Effect of isotonic and isometric knee extension exercises on mechanical and electromyographical specificity of fatigue

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Schmitz, R.J., Arnold, B.L., Perrin, D.H., Granata, K.P., Gaesser, G.A., & Gansneder, B.M. (2002) Effect of isotonic and isometric knee extension exercises on mechanical and electromyographical specificity of fatigue. Isokinetics and Exercise Science, 10:167-175

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Abstract.:

This study investigated the effects of isotonic and isometric knee extension exercises on strength, power, and surface EMG in male and female populations. Using the knee extensors, ten males and ten females performed a 120 s MVIC and 120 maximal isotonic contractions. Prior to each exercise (t = pre) knee extensor isometric peak torque (strength) and average peak power (power) were tested utilizing three, 3 s MVIC's and three maximal isotonic contractions, respectively. Following each exercise, strength and power were assessed immediately after (t =: 00) and at 2.5 (t =: 02.5), 5 (t =: 05), 10 (t =: 10), and 15 (t =: 15) minutes. All strength and power measures were normalized to the respective t = pre value. Vastus lateralis surface EMG signals were collected during all muscle testing and normalized to the respective tire value. Following isometric exercise, both strength and power at t =: 00 (68.7% ± 8.7% & 88.0% ± 8.7%) and t =: 02.5 (82.2% ± 17.8% & 95.2% ± 5.0%) significantly decreased from t=pre (100% ± 0.0%) ($p < 0.05$) with greater decreases in strength at each time point ($p < 0.05$). EMG analysis revealed a significant EMG amplitude decrease ($p < 0.05$) at t =: 00 and t =: 02.5 during strength testing with respect to t=pre. Following isotonic exercise, both strength and power at t =: 00 (68.0% ± 13.2% & 38.8% ± 10.7%) and t =: 02.5 (84.5% ± 14.9% & 81.6% ± 14.5%) significantly decreased from t=pre (100% ± 0.0%) with a greater power decrease at t =: 00 ($p < 0.05$). The EMG amplitude of males was significantly less at t =: 00 than the respective EMG amplitude for females ($p < 0.05$) (irrespective of testing condition). We conclude that muscle performance in the fatigued state is dependent upon the type of exercise performed.

Article:

INTRODUCTION:

During the past years of research addressing muscle performance during and following fatiguing exercise, the isometric contraction has been considered the gold standard of muscle force producing capability in the laboratory setting. The muscle force production values acquired from isometric contractions are often referred to as "strength" [11]. However in sporting activities the majority of muscle contractions are dynamic in nature. Power, a variable that takes into account contraction force and velocity, is important in sports that demand explosive movements. Throughout the remainder of this paper strength will refer to isometric torque production and power will refer to dynamic, maximal efforts of the muscle/joint complex.

It is unclear if fatiguing exercise will affect isometric strength and dynamic muscle power similarly. It has been reported that assessment of fatigue based on reductions in isometric force may underestimate impairment of actual dynamic performance [8]. Thus, it may be important to determine if peak power fatigue does have a different mechanism than isometric strength fatigue. Previous research has demonstrated a difference between dynamic power and isometric strength training [32]. Based on this, it is reasonable to suspect differences in fatigue mechanisms. If there are differences between power and strength fatigue, this would further support the need for muscle training methods that are specific.

The role of gender in resistance and recovery from fatiguing dynamic maximal contractions has not been fully elucidated. Kanehisa et al. [17] reported a comparison of males and females over 50 isokinetic knee extensions performed at 180° • s^{-1}. Both males and females experienced a 50% decrease in absolute force. The absolute force and force per cross-sectional area (CSA) fatigue curves of males and females were not significantly different over the course of 50 contractions. Because males had a significantly larger CSA, it appears CSA had no effect on extent of fatigue. No recovery values were obtained for the report.

Previous research has reported that fatiguing MVIC's lead to changes in the time-amplitude domain of the surface EMG signal [6]. The ability of surface EMG to index fatigue of maximal-effort dynamic contractions has been primarily investigated through the use of isokinetic dynamometers. However, it is unclear if EMG can index fatigue from isokinetic contractions. Some studies have reported surface EMG changes following isokinetic exercise [9,31]; while at least one has not [23]. When investigating the indexing of peak power it is of concern in these studies that isokinetic testing velocities were between 60–180° • s^{-1}. Peak power generation of the knee extensors has been reported to be optimized at 375° • s^{-1} [1]. Such speeds would be available through instrumented isotonic exercise available with several of the more recent commercially available dynamometers. We feel that gender should be addressed to identify any potential differences that may affect muscle contraction mechanics during exercise. We were unable to locate any literature that addressed gender in using surface EMG as an index of fatigue in maximal-effort dynamic contractions. Previously we investigated the knee extensors's response during maximal isotonic and isokinetic exercise [27]. However, it is still unclear if torque output and surface EMG changes are specific to the type of fatiguing exercise immediately after exercise and in the recovery phase. Thus, the purpose of this study was to investigate the effects of fatiguing maximal isotonic and isometric exercises of the knee extensors on strength, power, and surface EMG amplitude in men and women immediately after exercise and during recovery.

2. METHODS

2.1. Subjects

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) 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 university approved written informed consent before beginning the study.

2.2. 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 0.80 indicating a strong correlation between trials [26]. Torque, velocity, and position analog data were collected from the Dynatrac during all muscle performance measures and digitized for storage and later analysis. Simultaneously, the surface EMG signal from the vastus lateralis was collected with the Myosystem 2000 (Noraxon, Phoenix, AZ) (gain = 1000, input resistance = 16MΩ = 16MΩ, 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).

2.3. Set-up 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 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 the thigh and waist were fastened to the dynamometer seat with velcro stabilization straps to minimize extraneous movements.

2.4. Experimental protocol

Subjects underwent isotonic and isometric exercise protocols on separate days with testing days separated by at least 48 hr. Muscle performance measures (isometric strength and isotonic power) were assessed prior to exercise (t = pre); immediately after exercise (*t* =: 00) and at 2.5 (*t* =: 02.5), 5 (*t* =: 05), 10 (*t* =: 10), and 15 (*t* =: 15) minutes after exercise. Testing order was gender stratified then randomly assigned.

2.5. Muscle performance measures

Each subject performed three submaximal voluntary isometric contractions for isometric familiarization purposes. This was followed by three, 3 s maximal voluntary isometric contractions (MVIC's) of the quadriceps with a 1 minute rest between repetitions (t = pre). Isometric testing was performed with the knee in 60° of flexion. Following the isometric fatiguing exercise, subjects performed one MVIC of 3 s duration and then 3 maximal isotonic knee extensions at 25% of the MVIC immediately at *t* =: 00, and at *t* =: 02.5, *t* =: 05, *t* =: 10, and *t* =: 15 following exercise.

For isotonic exercise testing, the subject's knee was placed at 90° of flexion. Two minutes following the isometric *t* = pre tests, subjects performed three isotonic concentric warm-up repetitions at approximately 50%, 75% and 100% of maximal effort for purposes of familiarization. The subject then performed three, maximal concentric knee extensions (*t* = pre). 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. The resistance of the dynamometer was 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

[16], pilot testing revealed that a 33% load did not permit completion of the isotonic exercise, whereas a 25% load did. The subject repeated three, maximal knee extensions followed by a 3 s MVIC immediately at *t* =: 00 and at *t* =: 02.5, *t* =: 05, *t* =: 10, and *t* =: 15 following exercise.

2.6. Exercise protocols

The isometric exercise was a 120 s MVIC of the knee extensors. The isotonic exercise consisted of 120 continuous maximal isotonic knee extensions on the Dynatrac. The tester provided verbal encouragement throughout both exercise protocols.

2.7. Mechanical data extraction

For purposes of this study, peak torque was defined as the highest torque obtained for each isometric contraction and power was defined as the product of instantaneous torque and the respective instantaneous velocity. The peak torques of the three MVIC's at *t* = pre were averaged and the peak powers of the three pre-fatigue dynamic contractions were averaged. All isometric and isotonic contractions following fatiguing exercise had the peak torque expressed as a percentage of the peak torque at *t* = pre (%PT), and the peak power expressed as a percentage of the peak power at *t* = pre (%PP). This allowed statistical comparisons between the two types of muscle performance.

2.8. EMG data extraction

Onset and offset boundaries of static contractions were a 1000 ms window that encompassed the middle of the MVIC [4]. Onset and offset boundaries of the EMG signal of each dynamic 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. Root mean square (RMS) values were calculated from all isometric and isotonic contraction windows. To make comparisons between pre and post exercise values, all isometric and isotonic contractions were normalized to the EMG signal of the respective MVIC and isotonic knee extension at *t* = pre [19].

2.9. Statistical analysis

Separate 1-between (gender), 2-within (time and type of muscle performance) repeated measures ANOVAs were performed on the muscle performance (%PT and %PP) and EMG data for each exercise session. 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 $p < 0.05$.

3. RESULTS

3.1. Isometric exercise

The ANOVA calculated for the muscle performance data revealed a significant interaction for time and type of muscle performance ($F(5,90) = 4.963$, $p < 0.001$) with strength more decreased than power (Fig. 1). Additionally, the ANOVA calculated for the EMG data during the isometric exercise day revealed significant RMS amplitude decrease during strength testing ($F(5,90) = 4.693$, $p < 0.001$) (Fig. 2).

3.2. Isotonic exercise

The ANOVA for muscle performance data revealed a significant interaction for time and type of muscle performance ($F(5,90) = 31.607$, $p < 0.001$) with power more decreased than strength (Fig. 3) Additionally, the ANOVA for the EMG data revealed that the RMS amplitude of males was significantly less than females (irrespective of type of muscle performance) ($F(5,90) = 4.952$, $p < 0.001$) (Fig. 4).

4. DISCUSSION

4.1. Mechanical performance measures

4.1.1. Isometric exercise

Evidence of a exercise-specific fatigue mechanism with isometric performance being fatigued to a greater extent than isotonic performance following a 120 s MVIC is depicted by the interaction of time and type of muscle performance in Fig. 1. This is not in agreement with others who have demonstrated greater decreases in peak power than isometric force production following isometric exercise [8,13–15]. Previous findings have been attributed to the slowing of the half relaxation time of the fatigued muscle [8,15]. These authors hypothesized that the fast twitch fibers were fatigued to a greater extent than the slow twitch, thereby causing a slowing of the half relaxation time predominantly in the fast twitch fibers. This may cause the fast twitch fibers to mimic the twitch characteristics of slow twitch fibers with a resultant decrease in twitch force. This hypothesis is not tenable in the current investigation as the current results demonstrate that isometric performance was fatigued to a greater extent than was isotonic performance following a 120 s MVIC of the knee extensors.

A potential central mechanism for this finding of fatigue selectivity upon muscle performance may entail the motor unit recruitment differences in fast and slow twitch motor units. Grimby & Hannerz [10] investigated the firing rate and recruitment of motor units of the "short toe extensor muscle". Subjects performed maximal and submaximal isometric contractions and isotonic contractions of the toe extensors. EMG recording revealed that continuously firing long interval motor units (which were associated with slow twitch fibers) were the only motor units firing during prolonged maximal voluntary effort. The intermittently firing short interval motor units (which were associated with fast twitch fibers) were of predominant importance in contractions of increasing velocity. When firing patterns of the two types of motorneurons were compared, the authors concluded that in contractions involving acceleration, the synaptic input is distributed differently from the input strength contractions. The current findings of isometric force production being fatigued to a greater extent than isotonic power production may be explained by a selective recruitment of slow twitch motor units during the isometric fatiguing protocol. This would decrease the amount of work performed by the fast twitch fibers during the isometric fatigue protocol, resulting in less fatigue in the isotonic contractions that immediately followed the static exercise.

One reason for finding following the isometric exercise that isometric performance is fatigued to a greater extent than isotonic performance at t =: 00 may be a result of the methods and not an actual phenomenon. At each time point following the static fatigue protocol, static muscle performance was assessed before the isotonic muscle performance. Due to limitations of the Dynatrac dynamometer and testing protocol, the isotonic performance testing following the static fatiguing protocol occurred approximately 10–15 s after completion of the fatiguing exercise. It is possible that the muscle experienced a significant amount of recovery during this 10–15 s. Previous investigations have reported a

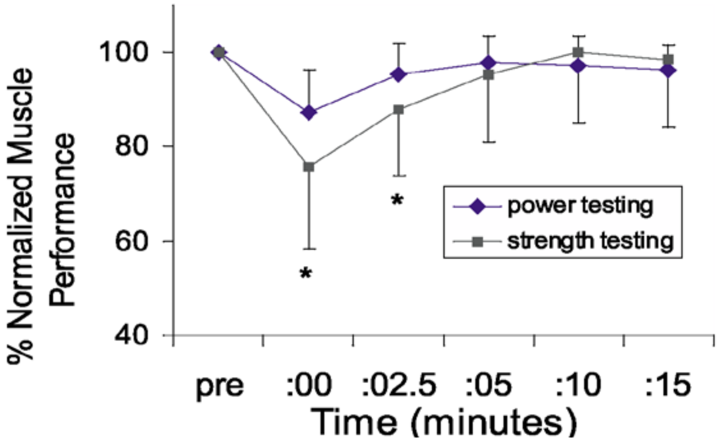

Fig. 1. Normalized strength and power values following isometric exercise. (* Strength decreased significantly more than power).

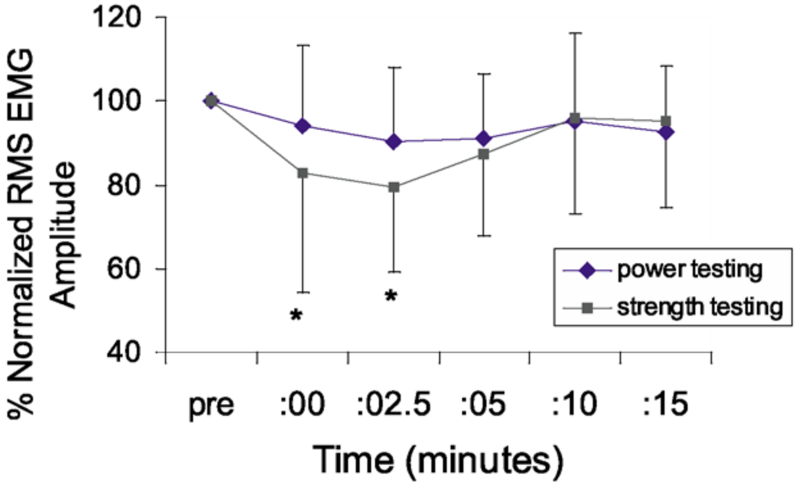

Fig. 2. Normalized EMG amplitude following isometric exercise. (* Significant decrease during strength testing ($p < 0.05$)).

very rapid recovery of the MVIC. Using a hand grip dynamometer and 60 s of maximal hand gripping exercise, it has been reported that there was a 36% recovery of isometric force production by 10 s [30]. However, at *t* =: 02.5, isometric performance was still fatigued to a greater extent than was isotonic performance. This finding supports the similar finding at *t* =: 00, and suggests that recovery may not be a factor irrespective of the dynamometer/experimental protocol concerns discussed previously as the muscle has had a longer time to recover.

Both contraction types returned to baseline levels at *t* =: 05. Using a hand grip dynamometer, it was demonstrated that following isotonic exercise, 72% of isometric strength returned in 60 s [30]. However, only 58% of isometric strength returned in 60 s following isometric exercise. This recovery pattern of the isotonic and isometric exercise supports the possibility of contraction-type specific fatigue mechanisms via selective motor unit recruitment.

4.1.2. Isotonic exercise

The greater decrease in isotonic peak power than isometric force at *t* =: 00 (Fig. 3) demonstrates that dynamic performance immediately following dynamic exercise decreased significantly more than static performance following dynamic exercise. This is opposite of the muscle performance results following static exercise where isometric force was fatigued to a greater extent. Once again the limitations of the dynamometer and testing protocol may have exaggerated the real difference of the extent of fatigue of the two types of muscle performance testing at *t* =: 00 as all isotonic testing (following the dynamic fatigue protocol) preceded isometric testing.

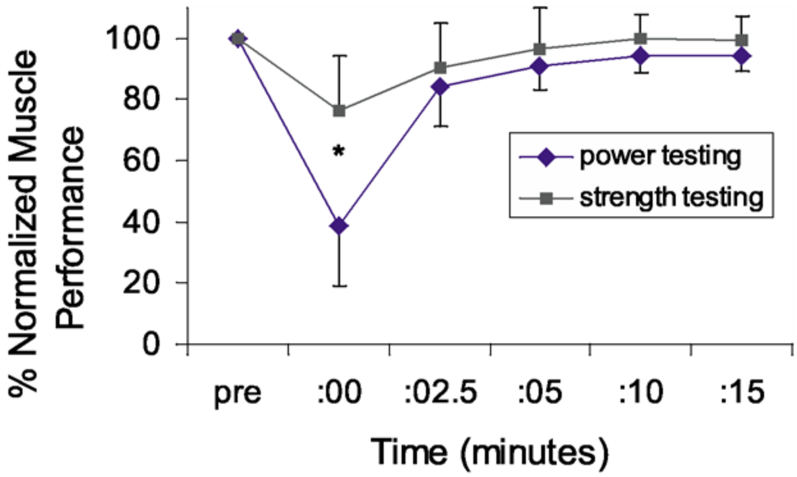

Fig. 3. Normalized strength and power values following isotonic exercise. (* Power decrease (from *t* = pre) significantly greater than strength decrease).

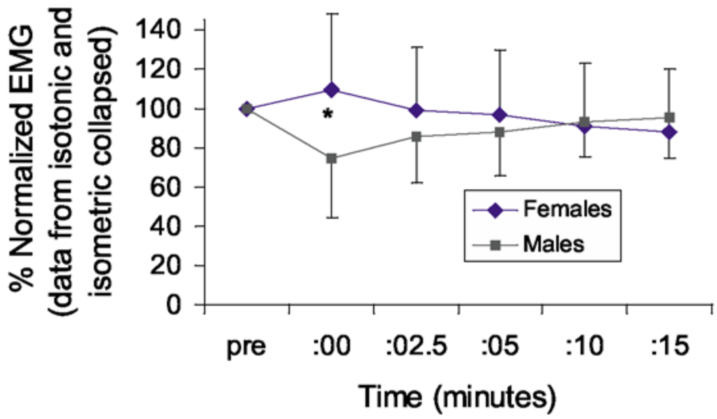

Fig. 4. Comparison of normalized EMG of males and females following isotonic exercise. (* Males significantly less than females).

Our findings agree with others that dynamic muscle force generating capacity being fatigued to a greater extent than isometric force generating capacity following dynamic exercise [14]. Following 6 minutes of isokinetic knee extensions, James et al. [14] reported a 50% decrease in peak instantaneous power output at $90°\cdot s^{-1}$ and only a 25% decrease in isometric force production. Our values of fatigue following 120 maximal isotonic contractions for isotonic and isometric muscle performance were 61% and 24%, respectively. While our fatiguing protocol was different, we are reporting similar decreases in isometric force (11% greater decrease in peak power production). Part of the explanation for this may be due to central fatiguing mechanisms. James et al. [14] used functional nerve stimulation (bypassing the central nervous system), thereby insuring that the muscle received maximal stimulation. It is possible in the current study that central pathways were fatigued, thereby accounting for the difference in dynamic force output.

By *t* =: 02.5, both dynamic and static muscle performance had returned to baseline levels following maximal isotonic exercise. This is in accordance with isometric recovery curves following 90 isotonic contractions on a hand dynamometer [30].

4.2. Surface EMG measures

4.2.1. Isometric exercise

It is well accepted that extended maximal isometric exercise will cause reductions in the time-amplitude domain of the surface EMG [5]. Our data are in agreement (Fig. 2). Our significant interaction between type of muscle performance and time is in agreement with the mechanical performance measures collected following the isometric exercise protocol. The RMS acquired from static contractions at *t* =: 00, and : 02.5 was significantly less than the RMS acquired from isotonic contractions following isometric exercise (Fig. 2). This finding is in agreement with other findings that surface EMG can be used as an index of fatigue in static muscle contractions [21,24,29].

The differences in RMS amplitude between isometric and isotonic contractions following isometric exercise were similar in nature to the differences in the muscle performance values following isometric exercise. It appears that time-amplitude processing of the surface EMG signal is a valid indicator of isometric contraction fatigue following isometric exercise. These decreases in the RMS amplitude (as measured in maximal isometric contractions) were likely the result of a slowing of the firing rate of motor units [5] and/or a decrease in the fiber conduction velocity [2,3].

The shape of the recovery curve of the RMS amplitude and the shape of the recovery curve of isometric torque production following isometric exercise are similar with one exception (Fig. 5). The shapes of the two curves intersect between time points :00 and :02.5 with RMS continuing to decline and with isometric torque rising. From time points :05 to :15 the slope of recovery of the two curves are similar. If central fatigue were the main cause of fatigue it would be expected that the slope of the RMS and torque production curves would recover similarly at all time points. Because of the intersection of time points :00 and :02.5, it is unlikely that central fatigue mechanisms were entirely responsible for all decrements in the mechanical muscle output.

During maximal sustained exercise the muscle primarily functions anaerobically [20] with lactate and [H+] accumulation [7] and phosphocreatine depletion [12]. The intersection of the two curves (the rise of isometric force and the fall of the RMS) may potentially be explained by recovery of local metabolic factors and not by central mechanisms with metabolic recovery occurring more quickly than recovery of central fatigue. However, local metabolic factors were not measured in the present study. It has been reported that recovery from maximal isometric exercise is primarily associated with changes in the metabolic state of the muscle [20]. More specifically, the phosphocreatine content and pH of the muscle may change. This potential fatigue mechanism incorporates both central and peripheral factors and emphasizes the complexity of the fatigue phenomenon.

Dynamic fatigue protocol. We present in the results a significant interaction of time and gender for the RMS data. When isometric and isotonic RMS data were combined at each time point, the RMS value for males at *t* =: 00 was significantly less than females at *t* =: 00 (Fig. 4). This is a finding that must be noted and may implicate potential gender differences in recovery of central fatigue. However, we feel there is no physiological basis to combine the EMG signal acquired from isotonic and isometric contractions. This just happens to be one of the interactions that was a product of our statistical design.

Dynamic contractions significantly fatigued the exercising muscle in the isotonic and isometric muscle performance tests following isotonic exercise. However, time-amplitude domain processing of the surface EMG signal collected from maximal dynamic contractions did not index of muscular fatigue or recovery from high velocity isotonic fatiguing exercise. Previous reports have suggested that the surface EMG signal may be used as an index of fatigue in maximal, dynamic closed-chain contractions [22]. The authors reported a decrease in the surface EMG of the gastrocnemius following 60 s of maximal leaping. Fiber composition may help to explain the differences in our findings. The gastrocnemius has been reported to be of a greater percentage of fast twitch fibers [22] while the vastus musculature is considered a mixed fiber type muscle [28]. It has been hypothesized that during high intensity dynamic exercise that the fast twitch fibers are of primary importance in the generation of power and thus the first to fatigue [18,23]. As the fast twitch fibers fatigue, the corresponding motor units fall out of the contraction process. The higher concentration of fast twitch fibers in the gastrocnemius may give a more powerful demonstration of how EMG may index dynamic fatigue of maximal dynamic exercise via measurement of the change in electrical potential associated with the fast twitch motor units.

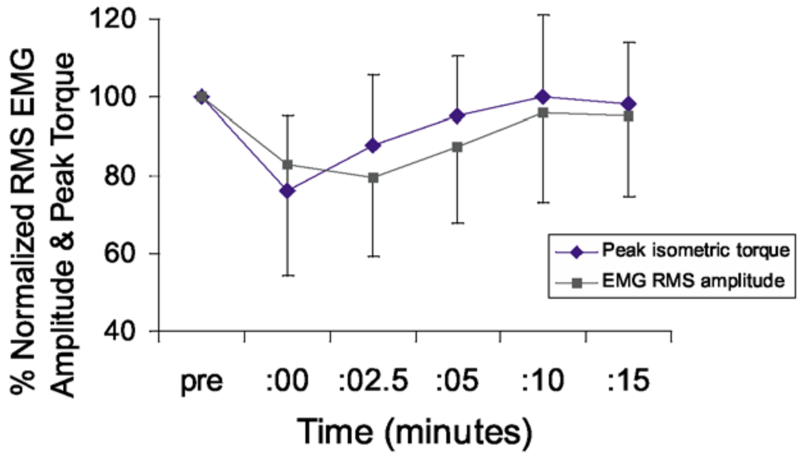

Fig. 5. Normalized EMG amplitude and strength values following isometric exercise.

Our data are in agreement with Nillson et al. [23] who also failed to demonstrate a change in the EMG activity level over the course of 100 isokinetic knee extensions performed at $180° \cdot s^{-1}$. They hypothesized that additional motor units (with less ability to produce force at high velocities) may have been recruited as the fast twitch motor units were fatigued. Thus, there would be little to no change in the surface EMG.

Another reason for not observing a significant decrease of RMS amplitude in fatigued isotonic contractions may be a result of the interaction between the surface electrode and the underlying muscle. In ballistic motions there are high levels of interactions between muscle geometry, musculotendinous material properties, cross bridge activity, and the electrode-muscle membrane tissue interface [25]. These tissue/electrode factors lead to difficulty in establishing a valid index of muscle fatigue through surface EMG measures.

5. SUMMARY

The findings of this investigation were that fatigue of muscle was specific to the type of fatiguing exercise performed. Specifically:

- Isometric exercise elicited greater decreases in isometric performance than isotonic performance.
- Similarly, isotonic exercise elicited greater decreases in isotonic performance than isometric performance.

These results may have implications upon muscle performance assessment in the clinical as well as the laboratory setting. If a true measure of fatigue is necessary, the test should be similar in nature to the exercise that induced the alterations of muscle performance.

Our inability to demonstrate surface EMG changes in dynamic contractions does not completely rule out the role of central factors in the fatigue of maximal isotonic contractions. However, we can offer no direct evidence to support central fatigue mechanisms. Although the current study presented no direct evidence of possible reasons as to why this difference occurred (via our inability to demonstrate changes in the surface EMG collected from isotonic contractions), it was hypothesized that motor recruitment patterns and metabolic factors combine to produce the fatigue phenomenon. Future research in the area of fatigue should be conducted by measuring changes in the central drive in conjunction with measuring changes in the peripheral factors involved with producing muscle force.

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