Changes in the mechanical and electromyographic output during isotonic and isometric exercise in men and women

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Abstract:

Purpose: The purpose of this study was to determine if surface electromyography (EMG) could be used to index fatigue during isotonic and maximal voluntary isometric contractions (MVIC) of the knee extensors in men and women.

Methods: Ten males (age = 22.1 ± 3.3 yr, ht = 180.3 ± 5.5 cm, mass 78.7 ± 5.1 kg) and ten females (age = 23.9 ± 4.6 yr, ht = 163.7.3 ± 11.1 cm, mass 63.2 ± 7.4 kg) underwent one isometric (120 s MVIC of the knee extensors) and one isotonic (120 maximal effort isotonic contractions at a resistance of 25% of the MVIC peak torque determined on the testing day) exercise session separated by at least 48 hrs. The EMG signal was collected from the vastus lateralis during both exercise protocols using standard EMG collection techniques. Average torque (AT) was calculated from each 3 s window of the 120 s MVIC, and the average peak power (APP) was calculated for every 3 consecutive contractions during the dynamic exercise.

Results: Both the isometric and isotonic fatigue protocols resulted in significant ($p < 0.05$) decreases in AT and APP, respectively. During the isotonic exercise protocol, decreases in APP during contractions 31–54 were significantly greater ($p < 0.05$) for males than females. Time-amplitude domain processing of the EMG data demonstrated significant decreases in the root mean square amplitude during the course of isometric exercise ($p < 0.05$) but not during isotonic exercise ($p > 0.05$). A main effect for gender ($p < 0.05$) revealed larger EMG amplitude for females when compared to males during isotonic exercise.

Conclusions: These results indicate that gender may be a factor in the development of dynamic fatigue and that EMG can index fatigue during a sustained MVIC.

Keywords: Fatigue, muscle assessment, EMG, power

Article:

INTRODUCTION

Over the past 50 years, a majority of the work performed in the field of muscle performance has focused on a number of factors that may potentially affect muscle function in the fatigued state. These items include, but are not limited to, central versus peripheral fatigue, the neuromuscular

junction, the excitation contraction coupling process, and the role of muscle metabolites in regulating muscle forces. While notable advancement has been achieved in understanding changes that occur during isometric contractions, we still understand little of the causes and time-course of fatigue during dynamic activity [16].

Strength values are commonly obtained from isometric tests and can be defined as the ability to exert force [12]. In contrast, power is the product of force and velocity of movement and may be potentially more directly related to functional measures of performance. Many sporting events such as sprinting, jumping, kicking, and throwing require optimal or peak power for optimal performance. It is unknown if the onset of fatigue during an exercise protocol designed to measure peak power follows a similar time-course as a sustained maximal voluntary isometric contraction (MVIC).

Few reports in the literature have investigated the effects of exercise on peak power [4,25,27]. Beelan and Sargeant [4] demonstrated velocity dependent effects on fatigued muscle following 6 minutes of cycling at 90% of maximal oxygen uptake. They reported a significant decrease in maximal power at higher testing velocities (630◦•s−1 and 720◦•s−1), and attributed this to selective fatigue of the fast twitch muscle fibers. Similarly, Moritani et al. [27] used maximal bilateral hopping to measure power and reported a decrease of mechanical power from 26W •kg−1 to 19 W• kg −1 following 60 s of jumping to maximal height. Although there is no consensus at this time as to what specific physiological mechanisms are responsible for peak power fatigue, the role of the fast twitch motor unit appears to be of paramount importance in the generation of power [4, 27].

Previous studies that have reported peak power output (not necessarily fatigued output) have used isokinetic dynamometers as the testing device for the measurement of power [3,11,14,30]. This method has potential limitations that could actually bias the measurement of peak power. Specifically, the speed of the dynamometer may be slower than isolated joint velocities occurring during athletic participation. Aagaard et al. [1] reported maximal unloaded knee extensor angular velocities of 693 ± 24◦•s^{-1}, and that power generation (at 50◦ of knee flexion) of the knee extensors was optimized at 375◦•s^{-1}. This value is at the upper end or above testing velocities currently available in most isokinetic dynamometers. If peak power output from an isolated joint is to be measured, an isotonic dynamometer with no limitations on the velocity of motion would be ideal.

Currently, it is unsure as to what role gender plays in the development of fatigue of peak power. Kanehisa et al. [18] reported no difference between men and women in the slope of force per cross sectional area or absolute force of the knee extensors during 50 isokinetic knee extensions at 180◦•s−1. Following 30 s of supramaximal cycling, muscle biopsies revealed that lactate concentration was significantly greater in males than females [15]. It has also been demonstrated that glycolytic enzyme activity is lower in females than males [19,29,34]. By combining these two findings, it has been hypothesized that females would experience a smaller declining percentage over the course of maximal exercise [18]. However this smaller decline of muscle force generating capacity in females has not been substantiated.

Surface electromyography (EMG) has been demonstrated to be an index of neuromuscular fatigue during isometric contractions. Previous studies have reported that fatiguing exercise of the muscle may lead to changes in the time-amplitude and frequency domains of the surface EMG signal [21–24,31]. However, less is currently known about fatigue mechanisms and corresponding EMG signal alterations during fatiguing dynamic contractions. There are a few reports in the literature of using surface EMG as an indicator of local muscle fatigue during dynamic muscle contractions [2, 27,36]. The ability of EMG to index fatigue of dynamic contractions has been attributed to substrate utilization [37], intramuscular pH [10], and preferential type II fiber recruitment [27,37]. However, these studies failed to report or used joint velocities below those associated with peak power generation.

Research has not yet determined if surface EMG can index decreases in power over extended maximal exercise in the isolated joint. Moreover, most studies investigating decreases in power in isolated joint testing have utilized isokinetic testing and have not determined if gender plays a role in the development of peak power fatigue. Therefore, the purposes of this study were to 1) determine changes in knee extensor strength and power during short-term, high-intensity exercise in men and women and 2) determine if surface EMG could index strength and power changes during short-term, high- intensity exercise in men and women.

METHODS

Subjects

Ten males (age = 22.1 ± 3.3 yr, ht = 180.3 ±5.5 cm, mass 78.7 f 5.1 kg) and ten females (age = 23.9 ± 4.6yr,ht= 163.7.3±11.1 cm, mass 63.2±7.4kg) were recruited from the general university population. They had no recent history of injury to the knee extensor mechanism or other knee joint pathologies that may have influenced their ability to perform work about the knee joint. All subjects gave written informed consent before beginning the study.

Instrumentation

All muscle testing was performed on the Dynatrac Isotonic Dynamometer (Baltimore Therapeutic Equipment, Hanover MD). Within-tester reliability coefficients (ICC's) for power tests of the knee extensors as measured by the Dynatrac have been reported to average above .80 indicating a strong correlation between trials [32]. Torque, velocity, and position analog data were collected from the Dynatrac during all muscle tests and digitized for storage and analysis. Simultaneously, the surface EMG signal from the vastus lateralis was collected with the Myosystem 2000 (Noraxon, Phoenix, AZ) (gain = 1000, input resistance = 16 MΩ, a common mode rejection ratio = 135 dB, sampling frequency bandwidth = 16 − 500 Hz) and recorded at a frequency of 2000 Hz on a Pentium-based microcomputer. All data extraction was performed with the Data Pac III Software package (Run Technologies, Laguna CA).

Experimental protocol

Subjects underwent isotonic and isometric exercise protocols on separate days with testing days separated by at least 48 hr. Testing order was gender stratified then randomly assigned.

Procedures

Each subject was prepared for EMG surface electrode placement by shaving the skin of each electrode location followed by abrasion with an alcohol wipe to reduce skin impedance. Two

surface electrodes (Blue Sensor, Medicotest, Olstykke, Denmark) were placed midway between the muscle belly and the distal tendinous insertion of the vastus lateralis and were left in place until the completion of the experiment (center to center distance of 2.0 cm). A reference surface electrode was placed over the contralateral patella. Following a 5 min warm-up on a cycle ergometer, the subject was placed on the chair of the dynamometer. All testing was performed on the non-dominant knee to maximize the effects of the exercise protocols. The anatomical axis of the knee was aligned with the axis of the dynamometer, and the distal arm of the dynamometer was placed 30 cm distal to the dynamometer axis. The dynamometer seat back was placed at 100°. The ankle was fastened to the dynamometer arm, and the thigh and waist were fastened to the dynamometer seat with velcro stabilization straps to minimize extraneous movements.

Isometric exercise protocol

The subject's knee was placed at 60° of flexion. For familiarization the subject performed three submaximal voluntary isometric contractions of 3 s duration followed by three 3 s MVIC's. Each ofthe MVIC's was separated by 60 s. The isometric exercise was a 120 s MVIC of the knee extensors with the tester providing verbal encouragement.

Isotonic exercise protocol

Prior to isotonic exercise, the isometric peak torque was determined. The subject's knee was placed at 60° of flexion. For determination of isometric peak torque, the subject performed three submaximal voluntary isometric contractions of 3 s duration followed by three 3 s MVIC's. Each of the MVIC's was separated by 60 s. The isotonic resistance of the dynamometer was then set at 25% of the peak torque previously recorded during the MVIC's. Although peak power is reported to occur at about 33% of peak force [17], pilot testing revealed that a 33% load did not permit completion of the exercise, whereas a 25% load did. For isotonic exercise testing, the subject's knee was placed at 90° of flexion. For familiarization to the isotonic resistance a series of three submaximal isotonic contractions were performed followed by a series of three maximal isotonic contractions. Before each maximal contraction the subject was instructed to kick out "as fast and hard as possible" to maximize the peak power generation and then allow the dynamometer to passively return the limb to the starting position (-90°) before beginning the next contraction. For purposes of this study peak power was defined as the product of instantaneous torque and the respective instantaneous velocity. The subject then performed 120 continuous maximal isotonic knee extensions on the Dynatrac with the tester providing verbal encouragement throughout the 120 contractions of the exercise protocol.

Mechanical data extraction

Average torque (AT) generation during the isometric exercise protocol was calculated for 40 consecutive 3 s windows and plotted over the course of the 120 s exercise. Peak power generation was calculated for each of the 120 isotonic contractions and averaged every 3 contractions for a total of 40 average peak power (APP) values, and subsequently plotted over time. To allow qualitative comparisons between the two, both AT and APP were normalized to their respective initial value.

EMG data extraction

From the isometric exercise protocol, the root mean square (RMS) amplitude EMG signal was calculated for 40 consecutive windows of 3 s duration. Onset and offset boundaries of the EMG

signal of each isotonic contraction were calculated according to a range of motion window between the start of the dynamometer movement and the peak extension point in the range of motion. The RMS amplitude was calculated for each of the 120 dynamic contractions using the parameters described previously. Three consecutive values were then averaged and plotted over 40 points. The value of the first data point was used to normalize each of the subsequent 39 points for the isometric and isotonic exercise protocols.

Statistical analysis

Three separate 1-between (gender) and 1-within (time) mixed model ANOVA's were performed on AT, APP and the EMG amplitude for the isometric and isotonic exercise protocols. Tukey post-hoc tests were used to identify which values were statistically different over time. The alpha level for all statistical tests was set at $p < 0.05$.

RESULTS

Mechanical data

For the isometric exercise protocol there was a significant main effect for time ($F(39, 702) = 86.74$, $p < 0.001$) with post hoc testing revealing a significant decrease in force output beginning at 7 s and continuing to 120 s (Fig. 1). For the isotonic exercise protocol there was a significant main effect for time ($F(39, 702) = 190.63$, $p < 0.001$) with subjects demonstrating a significant drop of average peak power beginning at 16 s. Additionally, there was a significant interaction for gender by time ($F(39,702) = 2.36$, $p < 0.001$) with males having a significantly greater decrease in average peak power than females from isotonic contractions 31 to 54 (average of 3 contractions from 11–18) (Fig. 2).

EMG data

The ANOVA calculated for the RMS data during the isometric exercise protocol revealed a significant main effect for time ($F(39, 702) = 26.29$, $p < 0.001$) with 7–120 s significantly lower than the initial 3 s value (Fig. 3). Also of note was that post hoc testing revealed no statistical difference between data points 18– 40 (which could be interpreted as a leveling of EMG amplitude). Post hoc testing also revealed at no time from 52–120 s was the normalized EMG level statistically different than the EMG level at 51 s. No significant differences were observed for gender by time interaction.

The ANOVA calculated for RMS during the isotonic exercise revealed a significant main effect for gender ($F(1,18) = 7.30$, $p = 0.015$) with females having a greater overall amplitude than males (Fig. 4).

DISCUSSION

The current study demonstrates an approximate 57% decrease in torque production during the 120 s MVIC of the knee extensors (Fig. 1). This is in agreement with previous investigations using MVIC's of 45–60 s in duration, and reporting force decrements between 30–60% [5,6].

Extended maximal dynamic exercise resulted in an approximate 65% decrease in average peak power (Fig. 2). Although we have been unable to locate other studies using open chain maximal isotonic exercise to fatigue the quadriceps, comparisons can loosely be made to fatigue of peak torque following extended isokinetic exercise, as isokinetic peak torque is the peak power

respective to the testing velocity. Previous isokinetic studies using velocities between 90–180◦·s−1 and 100–150 repetitions have reported decreases in peak torque of the knee extensors from 13% [39] to 45% [28] to 51% [20].

The velocity of contraction may potentially explain our finding of a slightly higher degree of fatigue. Velocity of the maximal dynamic contractions in the present study reached upwards of 500◦·s−1, but the previously mentioned isokinetic fatigue protocols have used maximal velocities of 180◦·s−1. It is possible during isokinetic testing that the fast twitch motor units were not completely recruited, whereas our higher velocity isotonic contractions may have more fully recruited all fibers. Therefore, the extent of fatigue may not have been as great with isokinetic testing.

Males experienced a more rapid onset of fatigue than did females during the course of dynamic fatiguing exercise (Fig. 2). While fiber composition was not measured in this study it may be possible to make the broad based assumption that males have a greater proportion of fast twitch fibers and a greater cross sectional area of fast twitch fibers than do females in the vastus lateralis [33]. As exercise progressed in the dynamic state, it is hypothesized that the fast twitch fibers became fatigued. If the males had a greater percentage of fast twitch fibers than females, it is possible that these fast twitch fibers would fatigue sooner than the slow twitch,

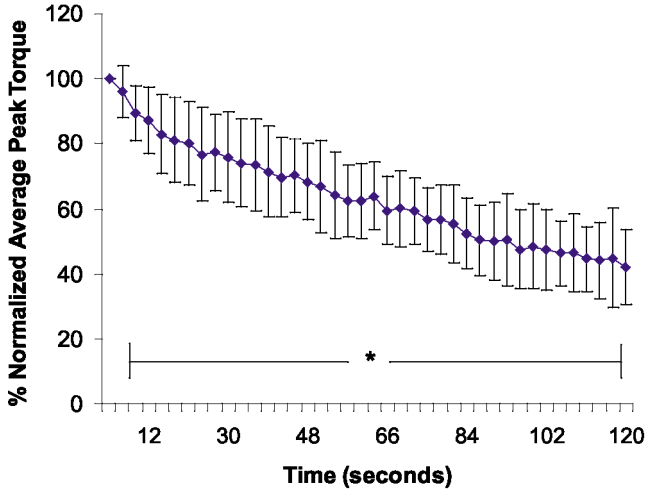

Fig. 1. % Normalized Average Torque during isometric exercise protocol for males and females combined. * Significantly less than initial 3 s value ($P < 0.05$).

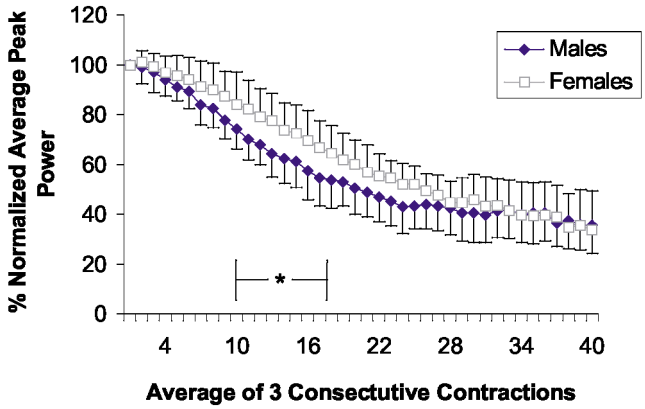

Fig. 2. % Normalized Average Peak Power during isotonic exercise protocol. Data interval equal to 3 consecutive isotonic contractions. * Males significantly less than females ($P < 0.05$).

producing an interaction between time and gender as was demonstrated in this study. Decreases of power have been reported to be correlated with percent of fast twitch fibers of the vastus lateralis following 60 s of maximal hopping [8]. Subjects were divided into a fast twitch group and a slow twitch group and as exercise progressed, those with a greater percentage of fast twitch fibers fatigued to a greater extent. It is interesting to note that the correlation between fiber type and power output became nonsignificant in the later stages of the 60 s exercise. This can be interpreted as those with a greater percentage of fast twitch fibers (possibly the males in the current investigation) may be more susceptible to a greater percentage of fatigue during maximal exercise.

Dynamic muscle output appears to fatigue to a greater extent than does isometric muscle output in response to the protocols used in the current study (65% as opposed to 58% (Fig. 5). However, during data intervals 1–10 isometric performance was fatigued to a greater extent than was isotonic performance. One reason for this may be the time course of the first 10 data points. These 10 data points are equivalent to 30 s of MVIC and 30 maximal isotonic contractions. In the beginning stages of exercise, these 30 isotonic contractions generally occurred in less than 20 s. The actual time difference in the beginning stages of the two fatigue curves was not calculated. But if a rough correction for time occurs, the two curves may appear more similar in shape over the initial stages of fatiguing exercise.

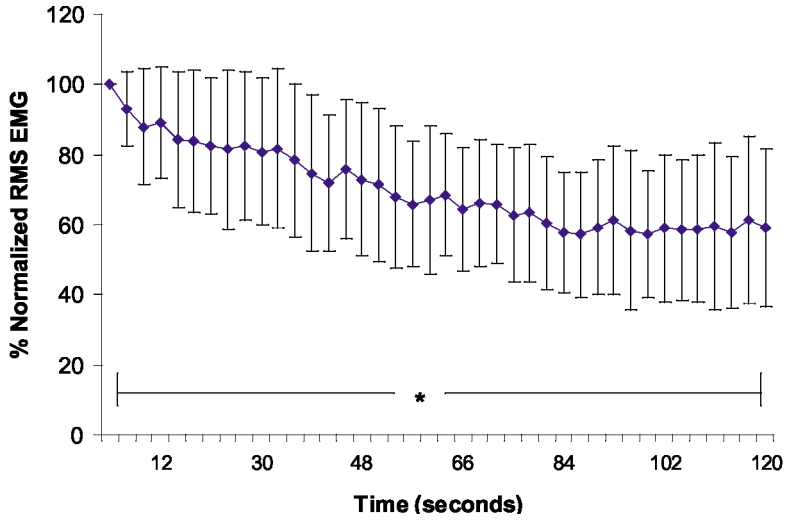

Fig. 3. % Normalized RMS EMG during isometric exercise protocol for males and females combined. * Significantly less than initial 3 s value ($P < 0.05$).

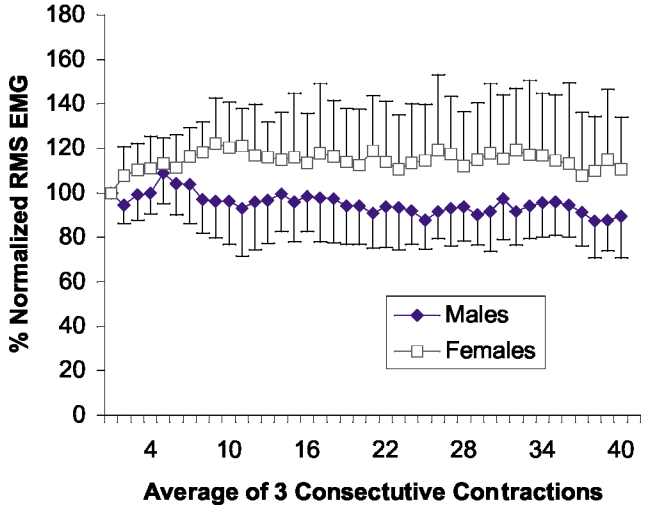

Fig. 4. % Normalized RMS EMG during isotonic exercise protocol. Data interval equal to 3 consecutive isotonic contractions. * Overall male RMS amplitude significantly less than overall female RMS amplitude ($P < 0.05$).

The current investigation did not statistically compare the relative exercise endpoint decreases between dynamic and static fatiguing exercise. Potential differences in absolute levels of fatigue in the current isometric and isotonic fatigue protocols may be explained by the amount of work performed. Comparisons of the amount of work done during the dynamic and static fatiguing protocols would allow for exact comparisons of fatigue protocols using various types of contractions. This difficulty lies in quantifying the work done during an isometric contraction. Mechanically, work is defined as the product of force and distance. Because there is no movement during isometric contractions, the mechanical work performed is equal to zero.

Comparisons between dynamic and static exercise could be accomplished by measuring changes in muscle metabolites via 31P nuclear magnetic resonance spectroscopy (31P-NMRS). Adenosine triphosphate (ATP) levels may potentially decline (albeit slightly) causing decreases

in force production [26]. Hydrogen ions may increase causing a decrease in the local muscle pH [9,26]. This decline in pH has been associated with a direct inhibition of the contractile process [9, 26]. Phosophocreatine depletion and a rise in inorganic

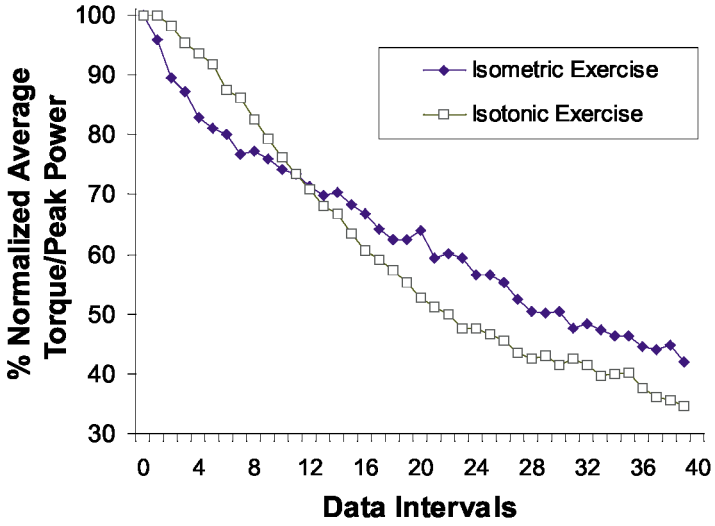

Fig. 5. % Normalized Average Torque/Average Peak Power for the isometric and isotonic exercise protocols, respectively. Data intervals are equal to 3 s and 3 isotonic contractions for the isometric and isotonic exercise protocols, respectively.

phosphate have also been associated with decreases in force generating capacity of the muscle [13,38].

The present results support the concept of using surface EMG amplitude processing to index muscle fatigue during the initial stages of a sustained maximal isometric contraction. However, these results do not support the concept that surface EMG amplitude measures can be used as an accurate index of muscle fatigue during the latter portion of a 120 s MVIC. The surface EMG amplitude and average torque production of each data point appear strongly related until approximately 80 s into the MVIC (Fig. 6). At this point there was a leveling off of the RMS amplitude and a continued decline of average torque. This is potential evidence that peripheral as well as a central fatiguing mechanisms are responsible for the decrement in torque production in later stages of sustained maximal isometric exercise. Another investigation has reported similar findings [35]. At the peripheral level, such decreases in force production have been associated with depletion of phosphocreatine [26] and changes in pH [9]. These changes are likely in the sustained MVIC as there is little blood flow to or from the muscle during the contraction [7].

The present findings of no decrease in the RMS amplitude (or even a slight increase of the RMS) and a corresponding decrease in power during the first 30 dynamic contractions have been previously reported [28]. A slight increase of the integrated EMG signal of the vastus lateralis occurred in response to approximately 25 knee extensions at 180◦·s−1. It was suggested that the findings could be theoretically explained by additional recruitment of motor units that did not have the force/velocity production capacity of the fast twitch motor units that are rapidly fatigued. The authors also gave a more likely explanation in that the neuromuscular junction did not fatigue, but some local metabolic factor was the primary factor in fatigue [28]. No specific metabolic factor was identified, but it has been demonstrated that phosphocreatine content of the

vastus lateralis decreases over the course of supramaximal cycling [13]. It has also been demonstrated that intramuscular pH of the quadriceps decreased following supramaximal cycling [10]. Local metabolic factors were not collected in the present study.

Others have reported a decrease in the surface EMG amplitude following repeated isokinetic contractions of the knee extensors [20,28,37]. Because of the novelty of the type of dynamic contraction used in this study to measure peak power, comparisons are difficult. These previous studies tested angular joint velocities of $180^{\circ}\cdot s^{-1}$ or less. It appears as though high velocity knee extensions cannot be indexed by the use of surface EMG. Potential reasons for the inability to observe changes in the surface EMG amplitude during fatigued maximal dynamic contractions include additional motor unit recruitment and tissue-electrode interface changes (signal stationarity decreases).

The finding of females having significantly greater EMG amplitude than males may be a result of the females potentially pacing themselves during the first several isotonic contractions. The first three isotonic

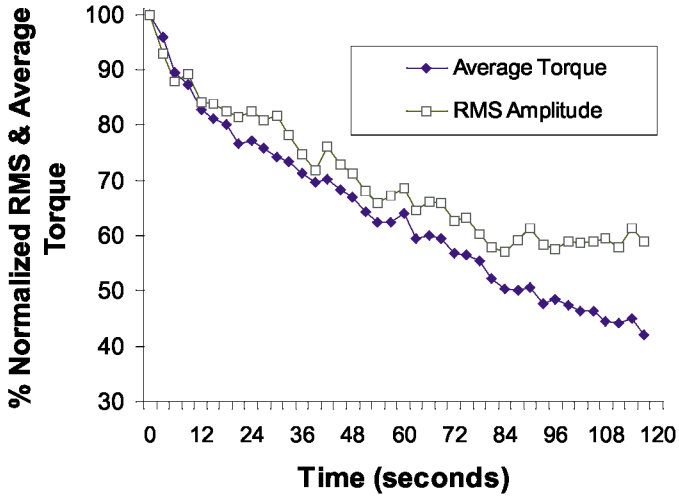

Fig. 6. % Normalized Average Torque/RMS EMG during the isometric exercise protocol.

contractions served as the normalization standard for the remaining 117 contractions. If pacing did occur and a maximal effort was not given during the first several contractions, as exercise progressed more motor units may have been recruited as needed to complete the exercise protocol.

In conclusion, the results of the present study indicate that gender may be a factor in the onset and extent of fatigue during isotonic exercise protocols measuring peak power output of the knee extensors. Additionally, surface EMG does not appear to be valid index of fatigue during isotonic exercise protocols measuring peak power output. However, surface EMG does appear to be a valid index of fatigue during the initial stages of a MVIC exercise of the knee extensors.

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