European Journal of Applied Physiology (2021) 121:1111–1124
https://doi.org/10.1007/s00421-020-04588-y

ORIGINAL ARTICLE

Similar performance fatigability and neuromuscular responses following sustained bilateral tasks above and below critical force

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Received: 6 August 2020 / Accepted: 17 December 2020 / Published online: 23 January 2021

Abstract

Purpose The present study examined the magnitude of performance fatigability as well as the associated limb- and intensity-specific neuromuscular patterns of responses during sustained, bilateral, isometric, leg extensions above and below critical force (CF).

Methods Twelve women completed three sustained leg extensions (1 below and 2 above CF) anchored to forces corresponding to RPE = 1, 5, and 8 (10-point scale). During each sustained leg extension, electromyographic (EMG) and mechanomyographic (MMG) amplitude (AMP) and mean power frequency (MPF) were assessed from each vastus lateralis in 5% of time-to-exhaustion (TTE) segments. Before and after each sustained leg extension, the subjects completed maximal voluntary isometric contractions (MVIC), and the percent decline was defined as performance fatigability. Polynomial regression was used to define the individual and composite neuromuscular and force values versus time relationships. Repeated-measures ANOVAs assessed differences in performance fatigability and TTE.

Results The grand mean for performance fatigability was 10.1 ± 7.6%. For TTE, the repeated-measures ANOVA indicated that there was a significant ($p < 0.05$) effect for Intensity, such that RPE = 1 > 5 > 8. There were similar neuromuscular patterns of response between limbs as well as above and below CF. EMG MPF, however, exhibited decreases only above CF.

Conclusions Performance fatigability was unvarying above and below CF as well as between limbs. In addition, there were similar fatigue-induced motor unit activation strategies above and below CF, but peripheral fatigue likely contributed to a greater extent above CF.

Keywords Fatigability · Ratings of perceived exertion · Critical force · Neuromuscular

Abbreviations

AMP	Amplitude
CV	Conduction velocity
CF	Critical force
EMG	Electromyography
RPE	Ratings of perceived exertion
TTE	Time to exhaustion

Communicated by William J. Kraemer.

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Introduction

Performance fatigability has been defined as “the magnitude or rate of changes in performance criterion relative to a reference value over a given time of task performance or measure of mechanical output” (Kluger et al. 2013; p.411). Previous investigations (Burnley et al. 2012; Ansdell et al. 2019) have used the concept of critical force (CF) to demarcate a point at which the etiology of performance fatigability may change from being primarily due to central versus peripheral impairments. Furthermore, in theory, CF represents the upper limit of the intensity spectrum that an individual can sustain “for a very long time without the fatigue” (Monod and Scherrer 1965; p. 329). It has previously been suggested that insight into the metabolic demands of a task and the mechanisms responsible for task failure can be investigated by determining the critical intensity (i.e., force) (Jones et al. 2008; Poole et al. 2016); that is, at intensities above CF, metabolites accumulate more rapidly (i.e., P_i, ADP, H^+, and extracellular K^+). Also, in terms of training-induced changes, the analogous endurance counterpart to CF, "critical power" has been shown to increase in response to training and creatine supplementation as well as decrease in the presence of hypoxic gas. Thus, in theory, similar outcomes would be expected with CF, and, perhaps, studies of low/high-loads should consider quantifying CF to ensure that individuals are within the appropriate intensity domain. It has also been demonstrated that there are unique fatigue characteristics above and below this theoretical threshold, such that peripheral impairments contribute to performance fatigability to a greater extent above CF, whereas central factors primarily influenced fatigue below CF (Burnley et al. 2012). These unique fatigue characteristics above and below CF may possibly be related to recent findings of Miller et al. (2020) which suggested that neural drive was greater after a single high-intensity contraction than after completing a fatiguing bout of lower intensity muscle actions. Thus, there is rationale to hypothesize that there may be discrete underlying mechanisms contributing to the magnitude of performance fatigability above and below CF. Enoka and Duchateau (2016; p.1001) and Duchateau (2018; p.2228), however, have cautioned against dichotomizing fatigue into central and peripheral fatigue, but rather suggest that investigations of performance fatigability should focus on outcome variables that characterize "real-world performance" such as time to exhaustion (TTE), ratings of perceived exertion (RPE), and changes in maximal voluntary isometric contraction (MVIC) forces. Neyroud et al. (2016) have previously proposed that fatigue-induced decreases in MVIC provide a description of global of performance fatigability (i.e., encompassing both peripheral and central factors). These previous studies, however, have exclusively utilized unilateral muscle actions, which have been shown to elicit different responses than bilateral tasks (Rossman et al. 2012, 2014; Thomas et al. 2018; Koral et al. 2020; Anders et al. 2020). Thus, little is known regarding fatiguing characteristics above and below CF during a sustained bilateral muscle action.

Comparisons of bilateral versus unilateral fatiguing tasks have been used (Rossman et al. 2012, 2014; Thomas et al. 2018; Koral et al. 2020; Anders et al. 2020) to examine the effect of the amount of engaged muscle mass on the magnitude of performance fatigability. Recently, Koral et al. (2020) reported 6% greater performance fatigability (as assessed by changes in MVIC) following a maximal unilateral task compared to a time-match bilateral task. In contrast to previous reports (Rossman et al. 2012, 2014; Thomas et al. 2018), however, there was no difference in the magnitude of peripheral fatigue between the two tasks (Koral et al. 2020) despite engaging different amounts of muscle mass. It is possible that unique neuromuscular mechanisms inherent to bilateral tasks such as interhemispheric inhibition and bilateral coupling contribute to the performance fatigability differences between unilateral and bilateral tasks (Oda and Moritani 1995; Matkowski et al. 2011; Škarabot et al. 2016). Anders et al. (2020), however, have shown that the neuromuscular patterns of responses were generally consistent between unilateral and bilateral tasks that involved 50 maximal, isokinetic leg extensions, despite approximately 20% greater performance fatigability for the unilateral task. It remains unknown if these neuromuscular-related findings (Anders et al. 2020) can be extended to submaximal, bilateral, and isometric leg extensions at various intensities that require different amounts of engaged muscle mass.

Typically, during submaximal, fatiguing tasks, there are increases in the amplitude (AMP) and decreases in the frequency content of the electromyographic (EMG) and mechanomyographic (MMG) signals (Beck et al. 2005; Farina et al. 2014). These responses have been attributed to fatigue-induced increases in muscle activation (EMG AMP) and motor unit recruitment (MMG AMP), as well as decreases in the global motor unit firing rate [MMG mean power frequency (MPF)] and muscle fiber action potential conduction velocity (CV; EMG MPF) (Lindstrom 1970; Beck et al. 2005; Farina et al. 2014). Furthermore, these neuromuscular parameters have been used to infer fatigue-induced changes to motor unit activation strategies (Beck et al. 2005; Farina et al. 2014; Anders et al. 2020), which ultimately may contribute to altering descending motor drive to limit metabolic activity and peripheral perturbations. These neuromuscular parameters, however, have not been examined above and below CF during sustained, bilateral, isometric leg extensions. Additionally, there remains a need to investigate if the neuromuscular system modulates the dominant and non-dominant limbs differently in response to the onset of fatigue above and below CF in women.

Therefore, the purpose of the present study was to address whether or not the magnitude of performance fatigability as well as the associated limb- and intensity-specific neuromuscular patterns of responses during sustained, bilateral, isometric, leg extensions varied above and below CF. Based on previous reports (Burnley et al. 2012; Rossman et al. 2012, 2014; Hunter 2016; Thomas et al. 2018; Ansdell et al. 2019; Koral et al. 2020), it was hypothesized that trials above CF would result in greater global performance fatigability as assessed by fatigue-induced changes in MVIC force. In addition, it was hypothesized that the trials above CF would exhibit fatigue characteristics consistent with peripheral fatigue, but there would be no difference in the neuromuscular patterns of responses between limbs. It is pertinent to test these hypotheses given our findings may practically serve, at least in part, as the basis for future study designs aiming to investigate differences between chronic resistance training with intensities above and below CF in women.

Materials and methods

Experimental design

This study utilized a randomized, within-subjects design to examine performance fatigability and neuromuscular responses as a result of bilateral, isometric, leg extensions sustained to exhaustion at three different levels of force production. Each subject's CF as well as the force values that corresponded to RPE values of 1, 5, and 8 (on the 10-point OMNI-RES) were determined prior to the three sustained, bilateral, isometric leg extensions. Prior to and following each sustained leg extension, MVIC force was assessed. In addition, neuromuscular responses were assessed throughout each sustained leg extension.

Subjects

Fifteen college-aged recreationally active women (Pescatello 2013) with no known cardiovascular, metabolic, or muscular diseases volunteered to participate in this investigation. Specifically, the women participated in resistance training 2–3 sessions wk^{-1} ($n = 15$), recreational soccer ($n = 5$), running ($n = 8$), and swimming ($n = 2$). These subjects were from a large, multi-independent and -dependent variable data collection. Pilot data demonstrated that for most subjects, an RPE of 1 corresponded to a force value that was less than their CF, while RPE values of 5 and 8 were above CF. Twelve ($\bar{X} \pm$ SD: 168.1 ± 5.4 cm; 64.0 ± 7.9 kg; 19.5 ± 0.8 years) of the 15 subjects exhibited force values at RPE of 1 that were less than CF as well as force values at RPE of 5 and 8 that were greater than CF and, therefore, were selected for this study and further analysis (Table 1). Based on previously reported performance fatigability data (Matkowski et al. 2011; Anders et al. 2020) for bilateral tasks, the a priori sample size calculations (G*Power version 3.1.9.7, Düsseldorf, Germany) indicated that a power of 0.8 required 7–12 subjects. The 12 subjects in the current study were instructed to continue their typical dietary, hydration, and exercise habits throughout the study. For each subject, the testing was completed at approximately the same time of day (± 2 h) and within 4 weeks. The University Institutional Review Board for Human Subjects approved the study (IRB#: 20190619436EP), and during the familiarization visit, the subjects completed a health history questionnaire and gave written informed consent.

Familiarization visit

During the familiarization visit, the subject's dominant leg (based on kicking preference), height, and body mass were recorded, and the subjects were oriented to their seated position on the isokinetic dynamometer (Cybex 6000, Cybex International Inc. Medway, MA). The subjects were familiarized to the 0–10 OMNI-RES (Robertson 2004) and read standardized anchoring instructions (Gearhart et al. 2001; Keller et al. 2018) which stated, "You will be asked to set an anchor point for both the lowest and highest value on the perceived exertion scale. To set the lowest anchor, you will be asked to sit quietly without contracting your leg muscles to familiarize yourself with a zero. Following this you will be asked to perform two maximal voluntary isometric contractions to familiarize yourself with a 10. When instructed to give an effort corresponding to the OMNI-RES scale, perceived exertion should be relative to these defined anchors." The subjects then completed a standardized warm-up consisting of five submaximal, bilateral, isometric leg extensions at a perceived moderate intensity (~ 60–70% of their maximal effort) and practiced MVICs.

Force values corresponding to RPE = 1, 5, and 8

The subjects were once again read the standardized instructions corresponding the OMNI-RES and then completed randomly ordered bilateral leg extensions anchored to RPE corresponding to 1, 5, and 8 on the OMNI-RES. The initial (i.e., first 5% of TTE) self-selected, absolute force values that corresponded to RPE = 1, 5, and 8 for each subject were recorded and used to anchor the sustained leg extensions of the current study.

Determination of critical force

Critical force was determined based on the procedures of Monod and Scherrer (1965) and Hendrix et al. (2009a, b) by completing randomly ordered sustained, bilateral, leg extensions at four percentages of MVIC (25, 35, 45, and 55%) on separate days. The subjects sustained each force until task failure to determine time-limit (T_{lim}), which was defined as an inability to maintain the assigned percentage of MVIC (≥ 5% reduction in force for three consecutive seconds). During each CF trial, the subjects were given strong verbal encouragement and were able to track force production via visual feedback on a computer monitor. After completion of the four CF trials, work limit (W_{lim}) was calculated by multiplying the force produced during a trial by the corresponding T_{lim} (Monod and Scherrer 1965). Subsequently, the four W_{lim} values were plotted as a linear function of the corresponding T_{lim} values with CF defined as the slope coefficient of the W_{lim} versus T_{lim} relationship (Monod and Scherrer 1965).

Table 1 Data for each subject for the initial maximal voluntary isometric contraction (MVIC) and each critical force (CF) trial

Subject	MVIC (kg)	Force (kg)	*T*lim (s)	r^2	CF (kg)	CF (%MVIC)	RPE=1 (%MVIC)	RPE=5 (%MVIC)	RPE=8 (%MVIC)
1	66.9	16.7	116.4	0.57	10.1	15.1	11.4	53.2	65.5
		23.4	83.7						
		30.1	71.8						
		36.8	29.3						
2	48.5	12.1	161.4	0.37	6.7	13.7	7.9	31.9	47.7
		17.0	160.8						
		21.8	118.0						
		26.7	60.4						
3	70.7	17.7	174.0	0.79	10.4	14.7	12.3	44.3	80.4
		24.7	115.0						
		31.8	84.0						
		38.9	41.0						
4	44.2	11.0	148.4	0.79	7.1	16.1	14.9	58.3	89.6
		15.5	112.8						
		19.9	68.5						
		24.3	35.2						
5	42.9	10.7	196.0	0.97	7.2	16.8	15.2	52.6	68.8
		15.0	102.6						
		19.3	50.4						
		23.6	47.5						
6	61.3	15.3	202.0	0.75	11.4	18.6	13.4	60.6	75.1
		21.4	174.6		25.4				
		27.6	99.6						
		33.7	44.8						
7	55.5	13.9	230.4	0.92	7.3	13.2	11.9	59.4	73.8
		19.4	124.4						
		25.0	100.8						
		30.6	60.4						
8	76.0	19.0	232.2	0.91	10.3	13.6	4.8	25.1	54.7
		26.6	149.4						
		34.2	79.2						
		41.8	71.1						
9	53.3	13.3	165.6	0.91	8.3	15.5	11.0	30.6	44.7
		18.7	103.8						
		24.0	65.2						
		29.3	37.7						
10	58.2	14.5	220.0	0.80	8.5	14.6	11.4	45.2	70.5
		20.4	135.0						
		26.2	106.0						
		32.0	50.9						
11	72.6	18.1	229.2	0.89	10.7	14.8	11.7	45.2	72.0
		25.4	160.2						
		32.7	86.3						
		39.9	61.8						
12	57.5	14.4	114.0	0.92	4.9	8.6	5.8	52.2	59.1
		20.1	76.4						
		25.9	50.2						
		31.6	41.6						

Experimental sustained leg extensions

On separate days, the subjects completed one of three randomly ordered sustained, bilateral, isometric, leg extensions at a force value that corresponded to RPE = 1, RPE = 5, or RPE = 8 at constant joint angle of 120° (180° corresponding to full extension) with the axis of rotation aligned with the center of the knee joint. The subjects sustained each of these leg extensions to exhaustion (≥ 5% reduction in force production for three consecutive seconds). Two, separate, calibrated, low-profile pancake load cells (Honeywell Model 41, Morris Plains, NJ) attached to the footpads (Velcro strapped around ankles) at the end of the dynamometer lever arm (Fig. 1) were used to determine force (kg). The force signals were collected at a rate of 1000 samples/s and amplified (gain × 200; DA 100C Biopac Systems, Inc., Santa Barbara, CA). Prior to and following each sustained leg extension, MVIC trials were performed. Performance fatigability was calculated as the percent change in MVIC force from pretest to posttest for the dominant leg (DL), non-dominant leg (ND), and bilateral condition (sum of DL and NL).

Neuromuscular measurements

During the three experimental, sustained leg extensions and in accordance with the SENIAM recommendations (Hermens 1999; Hermens et al. 2000), pre-gelled surface EMG electrodes (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) were placed in a bipolar arrangement (30 mm center-to-center) on the vastus lateralis of each thigh and oriented 20° (parallel to the pennation angle) with respect to the reference line between the lateral side of the patella and the anterior superior iliac spine (Barbero et al. 2012) (Fig. 1). The MMG signals were recorded simultaneously with EMG using an accelerometer (Entran EGAS FT 10, bandwidth 0–200 Hz, dimensions: 1.0 × 1.0 × 0.5 cm, mass: 1.0 g, sensitivity 649.5 mV·g-1) on each leg. The accelerometers were placed between the proximal and distal EMG electrodes of the bipolar arrangement using double-sided tape (Fig. 1). The raw EMG and MMG signals were digitized at 2000 Hz with a 32-bit analog-to-digital converter (Model MP150, Biopac Systems, Inc.), and the EMG signals were amplified (gain: × 1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA). Also, the EMG and MMG signals were zero-meaned and digitally bandpass filtered (fourth-order Butterworth) at 10–500 Hz and 5–100 Hz, respectively. Fast Fourier transform was used to derive the power density spectrum, and all signal processing was done offline utilizing customized LabView software. To assess neuromuscular responses throughout each of the three experimental, sustained leg extensions, a 1 s epoch length (2000 data points) for every 5% segment (i.e., average of 0–5%, 6–10%, etc. for a total of 20 data points) of the TTE was used to calculate the AMP (root mean square) for EMG (μVrms) and MMG (ms^{-2}) signals as well as the mean power frequency (MPF) values (in Hz).

Fig. 1 Example of experimental setup

Data analysis

All neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) and force values resulting from the three sustained leg extensions were normalized to corresponding MVIC values and were examined in 5% segments of TTE. Thus, each of these outcome variables had a total of 20 data points across time. Polynomial regression (linear and quadratic) analyses were used to define the individual and composite normalized EMG AMP, EMG MPF, MMG AMP, MMG MPF, and force values versus normalized time (every 5% segment) relationships during the experimental, sustained leg extensions. To assess performance fatigability resulting from these sustained leg extensions, a three (Intensity: Force at RPE = 1, Force at RPE = 5, and Force at RPE = 8) × 3 (Condition: Dominant Leg, Non-dominant Leg, and Bilateral) repeated-measures ANOVA was used to examine mean differences in percent change from pretest MVIC to posttest MVIC. Mean differences in TTE were assessed with a one-way repeated-measures ANOVA for the three levels of force. Significant interactions were decomposed with follow-up repeated-measures ANOVAs as well as planned, paired comparisons. Partial eta squared (η_p^2) and Cohen's d (d) were used as measures of effect for ANOVA models and paired comparisons, respectively. An intraclass correlation coefficient (ICC) was calculated for pretest MVIC values utilizing the 2, 1 model as recommended by Weir (2005), and the systemic mean differences were examine with a repeated-measures ANOVA. The Greenhouse–Geisser correction was applied when sphericity was not met (assessed with Maulchy's Test of Sphericity). All calculations and statistical analyses were conducted utilizing Microsoft Excel and Statistical Package for the Social Sciences software (version 26.0. SPSS Inc. Chicago, Ill, USA). A p value ≤ 0.05 was considered statistically significant, and all data were reported as mean ± SD.

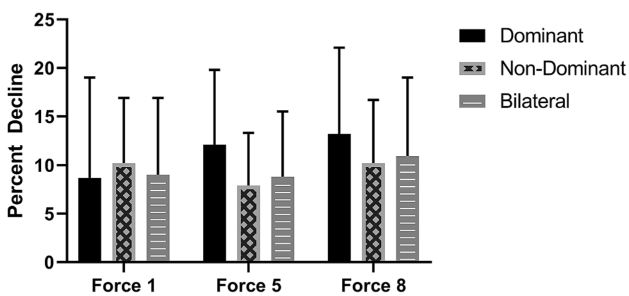

Fig. 2 There were no significant differences in the performance fatigability (mean ± SD) values among the dominant limb, non-dominant limb, and the bilateral condition during any of the three trials (Force 1, Force 5, and Force 8), and collapsed across trial and condition, performance fatigability was 10.1 ± 7.6%

Results

Pretest bilateral MVIC force reliability

The pretest bilateral MVIC force values from the three experimental visits indicated that there was an $ICC_{2,1} = 0.635$ ($CI_{95\%} = 0.303–0.864$) and that there was no significant ($F = 0.064$; $p = 0.938$) systemic mean differences between the visits (grand mean = 68.8 kg). The standard error of measurement was 6.71 kg (9.75% of the grand mean).

Critical force

Table 1 includes the CF data for each subject. The mean absolute CF value was 9.9 ± 5.0 kg, which normalized to MVIC was 14.6 ± 2.4%. The r^2 values for W_{lim} versus T_{lim} relationship ranged from 0.37–0.97.

Performance fatigability

The 3 × 3 repeated-measures ANOVA indicated that there was not a significant ($p = 0.100$, $\eta_p^2 = 0.171$) interaction or main effects (Intensity: $p = 0.685$, $\eta_p^2 = 0.028$ and condition: $p = 0.066$, $\eta_p^2 = 0.255$). The mean performance fatigability (collapsed across intensity and condition) was 10.1 ± 7.6% (Fig. 2).

Neuromuscular and force responses

Tables 2–7 include the individual and composite neuromuscular (EMG AMP, EMG MPF, MMG AMP, and MMG

Table 2 Polynomial regression model, correlation (Corr), and p values (if $p < 0.05$) of the women's dominant leg for normalized (normalized to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF vs. time during the sustained, submaximal isometric leg extension anchored to Force=1

Subject	EMG AMP			EMG MPF			MMG AMP			MMG MPF		
	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value
1	–	–	NS	–	–	NS	Quadratic	0.833	<0.001	–	–	NS
2	Quadratic	0.740	0.001	–	–	NS	Quadratic	0.885	<0.001	–	–	NS
3	–	–	NS	–	–	NS	Quadratic	0.847	<0.001	–	–	NS
4	Linear	0.951	<0.001	–	–	NS	Linear	0.924	<0.001	Linear	− 0.546	0.013
5	Linear	0.849	<0.001	Linear	− 0.594	0.006	Linear	0.623	0.003	–	–	NS
6	Linear	0.850	<0.001	Linear	− 0.453	0.045	Linear	0.835	<0.001	Linear	− 0.502	0.024
7	Linear	0.808	<0.001	Linear	− 0.466	0.049	Linear	0.776	<0.001	Linear	− 0.513	0.021
8	Linear	0.875	<0.001	–	–	NS	Linear	0.667	0.001	–	–	NS
9	Linear	0.874	<0.001	–	–	NS	Linear	0.778	<0.001	–	–	NS
10	Linear	0.946	<0.001	–	–	NS	Linear	0.891	<0.001	–	–	NS
11	Linear	0.885	<0.001	–	–	NS	Linear	0.843	<0.001	–	–	NS
12	–	–	NS	Linear	0.541	0.014	Linear	0.589	0.006	Linear	− 0.502	0.024
Composite	Linear	0.977	<0.001	–	–	NS	Linear	0.959	<0.001	Linear	− 0.692	0.001

MPF) responses versus time relationships for the dominant and non-dominant leg. There were no significant ($p > 0.05$) force versus time responses for either leg during any trial (i.e., force was held constant by design).

Force = 1

For the EMG AMP responses of the right leg (Table 2), the normalized individual and composite responses indicated that there were significant, positive, linear EMG AMP vs. time relationships ($r = 0.808$–0.977) for eight subjects and the composite. One subject demonstrated a significant, positive, quadratic relationship ($r = 0.740$) and three subjects demonstrated no significant relationships. For the left leg (Table 3), the normalized individual and composite responses indicated that there were significant, positive, quadratic EMG AMP vs. time relationships ($r = 0.866$–0.974) for five subjects and the composite. Six subjects demonstrated significant, positive, linear relationships ($r = 0.594$–0.904) and one subject exhibited no significant relationship.

For the EMG MPF responses of the right leg, the normalized individual responses indicated that there were negative significant, linear EMG MPF vs. time relationships for three subjects ($r = -0.453$ to -0.594) and a positive ($r = 0.541$) linear relationship for one subject. Eight subjects and the composite demonstrated no significant relationships. For the left leg, the normalized individual responses indicated that there was a significant, positive, linear EMG MPF vs. time relationship ($r = 0.652$) for one subject. Eleven subjects and the composite exhibited no significant relationship.

For the MMG AMP responses of the right leg, the normalized individual and composite responses indicated that there were significant, positive, linear MMG AMP vs. time relationships ($r = 0.589$–0.959) for nine subjects and the composite. Three subjects exhibited significant, positive, quadratic relationships ($r = 0.833$–0.885). For the left leg, the normalized individual and composite responses indicated that there were significant, positive, linear MMG AMP vs. time relationships ($r = 0.643$–0.923) for ten subjects and the composite. One subject exhibited a significant, positive, quadratic relationship ($r = 0.790$) and one subject exhibited no significant relationships.

For the MMG MPF responses of the right leg, the normalized individual and composite responses indicated that there were significant, negative, linear MMG MPF vs. time relationships ($r = -0.502$ to -0.692) for four subjects and the composite. Eight subjects exhibited no significant relationship. For the left leg, the normalized individual and composite responses indicated that there were significant, negative, linear MMG MPF vs. time relationships ($r = -0.450$ to -0.633) for three subjects and the composite. Nine subjects exhibited no significant relationships.

Force = 5

For the EMG AMP responses of the right leg (Table 4), the normalized individual and composite responses indicated that there were significant, positive, quadratic EMG AMP vs. time relationships ($r = 0.761$–0.780) for two subjects and the composite. Eight subjects demonstrated significant, positive, linear relationships ($r = 0.573$–0.906) and two subjects did not exhibit significant relationships. For

Table 3 Polynomial regression model, correlation (Corr), and p values (if $p < 0.05$) of the women's non-dominant leg for normalized (normalized to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF vs. time during the sustained, submaximal isometric leg extension anchored to Force=1

Subject	EMG AMP			EMG MPF			MMG AMP			MMG MPF		
	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value
1	–	–	NS	–	–	NS	–	–	NS	–	–	NS
2	Linear	0.678	0.001	–	–	NS	Linear	0.803	<0.001	Linear	− 0.450	0.047
3	Linear	0.594	0.006	–	–	NS	Quadratic	0.790	<0.001	–	–	NS
4	Linear	0.885	<0.001	–	–	NS	Linear	0.864	<0.001	–	–	NS
5	Linear	0.617	0.004	–	–	NS	Linear	0.841	<0.001	–	–	NS
6	Quadratic	0.935	<0.001	–	–	NS	Linear	0.923	<0.001	Linear	− 0.533	0.016
7	Quadratic	0.889	<0.001	–	–	NS	Linear	0.851	<0.001	–	–	NS
8	Quadratic	0.866	<0.001	–	–	NS	Linear	0.766	<0.001	–	–	NS
9	Linear	0.904	<0.001	–	–	NS	Linear	0.643	0.002	–	–	NS
10	Quadratic	0.936	<0.001	–	–	NS	Linear	0.895	<0.001	Linear	− 0.524	0.018
11	Quadratic	0.906	<0.001	–	–	NS	Linear	0.805	<0.001	–	–	NS
12	Linear	0.662	0.001	Linear	0.652	0.002	Linear	0.804	<0.001	–	–	NS
Composite	Quadratic	0.974	<0.001	–	–	NS	Linear	0.916	<0.001	Linear	− 0.633	0.003

Table 4 Polynomial regression model, correlation (Corr), and p values (if $p < 0.05$) of the women's dominant leg for normalized (normalized to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF vs. time during the sustained, submaximal isometric leg extension anchored to Force=5

Subject	EMG AMP			EMG MPF			MMG AMP			MMG MPF		
	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value
1	–	–	NS	–	–	NS	Linear	0.618	0.004	Linear	– 0.551	0.012
2	Quadratic	0.761	0.001	–	–	NS	–	–	NS	–	–	NS
3	Quadratic	0.780	<0.001	Linear	– 0.726	<0.001	–	–	NS	–	–	NS
4	Linear	0.895	<0.001	Linear	– 0.749	<0.001	Linear	0.606	0.005	–	–	NS
5	Linear	0.722	<0.001	Linear	– 0.781	<0.001	–	–	NS	–	–	NS
6	Linear	0.711	<0.001	Linear	– 0.841	<0.001	Linear	0.639	0.002	–	–	NS
7	Linear	0.906	<0.001	–	–	NS	Linear	0.884	<0.001	Linear	– 0.644	0.002
8	Linear	0.854	<0.001	–	–	NS	Linear	0.871	<0.001	Linear	– 0.496	0.026
9	Linear	0.896	<0.001	–	–	NS	Linear	0.523	0.018	–	–	NS
10	Linear	0.695	0.004	–	–	NS	-	-	NS	–	–	NS
11	–	–	NS	Linear	– 0.516	0.020	Linear	0.478	0.033	–	–	NS
12	Linear	0.573	0.008	–	–	NS	Linear	0.447	0.048	–	–	NS
Composite	Quadratic	0.944	<0.001	Linear	– 0.646	0.002	–	–	NS	Linear	– 0.564	0.010

Table 5 Polynomial regression model, correlation (Corr), and p values (if $p < 0.05$) of the women's non-dominant leg for normalized (normalized to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF vs. time during the sustained, submaximal isometric leg extension anchored to Force=5

Subject	EMG AMP			EMG MPF			MMG AMP			MMG MPF		
	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value
1	Linear	0.722	<0.001	–	–	NS	Linear	0.548	0.012	–	–	NS
2	Linear	0.723	<0.001	–	–	NS	–	–	NS	–	–	NS
3	Quadratic	0.691	0.015	Linear	– 0.561	0.010	–	–	NS	–	–	NS
4	Linear	0.850	<0.001	Linear	– 0.477	0.048	–	–	NS	–	–	NS
5	–	–	NS	Linear	– 0.885	<0.001	Linear	0.648	0.002	–	–	NS
6	Linear	0.898	<0.001	Linear	– 0.482	0.031	Quadratic	0.932	<0.001	–	–	NS
7	Linear	0.659	0.002	Linear	– 0.479	0.032	Linear	0.881	<0.001	–	–	NS
8	Linear	0.685	0.001	–	–	NS	Linear	0.847	<0.001	–	–	NS
9	–	–	NS	–	–	NS	–	–	NS	–	–	NS
10	Linear	0.616	0.004	–	–	NS	–	–	NS	–	–	NS
11	Linear	0.845	<0.001	Linear	– 0.841	<0.001	Linear	0.580	0.007	Linear	– 0.494	0.027
12	Linear	0.514	0.020	–	–	NS	Linear	0.748	<0.001	–	–	NS
Composite	Quadratic	0.960	<0.001	Linear	– 0.860	<0.001	Linear	0.873	<0.001	–	–	NS

the left leg (Table 5), the normalized individual and composite responses indicated that there were significant, positive, quadratic EMG AMP vs. time relationships (r=0.691 and 0.960) for one subject and the composite. Nine subjects demonstrated significant, positive, linear relationships (r=0.514–0.898) and two subjects exhibited no significant relationship.

For the EMG MPF responses of the right leg, the normalized individual and composite responses indicated that there were significant, negative, linear EMG MPF vs. time relationships (r=− 0.516 to − 0.841) for five subjects and the composite. Seven subjects did not exhibit significant relationships. For the left leg, the normalized individual and composite responses indicated that there were significant, negative, linear EMG MPF vs. time relationships (r=− 0.477 and − 0.860) for six subjects and the composite. Six subjects exhibited no significant relationships.

For the MMG AMP responses of the right leg, the normalized individual responses indicated that there were significant, positive, linear MMG AMP vs. time relationships (r=0.447–0.884) for eight subjects. Four subjects and the composite did not demonstrate a significant relationship.

For the left leg, the normalized individual and composite responses indicated that there were significant, positive, linear MMG AMP vs. time relationships ($r = 0.580$–0.881) for six subjects and the composite. In addition, one subject demonstrated a significant, positive, quadratic relationship ($r = 0.932$). Five subjects demonstrated no significant relationships.

For the MMG MPF responses of the right leg, the normalized individual and composite responses indicated that there were significant, negative, linear MMG MPF vs. time relationships ($r = -0.496$ to -0.644) for three subjects and the composite. Nine subjects did not exhibit significant relationships. For the left leg, the normalized individual responses indicated that there was a significant, negative, linear MMG MPF vs. time relationship ($r = -0.494$) for one subject. Eleven subjects and the composite exhibited no significant relationships.

Force = 8

For the EMG AMP responses of the right leg (Table 6), the normalized individual and composite responses indicated that there were significant, positive, quadratic EMG AMP vs. time relationships ($r = 0.793$–0.941) for two subject and the composite. Two subjects demonstrated significant, positive, linear relationships ($r = 0.850$ and 0.793) and eight subjects did not exhibit significant relationships. For the left leg (Table 7), the normalized individual and composite responses indicated that there were significant, positive, quadratic EMG AMP vs. time relationships ($r = 0.664$ and 0.862) for four subjects and the composite. Four subjects demonstrated significant, positive, linear relationships ($r = 0.678$–0.798) and four subjects exhibited no significant relationships.

For the EMG MPF responses of the right leg, the normalized individual and composite responses indicated that there were significant, negative, quadratic EMG MPF vs. time relationships ($r = -0.720$ to -0.803) for two subjects and the composite. In addition, two subjects demonstrated significant, negative, linear relationships ($r = -0.588$ and -0.600) and eight subjects did not exhibit significant relationships. For the left leg, the normalized individual and composite responses indicated that there were significant, negative, linear EMG MPF vs. time relationships ($r = -0.581$ and -0.843) for four subjects and the composite. Eight subjects exhibited no significant relationships.

For the MMG AMP responses of the right leg, the normalized individual and composite responses indicated that there were significant, positive, linear MMG AMP vs. time relationships ($r = 0.571$ and 0.813) for three subject and the composite. Nine subjects did not exhibit significant relationships. For the left leg, the normalized individual and composite responses indicated that there were significant, positive, linear MMG AMP vs. time relationships ($r = 0.476$ and 0.810) for three subjects and the composite. In addition, one subject demonstrated a significant, positive, quadratic relationship ($r = 0.890$). Eight subjects exhibited no significant relationships.

For the MMG MPF responses of the right leg, the normalized individual and composite responses indicated that there were significant, negative, linear MMG AMP vs. time relationships ($r = -0.492$ and -0.811) for five subjects and the composite. Seven subjects did not exhibit significant relationships. For the left leg, the normalized individual

Table 6 Polynomial regression model, correlation (Corr), and p values (if $p < 0.05$) of the women's dominant leg for normalized (normalized to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF vs. time during the sustained, submaximal isometric leg extension anchored to Force=8

Subject	EMG AMP			EMG MPF			MMG AMP			MMG MPF		
	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value
1	–	–	NS	–	–	NS	–	–	NS	–	–	NS
2	Quadratic	0.793	<0.001	–	–	NS	–	–	NS	–	–	NS
3	–	–	NS	–	–	NS	Linear	0.813	<0.001	–	–	NS
4	–	–	NS	–	–	NS	–	–	NS	Linear	− 0.492	0.028
5	–	–	NS	–	–	NS	Linear	0.647	0.002	Linear	− 0.553	0.011
6	Linear	0.941	<0.001	–	–	NS	–	–	NS	Linear	− 0.515	0.020
7	Linear	0.721	<0.001	–	–	NS	Linear	0.815	<0.001	Linear	− 0.519	0.019
8	Quadratic	0.850	<0.001	Quadratic	− 0.720	0.002	–	–	NS	Linear	− 0.543	0.013
9	–	–	NS	–	–	NS	–	–	NS	–	–	NS
10	–	–	NS	Linear	− 0.588	0.006	–	–	NS	–	–	NS
11	–	–	NS	Quadratic	− 0.741	0.001	–	–	NS	–	–	NS
12	–	–	NS	Linear	− 0.600	0.005	–	–	NS	–	–	NS
Composite	Quadratic	0.941	S	Quadratic	− 0.803	<0.001	Linear	0.571	0.008	Linear	− 0.811	<0.001

Table 7 Polynomial regression model, correlation (Corr), and p values (if $p < 0.05$) of the women's non-dominant leg for normalized (normalized to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF vs. time during the sustained, submaximal isometric leg extension anchored to Force=8

Subject	EMG AMP			EMG MPF			MMG AMP			MMG MPF		
	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value	Model	Corr	p value
1	Linear	0.798	<0.001	–	–	NS	–	–	NS	–	–	NS
2	–	–	NS	–	–	NS	–	–	NS	–	–	NS
3	Quadratic	0.664	0.007	–	–	NS	–	–	NS	–	–	NS
4	Quadratic	0.763	0.001	–	–	NS	–	–	NS	–	–	NS
5	–	–	NS	Linear	– 0.581	0.007	Linear	0.725	<0.001	–	–	NS
6	Quadratic	0.862	<0.001	Linear	– 0.698	0.001	Quadratic	0.890	<0.001	–	–	NS
7	Linear	0.705	0.001	–	–	NS	Linear	0.794	<0.001	–	–	NS
8	Linear	0.678	0.001	Linear	– 0.588	0.006	–	–	NS	–	–	NS
9	–	–	NS	–	–	NS	–	–	NS	–	–	NS
10	–	–	NS	–	–	NS	–	–	NS	–	–	NS
11	Linear	0.761	<0.001	Linear	– 0.806	<0.001	–	–	NS	–	–	NS
12	Quadratic	0.703	0.003	–	–	NS	Linear	0.476	0.034	–	–	NS
Composite	Quadratic	0.925	<0.001	Linear	– 0.843	<0.001	Linear	0.810	<0.001	Linear	– 0.692	0.001

and composite responses indicated that there was a significant, positive, linear MMG AMP vs. time relationships ($r = -0.692$) for the composite. The 12 individual subjects exhibited no significant relationships.

Time to exhaustion

The one-way repeated-measures ANOVA for TTE was significant ($p < 0.001$, $\eta_p^2 = 0.887$), and the follow-up Bonferroni corrected pairwise comparisons indicated Force = 1 (470.9 ± 125.4 s) was significantly ($p < 0.001$; $d = 3.78$ and 4.39) greater [mean differences = 356.1 (95% CI: 235.4–476.8 s) and 401.0 (95% CI: 296.6–505.4 s)] than Force = 5 (114.8 ± 44.8 s) and 8 (69.9 ± 30.7 s). Also, Force = 5 was significantly ($p = 0.013$; $d = 1.17$) greater than Force = 8.

Discussion

The primary aim of the current study was to examine the magnitude of performance fatigability as well as the associated limb- and intensity-specific neuromuscular patterns of responses during sustained, bilateral, isometric, leg extensions above and below CF. The results indicated: (1) performance fatigability was unvarying above and below CF as well as between limbs; (2) composite neuromuscular patterns of responses were similar above and below CF, except there was no change in EMG MPF below CF; and (3) there was substantial interindividual variation for the neuromuscular patterns of responses above and below CF.

The current study found that the women exhibited an overall 10.1 ± 7.6% decline in MVIC force from pretest to posttest as a result of the sustained, bilateral, isometric leg extensions, and there were no significant differences in the magnitude of performance fatigability above and below CF, or for either limb versus the bilateral condition (Fig. 2). This was the first study to examine performance fatigability defined as a decrease in MVIC force in women following sustained, bilateral tasks anchored to self-selected forces corresponding to RPE values above and below CF. Burnley et al. (2012) previously utilized seven intermittent, unilateral, isometric leg extensions to examine characteristics of fatigue above and below critical torque (i.e., CF), and found greater global fatigue (i.e., change in MVIC) and peripheral fatigue (i.e., change in involuntary potentiated twitch amplitude) following tasks above CF than below CF. There was, however, little variability in global fatigue and peripheral fatigue following the five trials above CF (Burnley et al. 2012). In agreement with these findings above CF (Burnley et al. 2012), Thomas et al. (2018) proposed that the effect of intensity on performance fatigability, as defined by a reduction in involuntary quadriceps potentiated twitch amplitude (i.e., peripheral fatigue), is negligible when the task is above CF and when the active muscle mass is small such as during unilateral tasks. Furthermore, Thomas et al. (2018) suggested that performance fatigability is inversely related to the amount of muscle mass recruited during a task due to the reduced likelihood of severe disruptions to systemic homeostasis when the active skeletal mass is small. This hypothesis (Thomas et al. 2018) was based, in part, on the findings of Rossman et al. (2012, 2014), who demonstrated a greater magnitude of global fatigue and peripheral fatigue following dynamic, unilateral, leg extensions compared to dynamic, bilateral leg extension at 85% peak workload (25 vs. 12% and 44 vs. 33%, respectively). Burnley et al. (2012) have also demonstrated that peripheral fatigue develops below CF, but stated that the origin of the peripheral impairment was not related to metabolic byproducts (i.e., H^+, P_i) (Jones et al. 2008) and alternatively may have been caused by a reduction in muscle glycogen and/or Ca^{2+}. Central fatigue was also observed above and below CF, but unlike peripheral fatigue, there was no difference in the magnitude of central fatigue above or below CF (Burnley et al. 2012). These findings were not consistent with previous findings (Søgaard et al. 2006; Yoon et al. 2007; Smith et al. 2007) that have suggested central mechanisms contribute to global fatigue to a greater extent below CF. While the current study only reported global fatigue (decrease in MVIC force) and did not dichotomize fatigue into central and peripheral components (Enoka and Duchateau 2016), the present findings do not align with previous data, suggesting that the degree of performance fatigability is affected by the exercise intensity relative to CF (Burnley et al. 2012) or the amount of muscle mass engaged (Thomas et al. 2018). That is, the current findings demonstrated that performance fatigability was unvarying above and below CF, as well as that the amount of engaged muscle mass did not influence performance fatigability given that, in theory, there was a greater amount of engaged muscle mass during the Force = 8 trial compared to the Force = 1 and 5 trials. In contrast to the hypothesis of Thomas et al. (2018) as well as the findings of Rossman et al. (2012, 2014), Koral et al. (2020) recently demonstrated that there was no difference in peripheral fatigue following time-matched sustained, maximal effort unilateral and bilateral leg extensions. Koral et al. (2020), however, reported that central drive was lower following the bilateral task compared to the unilateral task. Taken together, it is likely that performance fatigability is task- and definition-specific (Neyroud et al. 2016; Hureau et al. 2018), such that sustained, isometric muscle actions are likely regulated by different mechanisms than intermittent muscle actions as well as the definition of performance fatigability (global fatigue vs. peripheral fatigue vs. central fatigue) affects its interpretations. Under the current conditions and definition, however, the unvarying performance fatigability may have been influenced by an individual-specific sensory tolerance limit (Gandevia 2001), which suggests that performance fatigability is modulated by all available sensory feedbacks from the primary working muscles, activation of remote muscles, and feed forward signals to prevent individuals from exceeding a theoretical threshold of fatigue. It is also possible that fatigue occurred disproportionately at various locations within the neuromuscular system (i.e., supraspinal, distal to neuromuscular junction, etc.) depending on the intensity of the task (i.e., above or below CF) (Burnley et al. 2012), but regardless of the precise location of fatigue, the individuals continued each leg extension until their sensory tolerance limit was reached, which resulted in differences in the TTE but an unvarying magnitude of performance fatigability (i.e., global fatigue).

During the Force = 1 trial, the women exhibited composite increases in muscle excitation (EMG AMP) and motor unit recruitment (MMG AMP), as well as decreases in global motor unit firing rate (MMG MPF) in the dominant and non-dominant legs, but there was no change in CV (EMG MPF). Across both legs, there was an 83% (20/24), 79% (19/24), and 96% (23/24) agreement between the individual and composite directional responses for EMG AMP, EMG MPF, and MMG AMP, respectively. Thus, the composite responses characterized most of the individual fatigue-induced changes to motor unit activation strategies. There was, however, less agreement between the individual and composite responses for MMG MPF, which resulted in a 29% (7/24) match, while the other 17 individual responses reflected no change in global firing rate. Previously, Ryan et al. (2007) also demonstrated substantial interindividual variability following isometric step muscle actions, which resulted in a composite model decrease for MMG MPF, while 83% of the subjects remained unchanged. It has been suggested that morphological factors such as fiber-type composition, muscle size, and amount of adipose tissue contribute to the interindividual variability in the MMG signal (Beck et al. 2005). Thus, morphological factors may have contributed to the individual MMG MPF responses which remained unchanged, but once averaged, an overall decrease in global firing rate was exhibited. In addition, it has been reported that fatiguing tasks anchored to forces below ~ 30% MVIC were associated with little-to-no change in exercise-induced metabolic byproducts (Jones et al. 2008; Burnley et al. 2012), which may explain the current lack of change in EMG MPF, which is particularly sensitive to metabolic disturbances (Lindstrom 1970). Despite this lack of change in EMG MPF, performance fatigability was exhibited by all subjects and the composite neuromuscular models reflected fatigue-induced changes in motor unit activation strategies. As previously mentioned, the current investigation did not quantify individual components of fatigue. Based on the current composite neuromuscular patterns of responses, however, it was hypothesized that changes in the premotor regions of the brain or within the corticospinal motor pathway such as increases in intracortical inhibition (Smith et al. 2007) and/or decreases in central drive (Koral et al. 2020) as well as muscle spindle firing rates (Macefield et al. 1993) may have occurred. Thus, these fatigue-induced changes within the central nervous system may have been the primary factors leading to the ~ 10% decrease in MVIC force following the Force = 1 trial. In addition, these composite neuromuscular patterns of responses (increased motor unit recruitment, decreased global motor unit firing rate) were consistent with the Onion Skin scheme (De Luca and Contessa 2015), which proposes that, during submaximal tasks, fatigue is characterized by the recruitment of additional higher threshold motor units and an increase in the firing rates of the already activated motor units. The later recruited motor units, however, have lower firing rates than those initially recruited. The lower firing rates of the later recruited motor units are more influential and, therefore, there is a net decrease in the global motor unit firing rate (MMG MPF) (De Luca and Contessa 2015). Taken together, these fatigue-induced motor unit activation strategies below CF were likely induced by the women experiencing fatigue within the central nervous system given that there were likely no severe peripheral metabolic perturbations as reflected by the unchanged EMG MPF. Future studies should continue to examine the neuromuscular patterns of responses in women during the pretest and posttest MVIC trials and their relationship to performance fatigability to provide additional insight into the fatigue-induced neuromuscular changes below CF.

The neuromuscular composite models resulting from the trials above CF (Force = 5 and 8) indicated that there were differences in the patterns of responses above and below CF. Unlike below CF, during the Force = 5 and 8 trials, both limbs exhibited decrease in CV as reflected by the EMG MPF composite models, which suggested that peripheral factors contributed to the magnitude of performance fatigability (Lindstrom 1970; Jones et al. 2008; Burnley et al. 2012). Also, above CF, there was less agreement between the individual and composite responses as well as greater interindividual and limb variability than below CF. For example, during the Force = 5 trial, the composite MMG AMP model for the dominant leg remained unchanged, despite 8 of 12 individual responses exhibiting an increase. Thus, this MMG AMP composite model did not characterize the most prominent fatigue-induced change in motor unit recruitment. Similarly, during the Force = 8 trial, all 12 subjects exhibited no individual change in MMG MPF for the non-dominant leg, yet the composite model reflected a decrease in global motor unit firing. Also, across both limbs, the Force = 5 and 8 trials resulted in lower agreement between the individual and composite responses for EMG AMP (83 and 50%), EMG MPF (46 and 33%), MMG AMP (50 and 29%), and MMG MPF (58 and 21%) than the Force = 1 trial. It is likely that the greater magnitude of interindividual variability above CF compared to below CF was explained by the greater variability in self-selected forces above CF (SD ± = 3.3, 11.9, and 13.2% of MVIC, respectively). That is, the subjects exhibited greater differences in the self-selected force above CF than below CF, which may have increased the variability in the onset of fatigue-related responses (i.e., increases in motor unit recruitment and decreases in global firing rate). It is also possible that the MMG signals were influenced by individual-specific morphological factors (i.e., muscle size, fat content, and stiffness) (Beck et al. 2005; Ryan et al. 2007) that affected the agreement between the majority of individual responses and the composite models. Thus, the current findings further support the recommendation (Ryan et al. 2007; Anders et al. 2019) that inferences derived from these neuromuscular parameters should be based on individual neuromuscular patterns of responses. In accordance to this recommendation, the current study reported that during the Force = 5 and 8 trials, the women exhibited fatigue-induced increases in muscle excitation (EMG AMP) and motor unit recruitment as well as decreases in global motor unit firing rate (MMG MPF), which matched the neuromuscular patterns of responses below CF. Despite the potential differences in central versus peripheral manifestations of fatigue above and below CF, it was hypothesized that the Onion Skin scheme (De Luca and Contessa 2015) best explained the fatigue-induced changes to motor unit activation strategies above CF, as it did below CF. Interpretations of motor unit activation strategies in response to fatiguing tasks at high forces remain speculative (Piotrkiewicz and Türker 2017), but Hu et al. (2013) investigated muscle actions up to 50% MVIC and reliably demonstrated results consistent with the Onion Skin scheme. In the current study, on average, the Force = 5 and 8 trials, required forces of ~ 45% MVIC and ~ 65% MVIC, respectively. Therefore, after the examination of both individual and composite neuromuscular patterns of responses, force modulation in response to fatigue was likely consistent with the Onion Skin scheme during the Force = 5 and 8 trials.

There are several limitations to the current findings and interpretations such as the fatiguing task being isometric in nature, not dynamic, which may have fewer practical applications. In addition, several factors related to the convenience sample used as well as the available subject characteristics should be noted. For example, we did not report a fiber-type profile for our subjects, and Trevino et al. (2018) previously reported that neuromuscular differences such as motor unit action potential amplitudes differ between men and women likely as a result of greater type II characteristics in men. Thus, the current study needs to be replicated in men as well as by including methodology that can accurately provide fiber-type profiles (i.e., muscle biopsy + determination of % myosin heavy-chain area). Furthermore, while it was encouraged that the subjects maintain their typical dietary and hydration habits for the duration of the study, future studies should include nutritional and hydration analyses to ensure more adequate controls.

In summary, the current results demonstrated that performance fatigability was unvarying above and below CF as well as between limbs. This finding was not consistent with the previous results (Burnley et al. 2012; Rossman et al. 2012, 2014) or the hypothesis that performance fatigability is related to the amount of muscle mass engaged (Thomas et al. 2018). Based on the current results, however, it was hypothesized that the sensory tolerance limit (Gandevia 2001) may have modulated the degree of performance fatigability during each trial. Furthermore, there were generally no differences in the motor unit activation strategies above and below CF, but the EMG MPF responses suggested that there was likely a greater degree of peripheral fatigue above CF (Lindstrom 1970; Jones et al. 2008; Burnley et al. 2012). The individual responses supported the recommendation (Ryan et al. 2007; Anders et al. 2019) that the neuromuscular patterns of responses should be examined on a subject-by-subject basis to more accurately characterize the fatigue-induced changes in motor unit activation. Future studies should continue to examine motor unit activation strategies above and below CF as well as during other types of muscle actions to examine specific impairments (i.e., central vs. peripheral) underlying neuromuscular function associated with performance fatigability.

Acknowledgements We would like to thank all the participants for their time and for volunteering to comply with the protocol of the study. Also, we would like to thank the National Strength and Conditioning Association as well as the Northlands American College of Sports Medicine Chapter for funding this study.

Author contribution All authors conceived and planned the experiment. JLK, JPVA, and TJN carried out the data collection. JLK with support from TJH wrote the manuscript. JLK, JPVA and TJN performed the data analysis support. RJS and GOJ helped supervise the project. All authors provided critical feedback and contributed to the final version of the manuscript.

Funding This study was at least in part funded by the National Strength and Conditioning Association as well as the Northlands American College of Sports Medicine Chapter.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to report.

Ethical approval The University Institutional Review Board for Human Subjects approved the study (IRB#: 20190619436EP).

Consent to participate During the familiarization visit, the subjects completed a health history questionnaire and gave written informed consent.

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