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Ethan C Hill
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Terry J Housh
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Clayton L Camic
Department of Exercise & Sport Science, University of Wisconsin-La Crosse La Crosse, WI 54601

Cory M Smith
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Joshua L Keller
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Richard J Schmidt
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Glen O Johnson
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Correspondence
Ethan C Hill
Department of Nutrition and Health Sciences, Human Performance Laboratory University of Nebraska-Lincoln Lincoln, NE 68505, USA

Electromechanical efficiency tracks eccentric torque production

Ethan C Hill, Terry J Housh, Clayton L Camic, Cory M Smith, Joshua L Keller, Richard J Schmidt and Glen O Johnson

Abstract
It has been suggested that electromechanical efficiency may be useful for detecting changes in muscle function as it provides a direct measurement from the muscle being investigated. No previous investigations, however, have examined electromechanical efficiency during fatiguing eccentric exercise. Thus, the purpose of the present study was to examine electromechanical efficiency at velocities of $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$ during fatiguing, maximal eccentric muscle actions. Ten men performed 30 maximal eccentric muscle actions of the leg extensors at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$. Polynomial regression analyses were used to examine the composite patterns of responses for eccentric torque, electromyographic amplitude, mechanomyo graphic amplitude, and electromechanical efficiency across the fatiguing protocols. There were no significant relationships for torque or electromechanical efficiency across either of the fatiguing protocols. During the $60°\cdot s^{-1}$ protocol, however, electromyographic amplitude decreased linearly ($r = 0.579$) and mechanomyo graphic amplitude decreased quadratically ($R = 0.438$), while there were no changes during the $180°\cdot s^{-1}$ protocol. These findings indicated that electromechanical efficiency can be applied to fatiguing eccentric exercise and tracks eccentric torque production despite divergent electromyographic and mechanomyo graphic amplitude responses.

Keywords: Muscle lengthening, electromyography, muscle damage, motor control, isokinetic

1. Introduction

Surface electromyography (EMG) records and quantifies the action potentials that activate skeletal muscle fibers [2]. The amplitude of the EMG signal is generated by the summation of the action potential trains from the active motor units and is influenced by the number of active motor units, their firing rates, and synchronization [2, 3]. The power spectrum of the EMG signal is, in part, determined by average muscle fiber action potential conduction velocity [4] and the shape of the action potential waveforms [5]. Mechanomyography (MMG) is a non-invasive technique that has been described as the mechanical counterpart of motor unit activity as measured by EMG [6]. It has been suggested that the amplitude of the MMG signal is influenced by motor unit recruitment and the frequency content of the MMG signal is qualitatively related to motor unit firing rate [7, 9].

The simultaneous measurements of EMG and MMG have been used to examine various aspects of muscle function including electromechanical and phonomechanical delay [10], muscle fiber type distribution patterns [11], muscle atrophy [12], and excitation-contraction coupling associated with muscle fatigue [13]. EMG and MMG measurements have also been used in pediatric, adult, and geriatric populations to examine neuromuscular disorders such as myotonic dystrophy [14, 15], mandibular disorders [16], low back pain [17], cerebral palsy [18], to control prostheses [1], and to examine patellofemoral pain [19]. For example, electrical efficiency, originally described by Lenman [20] and deVries [21], is an indirect assessment of muscle function that is performed by plotting the integrated electrical activity (EMG) as a function of force production. With regard to clinical and athletic populations, it has been reported that electrical efficiency is lower in individuals with muscular disorders (i.e. muscular dystrophy) relative to asymptomatic individuals [20], and electrical efficiency decreases with the development of muscle fatigue [22], but electrical efficiency increases in response to exercise training (improved muscle efficiency) [20, 21]. Barry *et al*, [1] suggested, however, that

EMG and MMG together may be more useful for detecting changes in muscle function. Specifically, the ratio of MMG amplitude to EMG amplitude (electromechanical efficiency [$\text{efficiency}_{E\text{-}M}$]) may provide insight regarding the impairment of electrochemical coupling as a result of muscle fatigue [15, 19]. For example, $\text{efficiency}_{E\text{-}M}$ has been applied to examine fatiguing concentric and isometric exercise and has been shown to track the fatigue-induced decreases in torque production [23, 19]. No previous investigations, however, have examined if $\text{efficiency}_{E\text{-}M}$ can also be applied to fatiguing eccentric exercise.

It is well known that eccentric exercise is less demanding metabolically (i.e. mechanically efficient) [24, 25], fatigue-resistant [26, 27] and is associated with greater force production than concentric exercise [28]. Despite the fatigue-resistance nature of eccentric movements, there exists unresolved questions regarding the velocity-specific fatigue responses during eccentric exercise. For example, there is a velocity-related dissociation in eccentric torque production that deceases during eccentric exercise performed at slow velocities, but remains unchanged at faster velocities [29, 30, 26, 31]. To the best of our knowledge, no previous investigations have examined velocity-dependent changes in eccentric torque production as a function of $\text{efficiency}_{E\text{-}M}$ which may explain the differences in torque responses between fast and slow eccentric exercise. Therefore, the purpose of the present study was to examine $\text{efficiency}_{E\text{-}M}$ at velocities of 60 and 180°·s^{-1} during fatiguing, maximal, eccentric muscle actions.

2. Materials and Methods

2.1 Subjects

Fifteen men (mean age ± SD = 23.2 ± 3.2 yrs; body weight = 80.2 ± 7.8 kg; height = 179.7 ± 9.3 cm*)* volunteered to participate in this investigation. The subjects regularly participated in resistance training (6.0 ± 3.4 h per week) and had no known cardiovascular, pulmonary, metabolic, muscular and/or coronary heart disease, or regularly used prescription medication or nutritional supplements. The subjects visited the laboratory on 3 occasions separated by at least 72 h and were instructed not to perform lower body exercise 72 h prior to each visit. The study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

2.2 Procedures

Protocol and Determination of Isometric Peak Torque (PT). The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, the subjects performed submaximal and maximal isometric and eccentric muscle actions of the leg extensors at 60 and 180°·s^{-1}. During visits 2 and 3, the subjects warmed up on a cycle ergometer for 5 min at approximately 75 W and then performed 6 submaximal (50 – 75% max) isometric muscle actions followed by 15 submaximal (50 – 75% max) eccentric, isokinetic muscle actions of the dominant (based on kicking preference) leg extensors on a calibrated Biodex System 4 Pro dynamometer (Biodex Medical Systems, Inc.). After 2 min of rest, the subjects performed 2, 3-s pretest isometric PT trials at a knee joint angle of 120° (where 180° corresponds to full extension). The highest isometric torque from the 2 trials was selected as the pretest isometric PT. Following the determination of the pretest isometric PT, the subjects performed 30 repeated, maximal, eccentric, isokinetic muscle actions at a randomly ordered velocity of 60 or 180°·s^{-1}. After completing the eccentric muscle actions, the subjects performed 2 posttest isometric PT trials using the same procedures as the pretest.

Electrode and Accelerometer Placements and Signal Processing. During visits 2 and 3, a bipolar (30 mm center-to-center) surface EMG electrode (circular 4 mm diameter silver/silver chloride, BIOPAC Systems, Inc., Santa Barbara, CA) arrangement was placed on the dominate thigh over the rectus femoris muscle according to SENIAM recommendations [32]. The reference electrode was placed over the anterior superior iliac spine. Prior to each electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The MMG signals from the rectus femoris were detected using an accelerometer (Entran EGAS FT 10, bandwidth 0 – 200 Hz, dimensions: 1.0 x 1.0 x 0.5 cm, mass 1.0 g sensitivity 10 mV/g) that was placed between the proximal and distal EMG electrodes of the bipolar arrangement using double-sided adhesive tape. The raw EMG and MMG signals were digitized at 1000 Hz with a 12-bit analog-to-digital converter (Model MP100, Biopac Systems, Inc.) and stored in a personal computer (Latitude E5540 DELL Inc., Round Rock, TX) for subsequent analyses. The EMG signals were amplified (gain: x 1000), zero-meaned, and digitally bandpass filtered (fourth-order Butterworth, zero-phase shift) at 10 – 500 Hz. All signal processing was performed using custom programs written with the LabVIEW programming software (version 7.1, National Instruments, Austin, TX).

Determination of EMG Amplitude, MMG Amplitude, Eccentric Torque, and $\text{Efficiency}_{E\text{-}M}$. The EMG amplitude (µVrms) and MMG amplitude (m·s^{-2}) values for the eccentric muscle actions were calculated for a time period that corresponded to 30° range of motion from approximately 120° to 150° of leg extension (where 180° corresponds to full extension). Thus, at 60°·s^{-1} and 180°·s^{-1} signal epochs of 0.5 and 0.17 s were used to calculate the EMG amplitude and MMG amplitude values. Similarly, eccentric torque for each of the 30 repetitions was determined as the highest torque produced during the 30° range of motion. $\text{Efficiency}_{E\text{-}M}$ was calculated as the ratio of MMG amplitude to EMG amplitude [19].

2.3 Statistical Analyses

A 2 (Time [pretest, posttest) × 2 (Velocity [60°·s^{-1} and 180°·s^{-1}]) repeated measures ANOVA was used to analyze the isometric PT values. A significant 2-way interaction was decomposed with follow-up, Bonferroni-corrected dependent samples t-tests. In addition, Greenhouse-Geisser corrections were applied when sphericity was not met according to Maulchy's Test of Sphericity and partial eta effect sizes (η_p^2) were calculated for each ANOVA. Polynomial regression analyses (first, second, and third order) were used to examine the composite patterns of responses for EMG amplitude, MMG amplitude, eccentric torque, and $\text{efficiency}_{E\text{-}M}$ across the fatiguing exercise bouts. The F-test was used to determine if the increment in proportion of variance accounted for by a higher-order polynomial was significant [33]. For the polynomial regression analyses, all EMG amplitude, MMG amplitude, eccentric torque, and $\text{efficiency}_{E\text{-}M}$ values were normalized to their respective values from the initial measured repetition during each of the fatiguing protocols at 60°·s^{-1} and 180°·s^{-1}. All statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p \leq 0.05$ was considered statistically significant for all comparisons.

3. Results

3.1 Pretest versus Posttest Isometric PT Responses.

There was a significant 2-way interaction (Time × Velocity; *p* = 0.002, η_p^2 = 0.680) and analyses of the significant simple main effects indicated that isometric PT decreased from pretest to posttest by 16% and 8% as a result of the 60°·s^{-1} and 180°·s^{-1} fatiguing protocols, respectively (Table 1). There were not, however, significant differences in isometric PT between velocities (60°·s^{-1} vs. 180°·s^{-1}) at pretest or posttest.

3.2 Eccentric Torque versus Repetitions

The polynomial regression analyses indicated that were no significant relationships for normalized eccentric torque versus repetition across the 60°·s^{-1} (p = 0.289, r = 0.200) and 180°·s^{-1} (p = 0.460, r = 0.140) fatiguing protocols (Figure 1a).

3.3 EMG Amplitude versus Repetitions

The polynomial regression analyses indicated that there was a significant linear decrease for normalized EMG amplitude versus repetition across the 60°·s^{-1} (p = 0.001, r = 0.579) fatiguing protocol, but no change for normalized EMG amplitude versus repetition across the 180°·s^{-1} (p = 0.684, r = 0.077) fatiguing protocol (Figure 1b).

3.4 MMG Amplitude versus Repetitions

The polynomial regression analyses indicated that there was a significant quadratic decrease for normalized MMG amplitude versus repetition across the 60°·s^{-1} (p = 0.015, r = 0.438) fatiguing protocol, but no change for normalized MMG amplitude versus repetition across the 180°·s^{-1} (p = 0.769, r = 0.056) fatiguing protocol (Figure 1c).

3.5 Efficiency$_{E-M}$ versus Repetitions

The polynomial regression analyses indicated that there were no significant relationships for normalized efficiency$_{E-M}$ versus repetition across the 60°·s^{-1} (p = 0.745, r = 0.062) and 180°·s^{-1} (p = 0.819, r = 0.044) fatiguing protocols (Figure 1d).

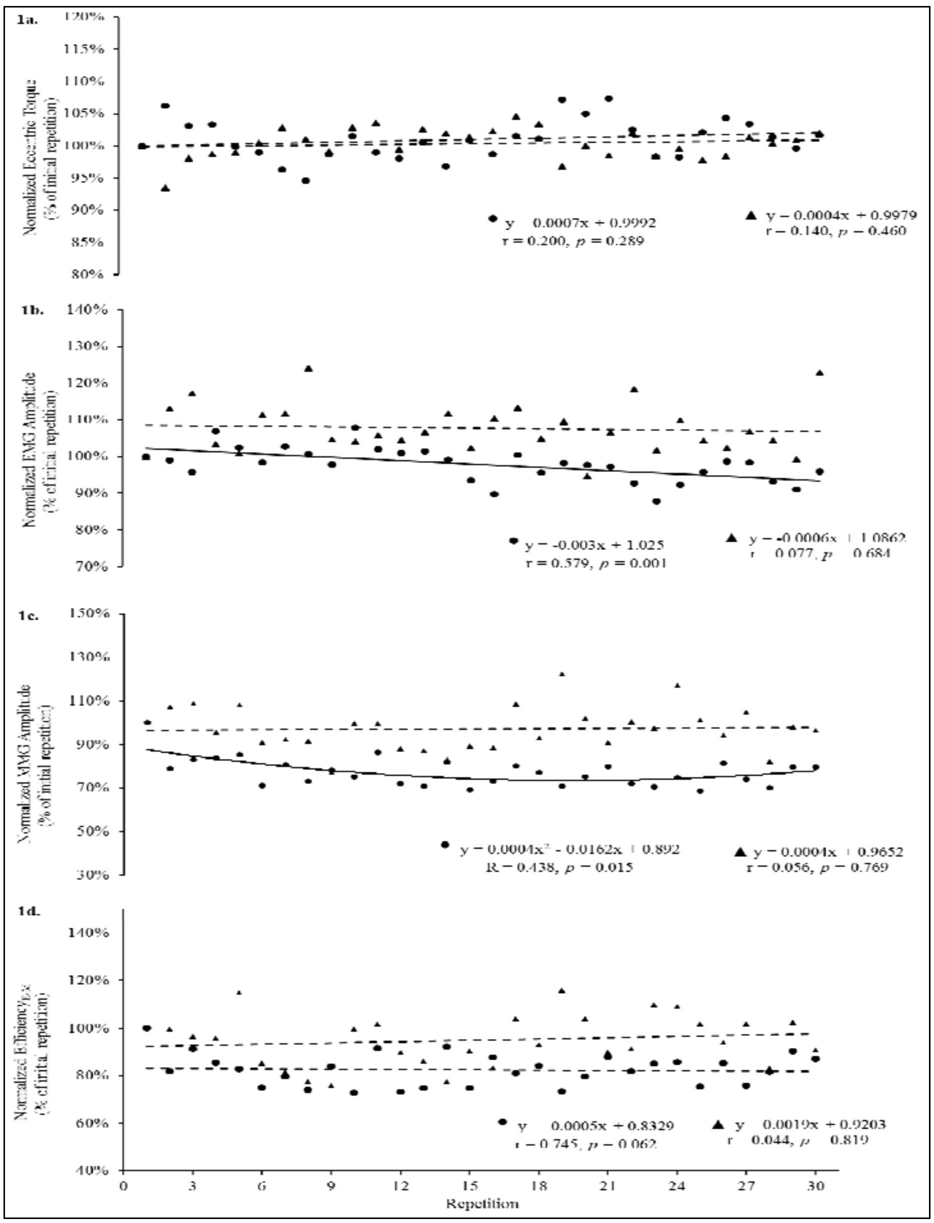

Fig 1a-d: The composite results of the polynomial regression analyses expressed as a percentage of the normalized (to the initial repetition) eccentric torque, electromyographic (EMG) amplitude, mechanomyographic (MMG) amplitude, and electromechanical efficiency (efficiency$_{E-M}$) values across the 30 maximal, eccentric muscle actions at 60°·s^{-1} (circles) and 180°·s^{-1} (triangles). A solid line indicates a significant ($p \leq 0.05$) relationship across repetition.

4. Discussion

4.1 Torque

In the present study, there were no changes in eccentric torque across either of the fatiguing protocols at $60°·s^{-1}$ or $180°·s^{-1}$. As a result of both fatiguing protocols, isometric PT decreased 16 and 8%, respectively which supported the fatiguing nature of the exercise protocols. These findings were in agreement with previous studies [26, 30, 34, 27] that have reported no changes in eccentric torque across 25 to 96 maximal eccentric repetitions at $60°·s^{-1}$ to $180°·s^{-1}$. As a result of performing 24 to 60 maximal eccentric muscle actions at $30°·s^{-1}$ to $180°·s^{-1}$, however, isometric PT has decreased 20 to 50% [35, 36]. Thus, the current findings and those of previous studies [24, 30, 34, 27, 37, 38] indicated that fatiguing eccentric exercise had no effect on maximal eccentric torque production, but there were mode-specific decreases in isometric PT [31, 34, 27, 35, 36, 38, 39].

4.2 Neuromuscular parameters.

There were velocity-specific EMG and MMG responses that remained unchanged during the $180°·s^{-1}$ protocol, but EMG amplitude and MMG amplitude decreased during the $60°·s^{-1}$ protocol. These findings were partially consistent with previous investigations [26, 37] that have examined EMG and MMG responses of the leg extensors during maximal eccentric muscle actions. For example, during 25 maximal eccentric muscle actions at $120°·s^{-1}$, there were muscle-specific (rectus femoris, vastus lateralis, vastus medialis) responses for EMG amplitude which increased or remained unchanged, and for MMG amplitude which decreased or remained unchanged [26]. During 30 maximal eccentric muscle actions at $30°·s^{-1}$, EMG amplitude remained unchanged, while MMG amplitude increased for the vastus lateralis [37]. Thus, the present findings in conjunction with previous investigations [26,37], indicated that there were muscle- and velocity-specific EMG and MMG responses as result fatiguing eccentric exercise.

Fatigue-induced decreases in EMG amplitude have been associated with decreased motor unit recruitment and/or decreased global motor unit firing rate, while fatigue-induced decreases in MMG amplitude have been associated with decreased motor unit recruitment, muscle wisdom, and/or decreased muscle compliance [40, 41, 9]. It is unlikely, however, that the concurrent decreases in EMG amplitude and MMG amplitude reflected decreases in motor unit recruitment since eccentric torque production remained unchanged during both protocols. Instead, the decreases in EMG amplitude and MMG amplitude with no change in torque production during the $60°·s^{-1}$ protocol were likely a function of muscle wisdom. Muscle wisdom is a motor unit activation strategy characterized by decreased muscle relaxation times and motor neuron discharge rates (decreased motor unit firing rate) as well as greater fusion of motor unit twitches to optimize force production (decreased muscle compliance) [42]. Thus, the decreases in EMG amplitude and MMG amplitude during the $60°·s^{-1}$ protocol may have reflected muscle wisdom which optimized force production. It is also possible, however, that the decrease in MMG amplitude during the $60°·s^{-1}$ protocol was a function of deceased muscle compliance. For example, increased intramuscular fluid pressure from repeated and prolonged muscle actions can decrease muscle compliance [43] and restrict the lateral oscillations of the activated muscle fibers, thereby decreasing MMG amplitude [44].

The lack of changes in EMG amplitude and MMG amplitude during the $180°·s^{-1}$ protocol was consistent with the lack of change in eccentric torque production. These findings indirectly suggested that eccentric exercise performed at $180°·s^{-1}$ does not share similar fatigue-induced mechanisms such as muscle wisdom and/or decreased muscle compliance that was observed during the $60°·s^{-1}$ protocol. Interestingly, despite velocity-specific EMG and MMG responses there were no effects on eccentric torque production during either protocol.

4.3 Efficiency$_{E-M}$.

In the present study, efficiency$_{E-M}$ was robust to the changes in velocity and tracked eccentric torque production during both the $60°·s^{-1}$ and $180°·s^{-1}$ fatiguing protocols. These findings were in agreement with previous investigations [19, 23] that have examined efficiency$_{E-M}$ during fatiguing exercise. For example, for the vastus lateralis and vastus medialis, efficiency$_{E-M}$ tracked the fatigue-induced decreases in concentric torque during 75 maximal concentric muscle actions of the leg extensors at $180°·s^{-1}$ [19]. Similarly, for the postural muscles of the lower back, efficiency$_{E-M}$ tracked isometric torque production during a sustained isometric contraction [23]. Like the effects of concentric and isometric fatiguing exercise, in the present study efficiency$_{E-M}$ tracked the lack of fatigue-induced changes in eccentric torque production. Therefore, the findings of the present study in conjunction with Ebersole and Malek [19] and Wright and Stokes [23] indicated that efficiency$_{E-M}$ may be a useful indicator of torque production during various modes of fatiguing exercise.

It has been reported [18, 14] that efficiency$_{E-M}$ may reflect fiber type differences among individuals and, therefore, may provide an indirect assessment of the fatigability of a muscle or muscle groups. For example, compared to asymptomatic populations, efficiency$_{E-M}$ was lower in individuals with cerebral palsy and myotonic dystrophy which was attributed to a reduction in the number of fast-twitch motor units [18, 14]. In addition, declines in efficiency$_{E-M}$ and torque production in previous investigations have been associated with the dropout of more fatigable fast-twitch motor units [19, 23]. In the present study, the lack of changes in eccentric torque production, EMG amplitude, MMG amplitude, and efficiency$_{E-M}$ indirectly suggested that fast-twitch motor units were not affected by the fatiguing eccentric protocols at $60°·s^{-1}$ or $180°·s^{-1}$. Specifically, the lack of changes in eccentric torque production indirectly indicated that all motor units were activated, even fatigue susceptible fast-twitch motor units. Therefore, compared to fatiguing concentric and isometric protocols, the fatigue-resistant nature of eccentric protocols may elicit more favorable muscle adaptations as eccentric exercise may be robust to fatigue-induced dropout of fast-twitch motor units. Consistent with this hypothesis, eccentric training has been shown to increase muscle strength to a greater extent than concentric training [45]. For example, eccentric-only training induces morphological changes (i.e. muscle hypertrophy) earlier than traditional concentric-eccentric exercise and may explain that increases in concentric strength without changes in neural strategies as a result eccentric-only training [28, 46]. Thus, eccentric exercise has the potential to overload the muscle of interest to a greater extent than traditional exercise and induce more favorable muscle adaptations in a shorter period of time. In support of this, the findings of the present study indicated that the eccentric fatiguing protocols had no effects on eccentric torque production which indirectly indicated that all motor units were activated throughout the duration of the fatiguing protocols, therefore, maximizing the training-induced effect of eccentric exercise on all of the motor units. Collectively, eccentric exercise has great importance in both clinical and athletic populations at increasing muscle function potentially to a greater extent than traditional concentric-eccentric exercise.

4.4 Summary

As a result of the fatiguing protocols at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, there were no changes in eccentric torque across either of the fatiguing protocols, but isometric PT decreased 16% and 8%, respectively. These findings were consistent with previous investigations that have also reported no changes in eccentric torque across repeated, maximal eccentric muscle actions, but decreases in isometric PT. There were velocity-specific EMG amplitude and MMG amplitude responses which decreased during the $60°\cdot s^{-1}$ protocol and may have reflected the effects of muscle wisdom and/or decreased muscle compliance. During the $180°\cdot s^{-1}$ protocol, however, there were no changes in EMG amplitude or MMG amplitude. Consistent with eccentric torque production, there were no changes in $\text{efficiency}_{E\text{-}M}$ during the $60°\cdot s^{-1}$ or $180°\cdot s^{-1}$ protocol. Thus, despite divergent EMG and MMG responses, $\text{efficiency}_{E\text{-}M}$ tracked eccentric torque production and was not affected by velocity. These findings, in conjunction with previous investigations, indicated that $\text{efficiency}_{E\text{-}M}$ tracks fatigue-induced changes in torque production during fatiguing exercise. Lastly, the lack of changes in eccentric torque production and $\text{efficiency}_{E\text{-}M}$ indirectly indicated that all motor units were active throughout the duration of each of the fatiguing protocols and were not affected by changes in velocity.

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