

Original Article

Time course of changes in torque and neuromuscular parameters during a sustained isometric forearm flexion task to fatigue anchored to a constant rating of perceived exertion

Robert W. Smith, Terry J. Housh, John Paul V. Anders, Tyler J. Neltner, Jocelyn E. Arnett, Richard J. Schmidt, Glen O. Johnson

Department of Nutrition and Human Sciences, University of Nebraska – Lincoln, Lincoln, USA

Abstract

Objective: This study examined the time course of changes in torque and electromyographic (EMG) and mechanomyographic (MMG) responses during a sustained isometric task anchored to a constant perception of exertion (RPE). **Methods:** Twelve college-aged men performed an isometric forearm flexion task to failure anchored to RPE=7 (OMNI-RES scale). The amplitude (AMP) and frequency (MPF) of the EMG and MMG signals from the biceps brachii were recorded. Repeated measures ANOVAs were used to examine differences for the normalized (%MVIC) torque and neuromuscular parameters. **Results:** The time to task failure (TTF) was 678.0 ± 468.1 s. Torque decreased significantly ($p < 0.001$, $\eta_p^2 = 0.774$) across time and all subjects reduced torque to zero. Post-hoc comparisons indicated that the torque values from 20–100% TTF were less than the value at 10% TTF. There were no significant ($p > 0.05$) changes from 10–100% TTF for the EMG and MMG parameters. **Conclusion:** We hypothesize that RPE was maintained by various mechanisms throughout the task: group III/IV afferent neurons, adequate blood flow, and a combination of reduced contractile efficiency, collective afferent feedback (group III/IV afferents) from muscles involved with forearm flexion, and motivation that resulted in an initial decrease, plateau, and final decline in torque to zero, respectively.

Keywords: Electromyography, Fatigue, Upper Body, Mechanomyography, RPE Clamp Model

Introduction

Ratings of perceived exertion (RPE) are used to quantify the level of exertion during an exercise bout and include feedback from the primary and synergistic muscles, as well as the cardiovascular, respiratory, and central nervous systems¹. Robertson and Noble² proposed that RPE is influenced by factors such as the intensity of effort, strain, discomfort, and/or fatigue experienced during a given task.

Ratings of perceived exertion have been used to prescribe exercise training intensity^{3,4}, autoregulate resistance training intensity and volume⁵⁻⁷, and assess the physiological mechanisms of fatigue⁸⁻¹².

Over the years, many definitions of fatigue have been proposed which has complicated the ability to define the characteristics of a fatiguing task^{13,14}. Kluger et al.¹³, however, proposed a unified taxonomy of fatigue that included the interdependent aspects of performance fatigability and perceived fatigability. Performance fatigability was defined 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"¹³. Enoka and Duchateau¹⁴ have stated that performance fatigability is modulated by factors associated with contractile function such as calcium kinetics, force capacity, blood flow, and metabolism, as well as muscle activation including voluntary activation, activation patterns, motor

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Corresponding author: Robert W. Smith, 540 N 16th Street, Lincoln, NE 68508-0626, USA

E-mail: bsmith80@huskers.unl.edu

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neurons, afferent feedback, and neuromuscular propagation. Perceived fatigability refers to "...subjective sensations of weariness, increases in sense of effort, mismatch between effort expended and actual performance, or exhaustion"¹³. Perceived fatigability is influenced by factors associated with the maintenance of homeostasis such as blood glucose, core temperature, hydration, neurotransmitters, metabolites, oxygenation, and wakefulness, as well as the individual's psychological state including arousal, executive function, expectations, mood, motivation, pain, and performance feedback¹⁴.

Recent studies¹⁵⁻²² have used the RPE Clamp Model of Tucker²³ to examine the interactions between the perception of fatigue and factors associated with performance fatigability during isometric leg extensions, cycle ergometry, and treadmill running. These studies anchored force¹⁵⁻¹⁸, power output^{21,22}, or running velocity²⁰ using the Borg (6–20) RPE Scale²⁴ or the OMNI-RES (0–10) RPE Scale^{25,26} and assessed oxygen consumption, heart rate, respiratory exchange ratio (RER), minute ventilation, and respiratory frequency, as well as electromyographic (EMG), and mechanomyographic (MMG) parameters during sustained exercise bouts. Simultaneous measurements of the time and frequency domain parameters of the EMG and MMG signal have been used to describe the fatigue-induced patterns of neuromuscular responses during various tasks²⁷⁻³³. Specifically, the amplitude (AMP) of the EMG signal reflects muscle activation²⁷, while the mean power frequency (MPF) is associated with muscle fiber action potential conduction velocity²⁸. Under some conditions, the AMP of the MMG signal reflects motor unit recruitment²⁹⁻³¹ and the MMG MPF qualitatively represents changes in the global firing rate of the activated, unfused motor units^{32,33}. Thus, physiological, and neuromuscular measures potentially allow for inferences to be made regarding fatigue-induced changes in metabolic responses and motor unit activation strategies. Previous findings indicated that the neuromuscular responses when the exercise bout was anchored to RPE were different than when anchored to a performance-related parameter like force, power output, or velocity^{15-18,20-22}. Thus, the neuromuscular responses were dependent upon the mode of exercise, level of perceived exertion, and the muscle groups involved. Anchoring a fatiguing task to RPE while assessing various aspects of performance responses^{13,14,34} allows for the examination of the interactions among factors associated with perceived fatigability and performance fatigability. It has been suggested³⁵ that the magnitude of performance fatigability is determined by the mode and intensity of exercise which dictates the amount of muscle mass activated and the subsequent demands on the various systems of the body during the task. According to Thomas et al.³⁵, smaller engaged muscle mass should produce less systemic perturbations and result in greater performance fatigability before "...the task is perceived as intolerable". This hypothesis has recently¹⁹ been examined by anchoring unilateral and bilateral leg extension tasks by RPE and examining the performance-related changes in force and

neuromuscular parameters. No previous studies, however, have used the RPE Clamp Model²³ to assess fatigue-induced changes in torque and neuromuscular responses for forearm flexion which includes even less activated muscle than that associated with the leg extensors. Therefore, the purpose of the present study was to examine the time course of the fatigue-induced changes in torque and neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) during a sustained, isometric forearm flexion task anchored to a constant RPE of 7 (OMNI-RES scale). Based on the findings of previous studies^{17,18,21,22}, it was hypothesized that there would be fatigue-induced decreases in torque and EMG AMP, increases in MMG AMP, and no changes in EMG MPF and MMG MPF throughout the sustained, isometric task.

Methods

Subjects

Twelve men (mean±SD: age=21.3±1.7 yrs.; height=181.1±6.7 cm; body mass=87.2±17.0 kg) volunteered to participate in this study. The subjects were recreationally trained and participated in resistance and/or aerobic exercise at least 3 d·wk⁻¹³⁶, and all of the subjects were free of upper body pathologies that would affect their performance. The subjects in the present study were part of a large multiple independent and dependent variable investigation, but none of the data in the present study have been previously published. The study was approved by the University Institutional Review Board for Human Subjects (IRB Approval #: 20201220785FB), and all subjects completed a Health History Questionnaire and signed a written Informed Consent prior to testing.

Familiarization Visit

During the familiarization visit, the subject's dominant arm (based on throwing preference), age, height, and body mass were recorded. In addition, the subject was oriented to their testing position on the isokinetic dynamometer with the lateral epicondyle of the humerus of the dominant arm aligned with the lever arm of the dynamometer and an elbow joint angle at 100° (Cybex 6000, Cybex International Inc. Medway, MA). While positioned, the subject was familiarized with the 0–10 OMNI-RES scale²⁶ and read the standardized OMNI-RES instructions^{15,26} that were used during the experimental visit. The OMNI-RES (0–10) RPE scale has been shown to be valid and reliable for quantifying the perception of exertion during resistance training²⁶. The subject then completed the standardized warm-up consisting of 6, submaximal (approximately 50-75% of their maximal effort), isometric forearm flexion tasks (at the elbow) as well as 2, 3 s maximal voluntary isometric contractions (MVICs) to set a perceptual anchor corresponding to RPE=10. Finally, the subject performed a brief (approximately 1–2 min), sustained, isometric task anchored to RPE=7 on the OMNI-RES scale to familiarize the subject with the testing procedures.

OMNI-RES Scale Standardized Anchoring Instructions

The anchoring instructions used in the present study were originally developed by Gearhart et al.³⁷ as a standardized method to gauge training intensity during lower body exercise. The instructions were adapted by Keller et al.¹⁵ to be utilized as anchoring procedures during an isometric leg extension task and have been modified for use during forearm flexion in the present study. Therefore, to promote the proper use of the OMNI-RES scale, the following standardized anchoring instructions were read to each subject during the familiarization visit and prior to the RPE trial, “You 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”.

Experimental Visit

Prior to the experimental visit, subjects were instructed to avoid upper body exercise at least for 24 hours prior to testing. During the experimental visit, the subject was positioned in accordance with the Cybex 6000 user's manual on an upper body exercise table (UBXT) with the lateral epicondyle of the humerus of the dominant arm aligned with the lever arm of the dynamometer and an elbow joint angle at 100°. Once positioned, the subject performed the standardized warm-up consisting of 6, 3 s, submaximal, isometric forearm flexion tasks followed by 1 min of rest. After the warm-up, the subject was read the OMNI-RES instructions relating to the anchoring procedures. The subject then performed 2, 3 s forearm flexion MVICs on a calibrated dynamometer (Cybex 6000, Cybex International Inc. Medway, MA). Strong verbal encouragement was provided during each MVIC trial, and the MVIC was performed to familiarize the subject with RPE=10 on the OMNI-RES scale. The elbow joint angle of 100° for forearm flexion was selected to reflect the point in the range of motion associated with maximal isometric torque production³⁸. Following the MVIC trials, the sustained, submaximal, isometric forearm flexion task anchored to RPE=7 on the OMNI-RES scale was performed at the elbow joint angle of 100°. During the sustained isometric task, the subject was blinded to torque and elapsed time to avoid pacing strategies^{19,39}. The RPE trial was sustained until task failure which was defined as a torque that would require RPE >7, or the torque was reduced to zero. Thus, during the RPE trial, the subject was free to decrease torque to maintain a constant RPE value. Following the cessation of the forearm flexion task, the time to task failure (TTF) was recorded. In addition, during the sustained isometric task, the subject was reminded to be attentive to sensations such as strain, intensity, discomfort, and fatigue felt during the contraction to maintain appropriate levels of exertion^{2,18}. Furthermore,

the subject was continuously reminded that there were no incorrect contractions or perceptions and were reminded to relate levels of exertion to the previously set anchors.

Electromyographic, Mechanomyographic, and Torque Signal Acquisition

During the experimental 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 Muscles⁴⁰. A reference electrode was 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 between the medial acromion and the fossa cubit, at one-third the distance from the fossa cubit over the BB. Using double-sided adhesive tape, a miniature accelerometer (ICP® Accelerometer, bandwidth 0-1000 Hz, dimensions 0.48 × 1.22 × 0.71 cm, mass 0.85 g, sensitivity 103.4 mV·g⁻¹; PCB Piezotronics, Depew, NY) were placed between the bipolar EMG electrodes to detect the MMG signals for the BB muscles.

The raw EMG and MMG signals were digitized at 2000 samples/second with a 12-bit analog-to-digital converter (Model MP150; Biopac Systems, Inc.) and stored on a personal computer (Acer Aspire TC-895-UA91 Acer Inc., San Jose, CA, USA) for analyses. The EMG signals were amplified (gain: × 1000) using differential amplifiers (EMG2-R Bionomadix, Biopac Systems, Inc. Goleta, CA, USA; bandwidth—10-500 Hz). The EMG and MMG signals were digitally bandpass filtered (fourth-order Butterworth) at 10-500 Hz and 5-100 Hz, respectively. Signal processing was performed using custom programs written with LabVIEW programming software (version 20.0f1, National Instruments, Austin, TX, USA). The TTF (0 – 100 %) was divided into 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 EMG (μVrms) and MMG ($\text{m}\cdot\text{s}^{-2}$) signals, as well as the mean power frequency (MPF in Hz) for both signals. The MPF was selected to represent the power density spectrum and was calculated as described by Kwatny et al.⁴¹. The torque signals were sampled from the digital torque of the Cybex 6000 dynamometer and stored on a personal computer (Acer Aspire TC-895-UA91 Acer Inc., San Jose, CA, USA) for analysis. The pretest forearm flexion MVIC with the greatest torque production was used to normalize the torque, EMG, and MMG parameters for each 10 % of the TTF, as well as the initial torque and the initial neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) of the first 3 s of the sustained, isometric, forearm flexion task anchored to RPE=7 (Figure 1).

Statistical Analysis

The mean differences across time for the normalized neuromuscular parameters (EMG AMP, EMG MPF, MMG

Table 1. Pretest MVIC (N·m), initial torque (N·m), normalized initial torque (% of pretest MVIC), and percent decline in torque from the initial torque at RPE=7 during the sustained, isometric muscle action to task failure.

Subjects	Pretest MVIC	Initial Torque	% MVIC	Torque at Task Failure	Percent Decline (%)
1	61	21.8	35.7	0	100
2	58	20.2	34.8	0	100
3	41	26.7	65.1	0	100
4	56	42	75.0	0	100
5	68	37.8	55.6	0	100
6	65	32.5	50.0	0	100
7	69	34.8	50.4	0	100
8	55	32.2	58.5	0	100
9	54	25	46.3	0	100
10	56	39.8	71.1	0	100
11	32	15.8	49.4	0	100
12	39	25.3	64.9	0	100
Mean±SD	54.5±11.6	29.5±8.3	54.7±12.8	0±0	100±0

AMP, and MMG MPF) were determined with four, separate 1 (Neuromuscular Parameter: % MVIC neuromuscular value) × 10 (Time: % TTF) repeated measures ANOVAs. A 1 (Torque: % MVIC) × 10 (Time: % TTF) repeated measures ANOVA was used to determine the mean differences across time for the torque values. Mean differences for the initial torque and the initial neuromuscular values versus the torque and neuromuscular values at 10 % TTF were assessed with paired samples t-tests. 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. Post-hoc Student–Newman–Keuls⁴² was used to identify the time course of when the normalized neuromuscular and torque values changed from the value at 10 % TTF. In addition, effect sizes were reported as η_p^2 and Cohen's *d* for ANOVAs and post-hoc pairwise comparisons, respectively. All calculations and statistical analyses were carried out in IBM SPSS v. 26 (Armonk, NY, USA). Finally, a *p*-value ≤0.05 was considered statistically significant and all the data was reported as mean ± SD.

Results

MVIC, Initial Torque, Percent Decline, and TTF

The pretest MVIC (N·m), initial torque (N·m and % of pretest MVIC), torque at task failure, and percent decline from the initial torque to task failure during the sustained task anchored to RPE = 7 are presented in Table 1. In addition, the TTF during the sustained isometric task was 678.0 ± 468.1 s (range=120–1797.6 s).

Initial Torque, Initial Neuromuscular Parameters, and 10% TTF

The initial torque was significantly (*p*<0.001, *d*=2.410) greater than the mean torque value at 10 % TTF (Figure 1E).

For the initial EMG values, the initial EMG AMP (*p*<0.005, *d*=1.160) and the initial EMG MPF (*p*<0.005, *d*=1.130) were significantly greater than the EMG AMP and EMG MPF values at 10 % TTF, respectively (Figure 1A and 1B). For the initial MMG values, the initial MMG AMP (*p*=0.077, *d*=0.45) and the initial MMG MPF (*p*=0.199, *d*=0.33) were not significantly greater than MMG AMP and MMG MPF values at 10 % TTF, respectively (Figure 1C and 1D).

Torque Responses

For the torque responses during the sustained task anchored to RPE=7, there was a significant (*p*<0.001, $\eta_p^2=0.774$) decrease across time and the mean values from 20–100% of the TTF were less than the value at 10% TTF (Figure 1E). Post-hoc comparisons, however, indicated no significant (*p*>0.05) differences between the mean values from 20–90% TTF (Figure 1E). In addition, post-hoc comparisons indicated that the mean torque value at 90% TTF was significantly (*p*<0.001) greater than the value at 100% TTF. An example of the changes in torque during the sustained, isometric forearm flexion task anchored to RPE=7 are presented in Figure 2.

EMG Responses and MMG Responses

For the EMG responses, there was no significant (*p*=0.180, $\eta_p^2=0.153$) change across time for EMG AMP (Figure 1A) or EMG MPF (*p*=0.802, $\eta_p^2=0.028$; Figure 1B). For the MMG responses, there was no significant (*p*<0.766, $\eta_p^2=0.015$) change across time for MMG AMP (Figure 1C) or MMG MPF (*p*<0.681, $\eta_p^2=0.027$; Figure 1D).

Discussion

During the sustained, isometric task at RPE=7 in the current study, task failure was defined as an RPE>7, or torque

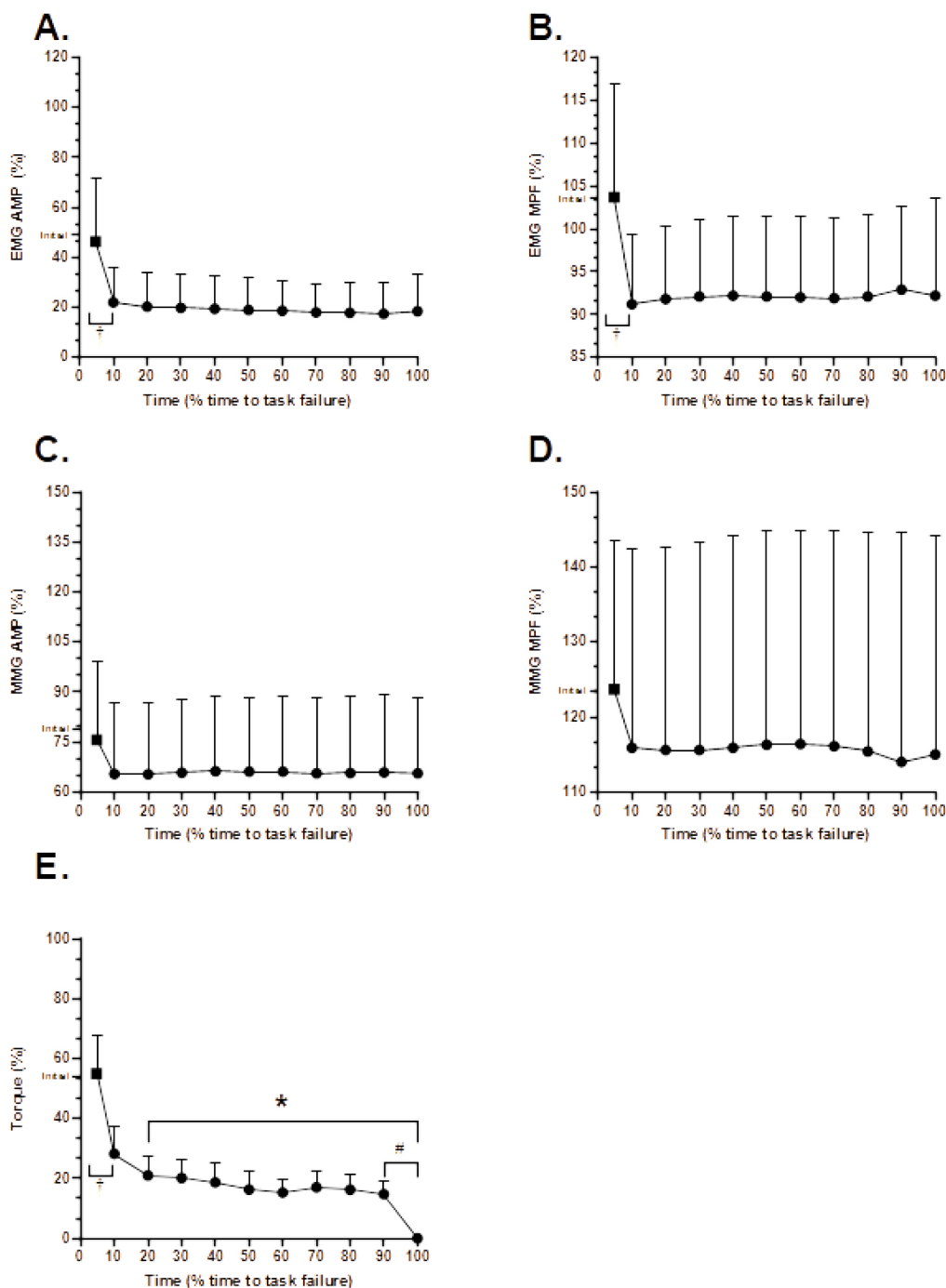


Figure 1. Time course of changes for the mean \pm SD normalized neuromuscular and torque values (% pretest MVIC) for the sustained, isometric forearm flexion muscle action anchored to RPE=7. A) Electromyographic amplitude (EMG AMP), B) Electromyographic mean power frequency (EMG MPF), C) Mechanomyographic amplitude (MMG AMP), D) Mechanomyographic mean power frequency (MMG MPF), E) Torque. *Significantly lower torque than the value at 10% TTF of the sustained muscle action based on post-hoc Student-Newman-Keuls mean comparisons; (■) normalized (% of pretest MVIC) initial torque and neuromuscular values of the first 3 s of the sustained isometric muscle action; (†) significantly ($p > 0.05$) greater initial torque, initial EMG AMP, and initial EMG MPF than the corresponding mean value at 10% TTF; (#) significantly ($p > 0.05$) greater torque at 90% TTF versus 100% TTF.

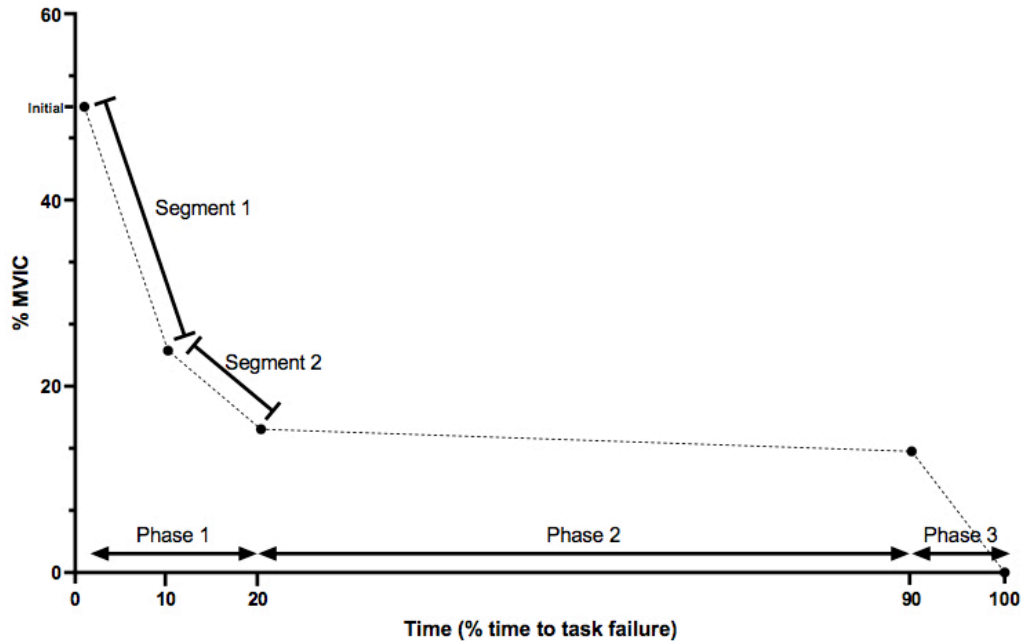


Figure 2. An example (Subject 6) of the changes in torque (% MVIC) during the sustained, isometric forearm flexion muscle action anchored to RPE=7.

was reduced to zero. Furthermore, during the fatiguing task, all subjects consciously reduced torque to zero to maintain RPE=7 (Table 1). These findings were in agreement with previous studies that applied the RPE Clamp Model²³ to examine changes in torque or force, running speed, and power output, during isometric leg extensions¹⁶⁻¹⁸, treadmill running²⁰, and cycle ergometry^{11,21}, respectively. Recently, Smith et al.⁴³ reported a $95.69 \pm 6.54\%$ decline in torque during a sustained, isometric forearm flexion task anchored to RPE=7 in women. The present findings, in conjunction with previous research, indicated that it was necessary to reduce the intensity of exercise to maintain the prescribed RPE^{11,16-18,20,21}.

The present study utilized the RPE Clamp Model²³ which suggests that during sustained tasks anchored to RPE, the initial exercise intensity is set in an anticipatory manner. Theoretically, the anticipatory component of the RPE Clamp Model is composed of physiological inputs such as muscle glycogen levels, fitness and nutritional status, and core temperature, psychological inputs like motivation and arousal, expected exercise duration, and previous experiences that are integrated and processed within the brain to set an optimal torque that matches the prescribed RPE²³. Thus, according to the RPE Clamp Model, the initial torque value at the beginning of sustained task in the present study (Figure 1E: 54.7 ± 12.8 % MVIC), was perceived to match the prescribed RPE of 7 based on an anticipatory component that integrated physiological, psychological,

and task-related factors. Additionally, these findings were consistent with previous studies that reported initial torque (or force) values during sustained, isometric tasks anchored to a high perceptual intensity^{43,44}. Specifically, Smith et al.⁴³ reported that during an isometric forearm flexion task anchored to RPE=7 in women, the initial torque was 59.7 ± 15.0 % MVIC and Keller et al.⁴⁴ reported that during isometric leg extensions anchored to RPE=8, the initial force values for men and women were 55.7 % and 58.5 % MVIC, respectively.

In the present study, there were three discernable phases for the changes in torque across time during the sustained, isometric forearm flexion muscle action anchored to RPE = 7 (Figure 1E and Figure 2). The first phase of the torque versus time relationship was from the initial torque (average of the first 3 s) to 20 % TTF (135.6 ± 93.6 s) and included two distinct segments (segment 1 and segment 2). Segment 1 was characterized by a precipitous decrease the initial value to 10 % TTF (54.7 ± 12.8 to $28.2 \pm 8.9\%$ MVIC; Figure 1E). The decreases in torque from the initial torque value occurred concurrently with decreases in EMG AMP and EMG MPF, but there were no changes in MMG AMP or MMG MPF (Figure 1). The large decline in torque from the initial value to 10% TTF (54.7 ± 12.8 to $28.2 \pm 8.9\%$ MVIC; Figure 1E) indicated that the initial torque, which was set in an anticipatory manner, was almost immediately perceived by the subject as too high to be maintained at RPE=7. It is possible that this initial conscious decision to adjust torque downward was

informed by afferent feedback, perhaps to the SMA of the brain⁴⁵, from group III (primarily mechanosensitive) neurons based on the initial perception of effort of the contraction⁴⁶ and the likelihood that there was not a substantial buildup of metabolic byproducts at that point^{46,47}. This may have caused a reduction in central motor drive which resulted in de-recruitment of motor units and reduced torque output.

After segment 1 of the first phase, torque continued to decrease throughout segment 2 from 10% TTF to 20% TTF, but at a reduced rate. Throughout segment 2, torque decreased from $28.2 \pm 8.9\%$ MVIC to $21.0 \pm 6.4\%$ MVIC (Figure 1E). These findings indicated that there were dissociations between the gradual decrease in torque from 10% TTF to 20% TTF, and the lack of changes in neuromuscular responses and RPE. During segment 2, it is likely that the decision to decrease torque to maintain RPE=7 was informed by afferent feedback from both group III and IV (metabosensitive) neurons due to increased levels of metabolic byproducts such as inorganic phosphate and hydrogen ions within the active muscle fibers^{23,46,48}. Therefore, the conscious decision to rapidly decrease torque during segment 1 was likely mediated via afferent feedback from primarily group III neurons, while the afferent feedback from both group III and group IV afferents likely contributed to the reduced rate of decrease in torque during segment 2. The present findings were consistent with previous research that utilized the RPE Clamp Model²³ during sustained, isometric leg extensions¹⁶⁻¹⁸ as well as during a forearm flexion task to failure⁴³. Specifically, Smith et al.⁴³ reported a decrease in torque, EMG AMP, and EMG MPF, but no changes in MMG AMP or MMG MPF from the initial value (average of the first 3 s) during a sustained, forearm flexion task anchored to RPE=7 in women. Keller et al.^{17,18} demonstrated that both women and men reduced force from the initial value (5% TTF) to 20% TTF, but there were no changes for any of the neuromuscular parameters. Like the current study, the changes in force or torque were not reflective of the lack of changes in the neuromuscular parameters.

During the second phase of the sustained isometric muscle action in the present study, torque was characterized by a plateau between 20% and 90% TTF for 542.4 ± 374.4 s at average torque of $17.4 \pm 2.3\%$ MVIC. Based on the RPE Clamp Model²³, this plateau in torque corresponded to an intensity that the subjects perceived as sustainable at RPE=7. During this period, all of the neuromuscular parameters and torque remained unchanged and tracked RPE. Thus, there were no perceptual or torque-related indicators of fatigue from 20-90% TTF. Furthermore, the consistent neuromuscular responses suggested the subjects were able to sustain RPE and torque across this 9-minute time period with no changes in muscle activation (EMG AMP), muscle fiber action potential conduction velocity (EMG MPF), motor unit recruitment (MMG AMP), or global firing rate of unfused activated motor units (MMG MPF). Previous studies⁴⁹⁻⁵² have reported that sustained, isometric tasks up to 25% MVIC could be maintained without attenuated blood flow which allows for clearance of metabolites and the

replenishment of energy substrates. Similar force or torque and neuromuscular responses were reported by Keller et al.¹⁶⁻¹⁸ and Smith et al.⁴³ which support the findings of the present study and the suggestion that this plateau in torque and neuromuscular parameters was due to an intensity that the subjects perceived as sustainable at RPE=7.

During the third phase of the sustained, isometric muscle action in the present study, torque decreased from $17.4 \pm 2.3\%$ MVIC to zero from 90% TTF to 100% TTF over the course of 67.8 ± 48.6 s. Although torque decreased to zero, RPE and the neuromuscular parameters remained unchanged. Like the present study, Smith et al.⁴³ reported decreases in torque to zero for five of the 11 (45.4%) subjects and a significant reduction in torque by task failure for the other six subjects, but no changes for any of the neuromuscular parameters from 90-100% TTF. The present findings indicated that there were dissociations for torque versus the perceptual and neuromuscular responses which demonstrated a decrease in contractile efficiency. These time-dependent patterns for torque, and neuromuscular parameters were consistent with peripheral fatigue and the characteristics of excitation-contraction coupling failure due to the effects of exercise-induced, intramuscular metabolic perturbations on calcium release and re-uptake kinetics, calcium sensitivity for binding with troponin, and actin-myosin binding properties⁵³⁻⁵⁵. It is also possible that the sum of feedback from all of the active muscles involved in forearm flexion via group III/IV afferent neurons as well as feedback from other systems directly or indirectly involved in the exercise task led to the reduction in torque and termination of the task based on the sensory tolerance limit (STL)⁵⁶. Hureau et al.⁵⁶ described the STL as a global model of fatigue where the sum of all feedback, from systems directly and/or indirectly involved in the exercise task, causes a reduction in performance or termination of the task. The lateral prefrontal cortex (LPFC) has been proposed as a region of the brain which is primarily responsible for the decision to continue or terminate exercise⁵⁷. Specifically, Robertson and Marino⁵⁷ proposed that the LPFC integrates afferent feedback as well as motivation and emotional responses sent from the anterior cingulate cortex (ACC) and the orbitofrontal cortex (OFC). Once this information has been integrated within the LPFC, the decision to modify exercise intensity or terminate exercise is passed through the premotor area (PMA) and the basal ganglia (BG) via feedforward mechanisms⁵⁷. It is also possible, however, that factors associated with perceived fatigability such as mood, pain, and/or motivation contributed to the decrease in torque to zero during the third phase^{13,14}. For example, Kluger et al.¹³ and Enoka and Duchateau¹⁴ have suggested motivation may cause a reduction in exercise performance to manage the development of fatigue. Thus, some subjects may have lost motivation to continue the task. The torque and neuromuscular findings for the third phase can be used to formulate testable hypotheses regarding whether motivation and/or fatigue-induced feedback from synergistic muscles involved with forearm flexion and handgrip contributed to the decision to decrease torque to zero and terminate the task.

In summary, the present study utilized the RPE Clamp Model²³ to examine the time course of changes in torque as well as the amplitude and frequency contents of the EMG and MMG signals. The torque responses indicated three distinct phases throughout the sustained, isometric muscle action anchored to RPE=7. Torque adjustments to maintain RPE=7 in each phase may have been informed by different mechanisms. The first phase included segment 1 and segment 2. Segment 1 was characterized by a precipitous decrease in torque which was likely informed by afferent feedback from group III mechanosensitive neurons. Like torque, there were decreases for each neuromuscular parameter during segment 1. Segment 2 of the first phase was characterized by a gradual decrease in torque at a reduced rate which was likely mediated by a combination of group III mechanosensitive and group IV metabosensitive neurons activated by an increase in metabolites. There were dissociations, however, between torque, RPE, and the neuromuscular responses, with no changes in RPE or the neuromuscular parameters during segment 2 of the first phase. The second phase was characterized by a plateau in torque which, according to the RPE Clamp Model²³, was due to a torque that was perceived by the subjects to be sustainable at RPE=7. The lack of changes in RPE, torque, or the neuromuscular parameters suggested there were no perceptual or torque-related indicators of fatigue during the second phase of the sustained, isometric muscle action. The third phase was characterized by a final decline in torque to zero which was dissociated from the neuromuscular responses and RPE which remained unchanged. The decrease in torque may have been influenced by a combination of factors. Specifically, peripheral fatigue, which was characterized by excitation contraction coupling failure, fatigue-induced feedback, likely due to group III/IV afferents, from muscles involved with forearm flexion and handgrip, and motivation which caused the subjects to terminate the exercise. A potential limitation of the present findings was that six of the 12 subjects reported daily consumption of creatine monohydrate which has been demonstrated to increase muscle mass and muscle strength as well as improve glycogen loading which may indirectly improve muscle endurance⁵⁸. Although motivation and pain were offered as possible mechanisms responsible for task termination, these variables were not measured and thus, follow-up studies should utilize these factors to determine if there was any measurable effect on the decision to terminate the task. Future studies should utilize the interpolated twitch technique and involuntary potentiated twitch to examine possible central and peripheral contributions to torque modulation during sustained tasks anchored to a constant RPE. Furthermore, the application of a pain scale would be useful to investigate potential interactions between pain and perceived exertion during a sustained task anchored to RPE. Finally, future research should incorporate the use of ultrasound or near-infrared spectroscopy (NIRS) to assess potential changes in blood flow and oxygenation of the active muscle(s) to examine effects of peripheral fatigue on torque response when anchored to RPE.

Authors' contributions

RWS was primarily responsible for data collection, analyses, manuscript writing, and accepts responsibility for the integrity of the data analysis. 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.

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