were required to demonstrate mean differences between and within 2 independent groups using repeated-measures ANOVAs, based on an effect size of $\eta^2_p$ = 0.722 (Keller et al. 2022), a power of 0.95, and an alpha of 0.05. Twenty college-aged, recreationally active (McKay et al. 2022) adults (10 men: age = 20.7 ± 1.2 years, height = 181.6 ± 6.0 cm, body mass = 83.7 ± 14.9 kg and 10 women: age = 20.8 ± 2.9 years, height = 169.0 ± 7.8 cm, body mass = 67.8 ± 7.2 kg) with no known cardiovascular, metabolic, or muscular diseases volunteered to participate in this study. The participants in the present study were part of a large multiple independent and dependent variable investigation (Arnett et al. 2022), but there is no overlap in data presented here except for age, height, and body mass of the men. None of the data in the present study have been previously published. The participants visited the laboratory for a familiarization and testing visit separated by at least 24 h, and all testing was scheduled at approximately the same time of day. In addition, the participants were instructed to avoid upper body exercise for at least 24 h prior to testing. The study was approved by the University Institutional Review Board for Human Participants (IRB Approval #: 20201220785FB), and all participants completed a Health History Questionnaire and signed a written Informed Consent prior to testing.

### *Familiarization visit*

The time course of procedures are presented in **Table 1**. During the familiarization visit, the participant's dominant arm (based on throwing preference), age, height, and body mass were recorded. In addition, the participant was oriented to their testing position on the upper body exercise table (UBXT) of the isokinetic dynamometer (Cybex II, Cybex International Inc. Medway, MA, USA) with the lateral epicondyle of the humerus of the dominant arm aligned with the lever arm of the dynamometer at the testing elbow joint angle of 100° ($EJ_{100}$). The participant was familiarized to the 10-point Omnibus-Resistance Exercise Scale (OMNI-RES) (Lagally and Robertson 2006; Robertson 2004; Robertson et al. 2003) and read the standardized OMNI-RES instructions (Gearhart et al. 2001; Smith et al. 2021) which stated, "You

**Table 1** Procedures

| *Familiarization session* | *Testing visit* |
|---|---|
| 1. Informed consent | 1. Positioned on Cybex II dynamometer |
| 2. Health History Questionnaire | 2. Standardized warm-up |
| 3. Age, height, and body mass recorded | 3. Read standardized anchoring instructions (OMNI-RES scale) |
| 4. Familiarized to testing position on Cybex II dynamometer | 4. Sustained, isometric forearm flexion task anchored to RPE = 8 (OMNI-RES scale) performed at an elbow joint angle of 100° until task failure (torque reduced to zero) |
| 5. Read standardized anchoring instructions (OMNI-RES scale) | |
| 6. Standardized warm-up; six, 3-s submaximal (50–75% of maximal effort) isometric forearm flexion contractions | |
| 7. Two, 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 at an elbow joint angle of 100° | |

will be asked to set an anchor point for both the lowest and highest values on the perceived exertion scale. In order to set the lowest anchor, you will be asked to lay quietly without contracting your forearm flexor muscles to familiarize yourself with a zero. Following this, you will be asked to perform a maximal voluntary isometric contraction to familiarize yourself with a 10. When instructed to match a perceptual value corresponding to the OMNI-RES scale, perceived exertion should be relative to these defined anchors." The participant then completed a standardized warm-up consisting of six, 3 s submaximal, (~ 50–75% of their maximal effort), isometric forearm flexion contractions at $EJ_{100}$ as well as two, 3 s isometric forearm flexion maximal voluntary isometric contractions (MVICs) at $EJ_{100}$ to set a perceptual anchor corresponding to RPE = 10. Finally, the participant performed a brief (approximately 1 min), sustained, isometric task anchored to RPE = 8 at $EJ_{100}$ to become familiarized with the testing/anchoring procedures.

### *Testing visit*

During the testing visit, the participant was positioned in accordance with the Cybex II user's manual on the UBXT with the same arm alignment determined during the familiarization visit. Once positioned, the participant performed the standardized warm-up, followed by 1 min of rest. Following the warm-up, the participant was again read the OMNI-RES instructions relating to the anchoring procedures. The participant then performed two, 3 s forearm flexion MVICs on the calibrated dynamometer at $EJ_{100}$. Strong verbal encouragement was provided during each MVIC trial. The MVICs also served to remind the participant of the perceptual anchor corresponding to RPE = 10. Following the MVIC trials, the sustained, isometric forearm flexion task anchored to RPE = 8 (OMNI-RES scale) was performed at $EJ_{100}$. During the sustained isometric task, the participant was unaware of torque and elapsed time to avoid pacing strategies (Albertus et al. 2005). The RPE 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 trial, the participant was free to adjust torque to maintain the prescribed RPE = 8. In addition, during the sustained isometric task, the participant was reminded to be attentive to sensations such as strain, intensity, discomfort, and fatigue felt during the task to maintain appropriate levels of exertion (Hutchinson and

Tenenbaum 2019; Robertson 2004). Furthermore, the participant was continuously reminded 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 participant was asked their RPE every 30 s to assure compliance with the prescribed RPE = 8. Upon task failure, the task was terminated and the time to task failure (TTF) was recorded.

### *Electromyographic and torque acquisition*

During the testing visit, bipolar (30-mm center-to-center) EMG electrodes (pregelled Ag/AgCl, AccuSensor; Lynn Medical, Wixom, MI) were attached to the biceps brachii (BB) of the dominant arm based on the recommendations of the Surface Electromyography for the Non-Invasive Assessment of Muscles (Hermens et al. 2000). A reference electrode was also placed on the styloid process of the radius of the forearm. Prior to electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The electrodes were placed over the BB between the medial acromion and the antecubital fossa, at one-third the distance from the antecubital fossa. The raw EMG signal was digitized at 2000 samples/second with a 12-bit analog-to-digital converter (Model MP150; Biopac Systems, Inc.) and stored on a personal computer (Acer Aspire TC-895-UA91 Acer Inc., San Jose, CA, USA) for analyses. The EMG signal was amplified (gain: 1000×) using a differential amplifier (EMG2-R Bionomadix, Biopac Systems, Inc. Goleta, CA, USA; bandwidth—10–500 Hz) and 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). The TTF (0 – 100%) was divided into 10% increments and a 1 s epoch from the center of each 10% increment (i.e., 500 ms before and 500 ms after) was used to calculate the AMP (root mean square) for the EMG (μVrms) signal. The torque signals were sampled from the Cybex II dynamometer and stored on a personal computer (Acer Aspire TC-895-UA91 Acer Inc., San Jose, CA, USA) for analysis. Our previous work (Smith et al. 2021) has indicated that when a sustained isometric task is anchored to a constant RPE, there are precipitous drops in torque and

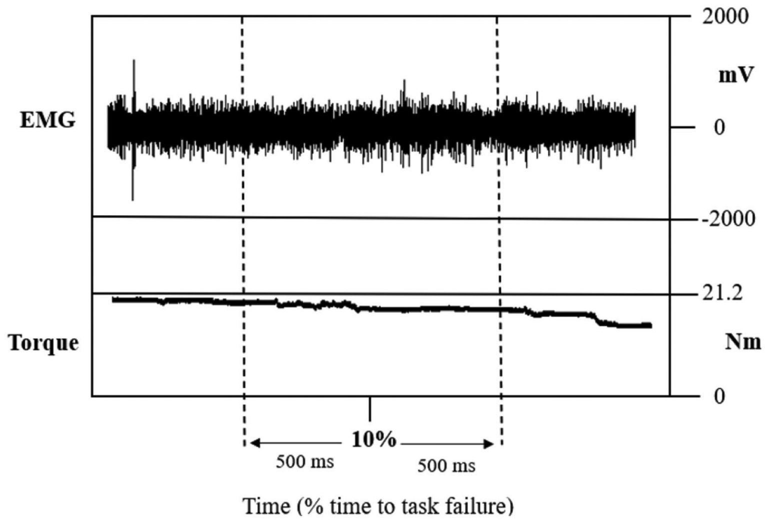


**Fig. 1** Example of the raw electromyographic (EMG) signal from the biceps brachii and the isometric torque (Nm) production curve from a sustained, isometric forearm flexion task at an elbow joint angle of 100° anchored to RPE = 8 at 10% of time to task failure. The portions of EMG and torque signals between the vertical dashed lines were selected for analysis

neuromuscular values from the initial value at the beginning of the sustained task to approximately 5% TTF. In the present study, the initial values were defined as the torque and EMG AMP values from the first 1-s of the sustained task anchored to RPE = 8. To examine the initial precipitous drops in torque and EMG AMP, we analyzed the responses for the initial value, 5% TTF, and from 10 to 100% TTF in 10% increments. A 1 s epoch from the center of the 3 s forearm flexion MVIC with the greatest torque production was used to normalize the torque and EMG AMP values. An example of the raw EMG signal from the BB and the isometric torque production curve from a sustained, forearm flexion task are presented in **Fig. 1**.

### *Statistical analysis*

Independent t tests were used to examine the mean differences between the men and women for TTF, pretest MVIC torque, and initial torque values. The mean differences for the normalized torque and EMG AMP values were determined with two, separate 2 (Sex: Women and Men) × 12 (Time: initial – 100% TTF) mixed factorial ANOVAs.

In addition, the mean differences for NME (defined as normalized torque/normalized EMG AMP) as described by Jones et al. (2016) were determined with a 2 (Sex: Women and Men) × 11 (Time: initial – 90% TTF) mixed factorial ANOVA. Tests for sphericity (Mauchly's Test of Sphericity) were conducted for all dependent variables and if sphericity was violated, the Greenhouse–Geisser correction was utilized. Significant interactions were decomposed with appropriate follow-up ANOVAs and Bonferroni corrected dependent t tests were used to identify the time course of when the normalized torque and neuromuscular values changed from the value corresponding to 5% TTF. In addition, Bonferroni corrected independent t tests were used to identify any differences for the normalized torque and neuromuscular values between the sexes (Women vs. Men) for each time point. Partial eta-squared ($\eta^2_p$) and Cohen's *d* were used to describe the effect size for each ANOVA and pairwise comparisons, respectively. An alpha value of $p \leq 0.05$ was considered statistically significant for the ANOVAs and Bonferroni corrected alpha values of $p \leq 0.0045$ were considered statistically significant for the dependent t tests across time and independent t tests between sexes, respectively. All the data were reported as mean ± SD and all calculations and statistical analyses were carried out in IBM SPSS v. 28 (Armonk, NY, USA).

## Results

### *TTF, pretest MVIC, and initial torque*

The individual and mean (± SD) TTF, pretest MVIC torque, and initial torque values are presented in **Table 2**. The independent t test for TTF indicated no significant ($p = 0.421$, $d = 0.090$) mean difference between the women (251.8 ± 74.1 s) and men (258.7 ± 77.9 s) for the TTF during the sustained, isometric task anchored to RPE = 8. There was, however, a significant ($p < 0.001$, $d = 2.341$) mean difference between women (30.5 ± 5.6 Nm) and men (51.1 ± 11.1 Nm) for the pretest forearm flexion MVIC values. In addition, there was a significant ($p < 0.001$, $d = 2.124$) mean difference between women (21.1 ± 6.7 Nm) and men (35.9 ± 7.3 Nm) for the initial torque values.

**Table 2** Time to task failure (s), pretest MVIC (Nm), initial torque (Nm), normalized initial torque (% of pretest MVIC), and percent decline in torque from the initial torque to task failure at an elbow joint (EJ) angle of 100° during the sustained isometric tasks to failure at RPE = 8 for men and women

| *Participants* | *TTF* | *MVIC* | *Initial torque* | *% MVIC* | *Torque at task failure* | *Percent decline* |
|---|---|---|---|---|---|---|
| Men | | | | | | |
| 1 | 315.0 | 46.7 | 41.3 | 88.1 | 0.0 | 100.0 |
| 2 | 174.5 | 60.9 | 41.7 | 66.9 | 0.0 | 100.0 |
| 3 | 269.4 | 57.5 | 33.0 | 58.1 | 3.7 | 88.9 |
| 4 | 192.4 | 61.0 | 29.3 | 47.7 | 0.0 | 100.0 |
| 5 | 180.0 | 30.1 | 24.1 | 80.1 | 0.0 | 100.0 |
| 6 | 228.6 | 47.4 | 29.0 | 73.4 | 8.3 | 71.3 |
| 7 | 330.0 | 34.6 | 31.9 | 92.6 | 1.9 | 94.2 |
| 8 | 417.5 | 57.1 | 44.5 | 78.0 | 0.0 | 100.0 |
| 9 | 270.0 | 56.3 | 44.0 | 78.1 | 4.0 | 90.9 |
| 10 | 209.4 | 59.2 | 40.3 | 64.9 | 12.6 | 68.8 |
| Mean ± SD | 258.7±78.0 | 51.1±11.1[a] | 35.9±7.3[a] | 72.8±13.6 | 3.0±4.3 | 91.4±12.0 |
| Women | | | | | | |
| 1 | 178.2 | 32.4 | 27.3 | 84.3 | 7.4 | 72.7 |
| 2 | 253.8 | 28.7 | 9.1 | 31.7 | 0.0 | 100.0 |
| 3 | 234.0 | 28.3 | 18.1 | 64.0 | 0.0 | 100.0 |
| 4 | 180.6 | 30.9 | 25.3 | 81.9 | 17.6 | 30.4 |
| 5 | 369.6 | 29.9 | 21.4 | 71.6 | 0.0 | 100.0 |
| 6 | 204.6 | 38.2 | 22.9 | 59.9 | 0.0 | 100.0 |
| 7 | 179.4 | 30.1 | 29.4 | 97.7 | 0.0 | 100.0 |
| 8 | 252.0 | 17.6 | 10.6 | 60.5 | 0.0 | 100.0 |
| 9 | 378.0 | 32.2 | 22.6 | 70.2 | 0.0 | 100.0 |
| 10 | 288.0 | 36.8 | 24.0 | 65.2 | 0.0 | 100.0 |
| Mean ± SD | 251.8±74.1 | 30.5±5.6 | 21.1±6.7 | 68.7±17.7 | 2.5±5.8 | 90.3±22.7 |

a. Significantly ($p < 0.001$) greater pretest MVIC and initial torque values (Nm) for men than women

## *Torque responses*

The normalized torque responses are presented in **Fig. 2**. For the normalized torque responses, the 2 (Sex: Women and Men) × 12 (Time: initial – 100% TTF) mixed factorial ANOVA indicated no significant ($p = 0.476$, $\eta^2_p = 0.098$) Sex × Time interaction. There was, however, a significant main effect ($p < 0.001$, $\eta^2_p = 0.939$) for Time (collapsed across Sex). A dependent t test indicated that the torque value at 5% TTF was less than the initial torque value ($p < 0.001$, $d = 1.862$). In addition, dependent t tests indicated that the torque values from 10 to 100% TTF were less than the torque value at 5% TTF ($p < 0.001$, $d$ range: 0.816–7.374).

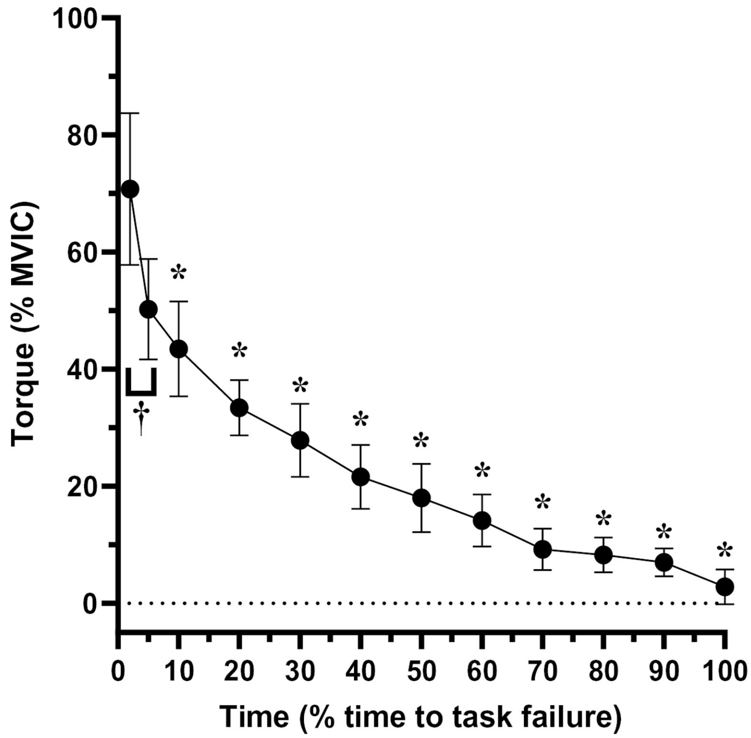


**Fig. 2** Time course of changes for the normalized (% of pretest MVIC) marginal mean (± SD) torque values (collapsed across sex) during the sustained, isometric forearm flexion task at an elbow joint angle of 100° anchored to RPE = 8. The initial torque values (% of the pretest MVIC) were determined during the first 1-s of the sustained, isometric task. †significantly ($p$ < 0.001) greater initial torque value than the torque value at 5% TTF of the sustained, isometric task. *Significantly ($p$ < 0.0045, Bonferroni corrected) lower torque values than the value at 5% TTF of the sustained, isometric task

### *EMG responses*

The normalized EMG AMP responses are presented in **Fig. 3**. For the normalized EMG AMP responses, the 2 (Sex: Women and Men) × 12 (Time: initial – 100% TTF) mixed factorial ANOVA indicated no significant ($p$ = 0.790, $\eta^2_p$ = 0.066) Sex × Time interaction. There was, however, a significant main effect ($p$ < 0.001, $\eta^2_p$ = 0.729) for Time (collapsed across Sex). A dependent t test indicated no difference between the EMG AMP value at 5% TTF and the initial EMG AMP value ($p$ = 0.171, $d$ = 0.372). In addition, dependent t tests indicated that the EMG AMP values from 10 to 100% TTF were less than the EMG AMP value at 5% TTF ($p$ < 0.004, $d$ range: 0.608–3.787), with the general direction of change decreasing across time.

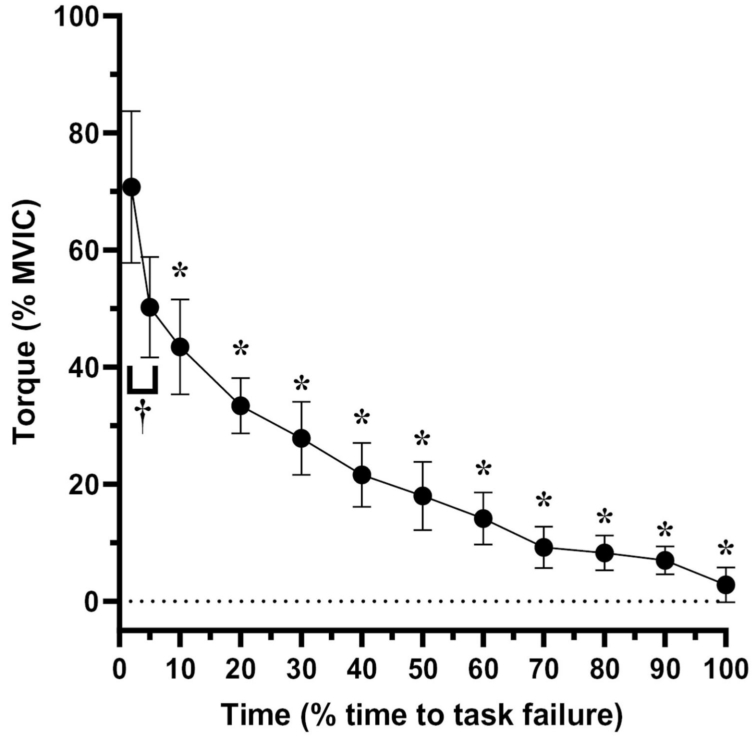


**Fig. 3** Time course of changes for the normalized (% of pretest MVIC) marginal mean (± SD) EMG AMP values (collapsed across sex) during the sustained, isometric forearm flexion task at an elbow joint angle of 100° anchored to RPE = 8. The initial EMG AMP values (% of the pretest MVIC) were determined during the first 1-s of the sustained, isometric task. *Significantly ($p$ < 0.0045, Bonferroni corrected) lower EMG AMP values than the value at 5% TTF of the sustained, isometric task

### *Neuromuscular efficiency responses*

The NME values are presented in **Fig. 4**. For NME, the 2 (Sex: Women and Men) × 11 (Time: initial – 90% TTF) mixed factorial ANOVA indicated no significant ($p$ = 0.982, $\eta^2_p$ = 0.031) Sex × Time interaction. There was, however, a significant main effect ($p$ < 0.001, $\eta^2_p$ = 0.809) for Time (collapsed across Sex). A dependent t test indicated that the NME value at 5% TTF was less than the initial NME value ($p$ < 0.001, $d$ = 1.798). In addition, dependent t tests indicated that the NME values from 20 to 90% TTF were less than the NME value at 5% TTF ($p$ < 0.001, $d$ range: 1.025–2.826), with the general direction of change decreasing across time.

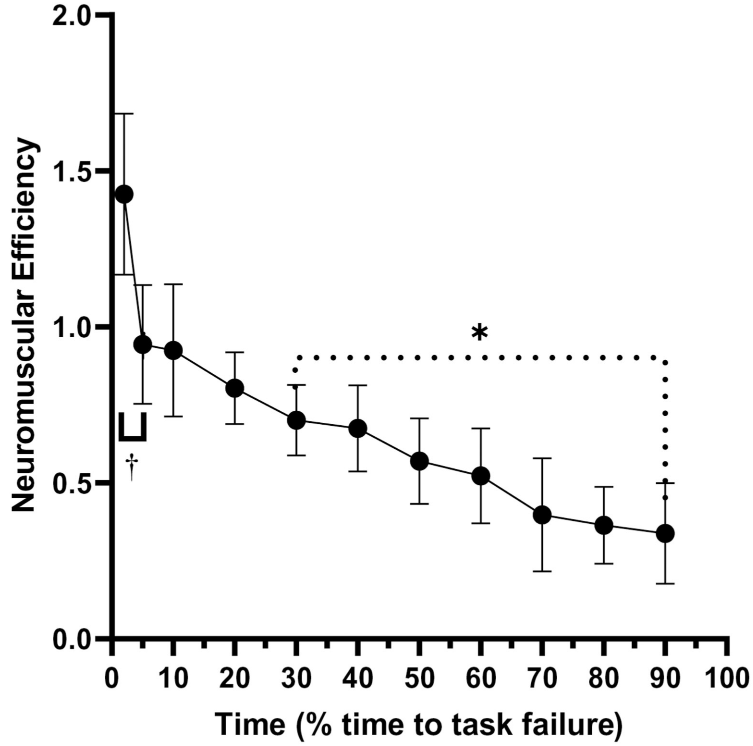


**Fig. 4** Time course of changes for the marginal mean (± SD) of NME (collapsed across sex) during the sustained, isometric forearm flexion task at an elbow joint angle of 100° anchored to RPE = 8. Neuromuscular efficiency was defined as normalized (% of pretest MVIC) torque/normalized EMG AMP at each respective time point. The initial NME values were from the first 1-s of the sustained, isometric task. †Significantly ($p$ < 0.001) greater initial NME value than the value at 5% TTF of the sustained, isometric task. *Significantly ($p$ < 0.005, Bonferroni corrected) lower NME values than the value at 5% TTF of the sustained, isometric task

## Discussion

The purpose of the present study was to examine the interactions between perceived fatigability and performance fatigability in women and men by utilizing the RPE-Clamp model (Tucker 2009) to assess the fatigue-induced effects of a sustained, isometric forearm flexion task anchored to RPE = 8 on TTF, torque, and neuromuscular responses. The results indicated that although the men were stronger than the women (pretest MVIC = 51.1 ± 11.1 N·m vs. 30.5 ± 5.6 N·m), there were no sex differences in TTF (women = 251.8 ± 74.1 s and men = 258.7 ± 78.0 s: Table 2). Sex differences in TTF tend to be more prevalent during low intensity (≤ 40% MVIC) sustained, isometric tasks anchored to force or torque (Hunter and Enoka 2001; Kahn and Monod 1984; Sato and Ohashi 1989) than moderate- and high-intensity tasks (Keller et al. 2022; Yoon et al. 2007). For example, Yoon et al. (2007) reported no significant difference in TTF between women (24.3 ± 6.6 s) and men (25.0 ± 6.5 s) during sustained, forearm flexion tasks to failure anchored to a constant torque of 80% MVIC. Petrofsky and Phillips (1980), however, reported greater TTF values for women than men during sustained, isometric forearm flexion tasks anchored to forces at 25, 40, 55, 70, and 90% MVIC. Perhaps, the modulating factors associated with perceived fatigability and performance fatigability (Enoka and Duchateau 2016) affect TTF differently in women and men when a task is anchored to a constant RPE versus a constant force or torque. The differences in findings between the current study and Petrofsky and Phillips (1980) may be explained by the suggestion of Hunter (2009) that, "... the magnitude of sex differences is specific to the task performed ..." (p. 113). Furthermore, Hunter (2009) reported a negative relationship ($r^2 = -0.42$) between the relative contraction intensity and the magnitude of sex difference for sustained, isometric contractions in women and men anchored to force, and concluded that when the task demands are altered, such as increasing the contraction intensity, "... the magnitude of the sex difference is diminished ..." (p. 121). Thus, the similar TTF values for the women and men in the present study may have been due to the unique nature of anchoring to a perceptual intensity and/or anchoring to a high perceptual intensity (RPE = 8), thereby diminishing the magnitude of sex-related differences in TTF. Future studies should examine sex differences in TTF during sustained, isometric forearm flexion tasks anchored to lower perceptual intensities such as RPE = 1 to RPE = 4.

The current study indicated that there was a negative, curvilinear torque versus time relationship throughout the sustained, isometric task anchored to RPE = 8 (Fig. 2). During a sustained fatiguing task, it is necessary to reduce exercise intensity to maintain a constant RPE (Flood et al. 2017; Keller et al. 2022; Tucker 2009). Throughout the sustained, isometric task in the present study, there were mean decreases in torque of 90.3 ± 22.0% for the women and 91.4 ± 12.0% for men. These findings were in agreement with previous studies of various modes of exercise that have used the RPE-Clamp model (Tucker 2009) and reported decreases in torque or force during sustained, isometric forearm flexion and leg extension tasks (Keller et al. 2018a, 2019, 2022, 2022a; Smith et al. 2021, b), running speed during treadmill running (Cochrane et al. 2015; Cochrane-Snyman et al. 2019), and power output during cycle ergometry (Flood et al. 2017). When anchoring to a constant RPE, however, not all participants reduce the exercise intensity to zero at task failure (Smith et al. 2021, 2022b). In the current study, 80% (eight of 10) of the women and 50% (five of 10) of the men reduced torque to zero, while the remaining participants perceived that they could no longer maintain RPE = 8, but did not reduce torque to zero (Table 2). Smith et al. (2022b) reported that 10 of 36 sustained, isometric tasks ended when the participant perceived that they could no longer maintain RPE = 7 and hypothesized that the participants may have lost motivation to continue the task as a result of perceived fatigability (Enoka and Duchateau 2016). Kluger et al. (2013) and Enoka and Duchateau (2016) identified motivation as one of the modulating factors of perceived fatigability. Perhaps, the women and men that did not reduce torque to zero in the present study, also lost motivation to continue the task due to perceived fatigability (Enoka and Duchateau 2016). It is also possible that the effects of perceived fatigability on the maintenance of torque are intensity-related, which may explain why 50% of the men in the present study did not reduce torque to zero to maintain an RPE = 8 compared to the findings of Smith et al. (2022a) who demonstrated that all of the men reduced torque to zero, during a sustained, isometric task at a lower perceptual intensity of RPE = 7. Interestingly, Smith et al. (2022b) reported that during sustained, isometric forearm flexion tasks anchored to RPE = 7 at elbow joint angles of 75°, 100°, and 125°, some participants reduced torque to zero at one joint angle, but not at other joint angles. Thus, the participants understood that torque could be reduced to zero, but in some cases, chose to end the tasks prior to doing so. Future research is needed to determine why, during sustained tasks anchored to a constant RPE, some participants decide to discontinue the task before reaching a torque of zero.

In theory, there is a proportional relationship between RPE from the OMNI-RES Scale and % MVIC torque (or force) such that the expected torque at RPE = 8 should be approximately 80% MVIC (Lagally and Robertson 2006). In the present study, however, for both the women (68.7 ± 17.7% MVIC) and men (72.8 ± 13.6% MVIC), the initial torque values at the beginning of the sustained, isometric task underestimated the expected torque of 80% MVIC at RPE = 8 by approximately 9–14%. These findings were consistent with previous studies (Keller et al. 2022; Smith et al. 2021, 2022a, b) that have anchored sustained, isometric tasks to RPE values of 7 or 8. Recently, Smith et al. (2021) and Smith et al. (2022b) reported underestimates of initial torque values of 59.7 ± 15.0% MVIC and 56.1 ± 12.1% MVIC for women and 54.7 ± 12.8% MVIC for men (Smith et al. 2022a) during sustained, isometric forearm flexion tasks anchored to RPE = 7. Keller et al. (2022) reported initial force values of 58.5% MVIC for women and 55.7% MVIC for men during sustained, isometric leg extensions anchored to RPE = 8. Tucker (2009) hypothesized that when exercise is anchored to RPE, there is an anticipatory component based on a combination of previous experiences and task modality, as well as physiological and psychological inputs which are processed in the brain to set an initial intensity that is perceived to match the prescribed RPE. The results of the present study, in conjunction with previous studies (Keller et al. 2018b, 2022; Smith et al. 2021, 2022a, b), indicated that when a task is anchored to a high RPE of 7 or 8, women and men underestimated the expected % MVIC by approximately the same magnitude. Furthermore, the underestimation has been reported for forearm flexion, leg extension, and leg flexion muscle actions (Keller et al. 2018b, 2022; Smith et al. 2021, 2022a, b). These findings suggest that the processing of the factors that contribute to the anticipatory component described by Tucker (2009) for tasks anchored to high perceptual intensities results in underestimations of the expected % MVIC in various muscle groups for women and men.

In the present study, the general pattern of decrease in torque throughout the sustained, isometric task anchored to RPE = 8 (Fig. 2) suggested three phases: Phase 1 was characterized by an initial precipitous decrease from the initial torque values to 5% TTF; during Phase 2, there was a continuing decrease in torque at a more gradual rate from 5 to 40% TTF; and Phase 3 exhibited an even less pronounced rate of decrease in torque from 40% TTF to task failure. At the beginning of the sustained task (Phase 1), torque decreased precipitously by a mean of 29% (2.26% per second) from the initial torque value (marginal mean ± SD collapsed across sex = 70.8 ± 13.0% MVIC) to the value at 5% TTF (50.3 ± 8.6% MVIC) across 12.8 ± 3.7 s. This rapid decrease in torque was consistent with previous studies (Smith et al. 2021, 2022a, b) of sustained, isometric forearm flexion tasks anchored to RPE = 7 for women and men. At RPE = 7, Smith et al. (2022b) reported an approximate 31% decrease in torque from the initial torque value during the first 5% TTF of the sustained, isometric task in women. There was a difference, however, for the EMG AMP responses in the present study compared to those reported by Smith et al. (2022b). Specifically, Smith et al. (2022b) found that EMG AMP decreased during this initial segment of the task, which tracked the decreases in torque, while in the present study, the neuromuscular parameters did not track the decreases in torque. Perhaps, the differences in the intensity of the initial torque value in the present study (RPE of 8 = 70.7% MVIC) versus that of Smith et al. (2022b) (RPE of 7 = 58.3% MVIC), as well as the time corresponding to the period from the initial torque value to 5% TTF in the present study (12.8 ± 3.7 s) versus the time reported by Smith et al. (2022b) (36.3 ± 19.0 s) resulted in different EMG AMP responses that were intensity- and time-related. Smith et al. (2022b) hypothesized, that the rapid initial decreases in torque and EMG AMP were likely mediated by afferent feedback from group III, primarily mechanosensitive neurons, which informed the perception of the intensity of the contraction and led to a voluntary reduction in central motor command, derecruitment of motor units (MU), and reduced torque output. According to Smith et al. (2022b), the inhibitory feedback from the group III afferent neurons and the changes to torque and EMG AMP that followed were best explained by the feedback component of the RPE-Clamp model (Tucker 2009). Specifically, Tucker (2009) suggested that during tasks anchored to RPE, mechanical and metabolic perturbations within the primary and synergistic muscles involved in the task can cause increased afferent feedback to the brain, perhaps to the supplementary motor area (SMA) (Zenon et al. 2015). Theoretically, this feedback leads to continuous adjustments to exercise intensity by reducing the central motor command to return the conscious RPE to the prescribed level (Tucker 2009). Furthermore, it has been suggested (Marcora 2009), that the premotor and primary motor areas generate an efferent copy of the central motor command that sends immediate neural feedback to the SMA to determine whether the reduction in torque is sufficient to match the prescribed RPE. Therefore, based on the findings reported in the present study, in conjunction with previous research (Pageaux 2016; Smith et al. 2022b; Tucker 2009), it is hypothesized that the anticipatory setting of the initial torque was immediately perceived as an overestimation of the intensity that could be maintained at RPE = 8, and feedback from group III (mechanosensitive) neurons was fed forward from the SMA to the premotor and primary motor areas, and caused the participants to voluntarily reduce central motor command. In addition to a voluntary reduction in central motor command, the rapid decrease during Phase 1 in torque in the present study, with no change in EMG AMP, also indicated an initial decrease in NME (initial value = 1.42 ± 0.26 vs. 5% TTF value = 0.94 ± 0.19). This was likely mediated by peripheral fatigue during the first few seconds of the task (Amann et al. 2013; Azevedo et al. 2021; Drouin et al. 2022; Drouin and Tschakovsky 2019; Hargreaves and Spriet 2020; Hultman and Sjoholm 1983; Wan et al. 2017) as a result of intramuscular pressure on the occlusion of vascular beds, blood flow restriction (Bonde-Petersen et al. 1975), and the buildup of metabolic byproducts including inorganic phosphate ( $P_i$), extracellular potassium ($K^+$), and reactive oxygen species (ROS), such as superoxide anion ($O^{2-}$), hydrogen peroxide ($H_2O_2$), and hydroxyl radical (HO) (Allen et al. 2008; Allen and Trajanovska 2012; Ray et al. 2012; Wan et al. 2017). Peripheral fatigue disrupts excitation–contraction coupling and causes a decrease in NME through the effects of intramuscular metabolic perturbations on calcium release and re-uptake kinetics, calcium sensitivity for binding with troponin, and actin-myosin binding properties (Allen et al. 2008; Maclaren et al. 1989). Thus, it is hypothesized that the precipitous decrease in torque from the initial torque value to 5% TTF for the women and men in the present study resulted from a combination of: (1) integrated group III (mechanosensitive) and group IV (metabosensitive) afferent feedback that informed a perception that the torque value was too high to maintain RPE = 8, and led to voluntary decreases in central motor command and torque production; and (2) peripheral fatigue which interrupted excitation–contraction coupling as evidenced by decreased NME.

During Phase 2 from 5 to 40% TTF, torque decreased continuously from 50.3 ± 8.6% to 21.6 ± 5.5% MVIC or 57% (Fig. 2) at a rate of

0.64% per second which was only 28% of the 2.26% per second rate during Phase 1. Unlike Phase 1, however, there was also a decrease in EMG AMP (38%; Fig. 3) across 89.3 ± 26.6 s. In addition, NME decreased from 0.94 ± 0.19 at 5% TTF to 0.68 ± 0.14 at 40% TTF (Fig. 4). Based on these findings, it is hypothesized that like Phase 1, the decrease in torque during Phase 2 was mediated through contributions from both group III and group IV afferent feedback. It is likely, however, that the relative contributions of mechanosensitive feedback (group III) and metabosensitive feedback (group IV) were different between the phases. For example, the torque values (% MVIC) and the rate of change in torque from 5 to 40% TTF (Fig. 2) were less than those during Phase 1. This suggests that during Phase 2 there was less of a need for a precipitous decrease in torque to maintain RPE = 8 than during Phase 1. Thus, perhaps, there was less group III, mechanosensitive feedback to voluntarily decrease torque during Phase 2 which contributed to the more gradual rate of decrease in torque than during Phase 1. The decrease in NME across Phase 2 compared to 5% TTF, however, suggested an increase in metabolic perturbations, which likely increased excitation–contraction coupling failure and decreased torque production. Therefore, it is hypothesized that as the fatiguing task anchored to RPE = 8 continued through Phases 1 and 2, the contribution from the voluntary reduction in torque decreased and the contribution from peripheral fatigue increased.

From 40% to task failure (Phase 3), torque decreased from 21.6 ± 5.5% to 2.8 ± 3.0% MVIC or 87% (Fig. 2) at a rate of 0.57% per second which was 11% less than the 0.64% per second rate during Phase 2. In addition, EMG AMP decreased by 40% (Fig. 3). Furthermore, NME decreased from 0.68 ± 0.14 to 0.34 ± 0.16 at 90% TTF over the 153.1 ± 44.5 s period. Neuromuscular efficiency was presented at 90% TTF because 13 of the 20 participants reduced torque to zero at task failure and for these participants it was not possible to calculate a ratio for NME (normalized torque/ normalized EMG AMP) because the numerator (normalized torque) was zero. Thus, our results indicated that, like Phase 1 and 2, the decreases in torque during Phase 3 were likely mediated by inhibitory feedback from group III (mechanosensitive) and group IV (metabosensitive) neurons, but the relative contributions differed from those in Phase 2. For example, the torque values (% MVIC), and the rate of change in torque during Phase 3 were less than Phase 2. Thus, it is likely that the lack of a need to precipitously reduce torque continued throughout Phase 3, which resulted in even less group III, mechanosensitive feedback, and, therefore, a slower rate of decrease in torque during Phase 3 than Phase 1 and Phase 2. In addition, the continued decrease in NME suggested additional metabolic perturbations across Phase 3, increased excitation–contraction coupling failure, and decreased torque output. Therefore, it is hypothesized that as the sustained task anchored to RPE = 8 continued, the need for rapid voluntary reductions in torque decreased and the contribution from peripheral fatigue increased throughout Phases 1, 2, and 3.

Two testable hypotheses for the decision to terminate the task in Phase 3 of the present study include: (1) a loss of motivation to continue the task (de Morree and Marcora 2015; Enoka and Duchateau 2016; Kluger et al. 2013); and/ or (2) the participants reached their sensory tolerance limit (STL) (Hureau et al. 2018). Loss of motivation has been identified (Enoka and Duchateau 2016; Kluger et al. 2013) as one of the modulating factors of perceived fatigability and it may be that 7 of 20 participants in the present study decided that they did not want to maintain the task requirements and, therefore, discontinued the task prior to reaching a torque value of zero, even though they were able to continue. According to the STL model, it is also possible that the effects of peripheral fatigue and the sum of all neural feedback from the primary and synergistic muscles involved with forearm flexion and handgrip led to a reduction in torque and, ultimately, termination of the task (Hureau et al. 2018). It is also possible, however, that a combination of a loss of motivation to continue and peripheral fatigue caused the participants to terminated the task.

Although the participants in the present study were familiarized with the testing procedures (i.e., isometric forearm flexion task) and the anchoring procedures, exercise experience has been suggested (Halperin and Emanuel 2020; Tucker 2009) as a mediator of the relationship between RPE and perceived fatigability. Thus, it may be that a lack of experience with the isometric, forearm flexion task could have influenced the participant's ability to determine their RPE. A strength of the present study, however, was that the RPE anchoring procedures were standardized and participants were encouraged to clarify any misconceptions they might have had prior to beginning the task. Another potential limitation of the present study was the normalization procedures used to determine NME, as it has been suggested previously (Arabadzhiev et al. 2010) to potentially result in an inappropriate interpretation of fatigue-induced changes in central motor command. Finally, menstrual cycle and/or use of oral contraceptives was not considered. Previous studies (Hooper et al. 2011; Mattu et al. 2020) have suggested that RPE may be influenced by different phases of the menstrual cycle, as well as the timing of oral contraceptive use. Given this information, the processing of RPE during the task for the women in the present study may have been influenced depending on the phase of the menstrual cycle and the timing of oral contraceptive use.

In summary, the present study utilized the RPE-Clamp model (Tucker 2009) to examine the interactions between perceived fatigability and performance fatigability and to assess the fatigue-induced effects of a sustained, isometric task anchored to a high perceptual intensity of RPE = 8 on TTF, torque, and neuromuscular responses in women and men. The results of the present study demonstrated that the TTF, torque, EMG AMP, and NME responses during the sustained, isometric task anchored to RPE = 8 were similar for the women and men. Based on the current findings, it is hypothesized that the three phases of torque reduction during the sustained task anchored to RPE = 8 were likely mediated by feedback from group III (mechanosensitive) and group IV (metabosensitive) afferent neurons, which led to voluntary reductions in torque and peripheral fatigue that resulted in excitation–contraction coupling failure as evidenced by decreased NME. The decreases in NME suggested, however, that the contributions of voluntary reductions in torque decreased throughout the task, while peripheral fatigue increased. Furthermore, it was hypothesized that the decision to terminate the task was due a loss of motivation to continue the task, peripheral fatigue from the primary and secondary muscles involved with forearm flexion and handgrip that caused the participants to reach their STL, and/or a combination of the two. Future studies should assess various psychological factors such as motivation and pain perception to determine if they contribute to the decision to terminate a task anchored to a constant RPE. Additional studies should incorporate the use of ultrasound and near-infrared spectroscopy (NIRS) to assess potential changes in blood flow and oxygenation of the active muscle(s), as well as nuclear magnetic resonance (NMR) to measure intramuscular metabolites and their effects on the torque and EMG AMP responses during tasks anchored to RPE. Furthermore, future studies should use the interpolated twitch and potentiated twitch amplitude technique to examine the relative contributions of central and peripheral mechanisms to torque modulation during tasks anchored to a constant RPE.

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**Author contributions** RWS was primarily responsible for analyses, manuscript writing, and accepts responsibility for the integrity of the data analysis. RWS and JEA were primarily responsible for data collection. 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.

**Data availability** The datasets generated during and/or analyzed during the present study are available from the corresponding author upon reasonable request.

**Conflict of interest** The authors declare that they have no conflicts of interest.

**Ethical approval** This study was approved by the University Institutional Review Board (IRB Approval #: 20201220785FB).

**Consent to participate** During the familiarization visit, the participants read and signed an informed consent document approved by the University Institutional Review Board.

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