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Exploration of Warm-up Protocols on Muscular Fatigue

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EXPLORATION OF WARM-UP PROTOCOLS ON MUSCULAR FATIGUE

by

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ABSTRACT

Muscular dystrophy is a genetically linked myopathy with no cure available. The lack of a cure makes early detection and treatment of muscular dystrophy imperative. When reviewing protocols examining muscular fatigue at submaximal isometric contractions, proper warm-up appeared to be absent and could have caused skewed results and conclusions. This study examines the effects of implementing a warm-up protocol before fatiguing trials. In this study, 10 adult subjects conducted fatiguing protocols with the right rectus at submaximal isometric contractions. The warm-up period included a light walk along with contractions at 20% and 33% of maximal voluntary isometric contraction (MVIC) levels. Active recovery measures were also taken into consideration as subjects conducted the fatiguing protocol to relieve the onset effects of lactic acidosis. The contraction durations with and without warmup were found to be significantly different ($p=0.001$, t-test). Subjects without warmup had a 73.30 second contraction duration difference between their first and second fatiguing contraction, whereas subjects with warmup had a difference of 5.94 seconds. Future studies may investigate the effects the warm-up on the electromechanical efficiency (EME) and mechanomyography (MMG) frequency relationship.

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INTRODUCTION

Motivation

Muscular dystrophy is a genetically linked myopathy that has no available cure. Muscular dystrophy has many molecular complications that lead to weakening of the muscles which causes lack of mobility to complete everyday tasks. Since muscular dystrophy is a muscular disease, it has the potential to cause life-threatening harm to the pulmonary system. With the lack of a cure and a multitude of complications that can have a major impact on a person's life, early detection and treatment of muscular dystrophy is imperative. In the initial study conducted by Rehana Koilpillai, the protocol lacked a proper warm-up routine that addressed the specific physiology of the leg muscles. This study will evaluate the effect of a warm-up protocol on the results of the previous study.

Hypothesis

The objective of this experimentation is to establish parameters that will help characterize symptoms for muscular dystrophy. From an understanding based on previous studies around muscular dystrophy, the behaviors of some characteristics can be hypothesized. The goal will be to differentiate the different frequencies from surface electromyography (sEMG) and mechanomyography (MMG) signals. Using data from these inputs, we can also characterize electromechanical efficiency (EME) and determine the trends that can be expected in healthy muscle and the expected trends of diseased muscle. From the literature review, it can be expected to see sEMG frequency will increase and MMG frequency will decrease leading to a decrease in

EME. The purpose of this study will be to compare the data signals collected and determine if the warm-up protocol established will

Background

To understand muscular dystrophy, an understanding of the physiology of skeletal muscles is necessary.

Muscular Physiology

Anatomy of Skeletal Muscle

Muscles are used to generate force and movement in our bodies. They can be characterized into three separate groups: skeletal, cardiac, and smooth muscles. Skeletal muscles are responsible for voluntary movement of the human skeletal system (Noto et al. 2021). The structure of skeletal muscles can be understood in a cascading manner. Muscles are groups of fascicles, these fascicles are groups of muscle fibers, and these muscle fibers are groups of myofibrils (Noto et al. 2021). The myofibril can be broken down into sarcomeres which consists of the actin and myosin filaments which are responsible for muscle contraction via the sliding filament theory.

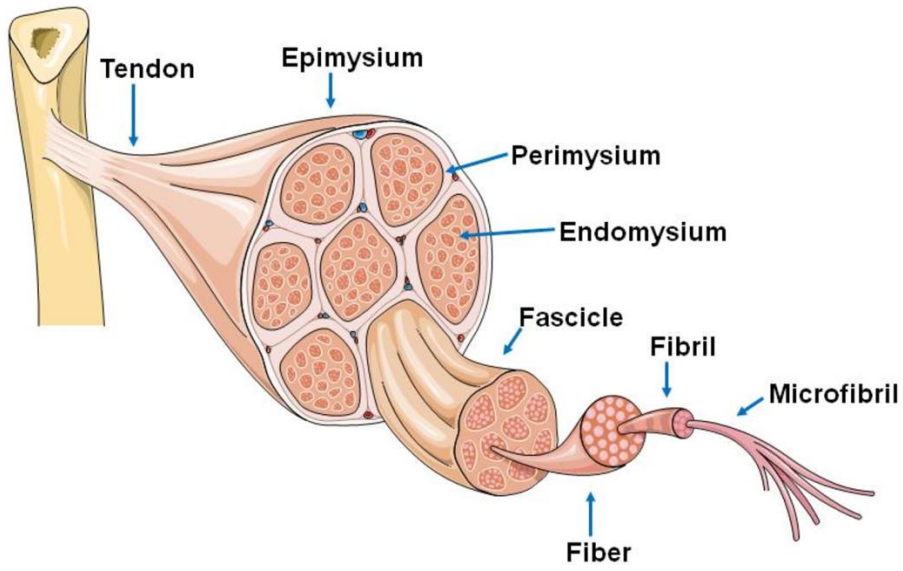

Figure 1: Anatomy of Skeletal Muscle

Adapted From Https://Www.Semanticscholar.Org/Paper/Identification-Of-PDLIM7-As-A-Nedd4-1-Substrate-In-D'Cruz/26858e846c3fa5bc5d6422e04b6f1d116108dc79

Sliding Filament Theory

The sliding filament theory is a theory that explains the contraction and relaxation of muscles. When muscles contract, the myosin and actin filaments slide past each other due to interactions with calcium. This interaction is prompted by the release of acetylcholine which leads to depolarization. Due to the depolarization, calcium is released from the sarcoplasmic reticulum. The calcium will then bind to troponin which is already attached to tropomyosin. Due to the calcium bond with troponin, tropomyosin detaches from the actin filament. This allows myosin to bind to the actin filament. Adenosine triphosphate (ATP) is broken down via hydrolysis to release energy and allow myosin to pull the actin filament (Cooke 2004). Finally, ATP is hydrolyzed to remove the myosin from the actin. This overall process is a small cycle that is

conducted repetitively many times to cause muscle contraction. For muscles to relax, calcium is returned to the sarcoplasmic reticulum, causing actin and myosin filaments to slide past each other in the opposite direction.

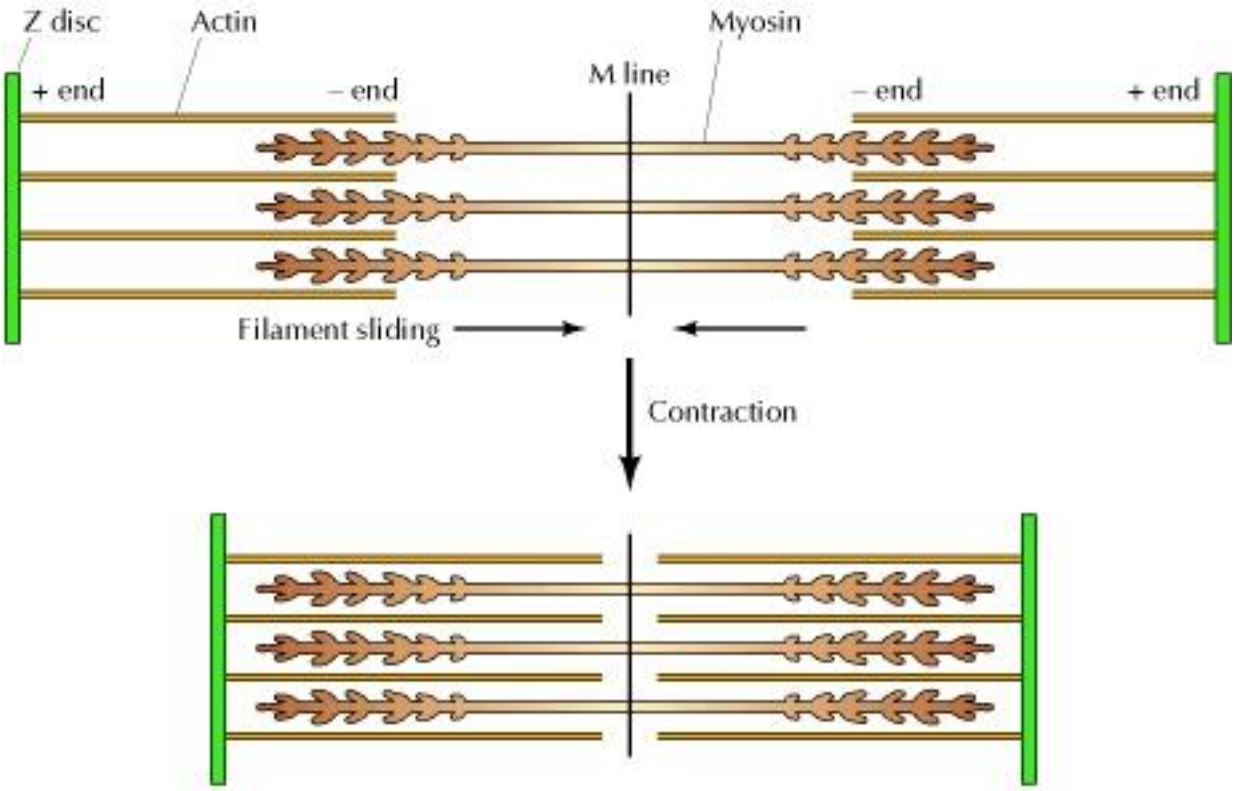

Figure 2: Sliding Filament Theory

Adapted from https://teaching.ncl.ac.uk/bms/wiki/index.php/The_Sliding_Filament_Theory

Duchenne Muscular Dystrophy (DMD)

There are many different forms and mutations of muscular dystrophy. The specific mutation that will be the focus of this study is Duchenne Muscular Dystrophy (DMD). DMD is usually found in young children, typically male. It is caused by a mutation in the dystrophin gene which leads to the structure and integrity of muscles to be compromised (Szabo 2021). This is important to

understand since it can help analyze and discuss the data that is collected. The effects of DMD are vast, including loss of ambulation (LOA), scoliosis, cardiomyopathy, and mortality. LOA is seen in about 30% of subjects by age of 10 and 90% of subjects by age of 15. Scoliosis is developed at about an average age of 14 years and 70% of subjects by age of 15 have had a form of cardiomyopathy (Szabo 2021). With many life-altering and life-threatening effects, early detection, and treatment of DMD can help subjects severely.

Mechanomyography (MMG)

Mechanomyography (MMG) is a low frequency vibration that can measure the mechanical changes in muscles during contraction and relaxation. This vibration is usually measured via a surface accelerometer that can sense changes in muscle contraction and relaxation. Along with this frequency, MMG can give information regarding motor unit size and firing rate during a voluntary contraction (Merletti and Parker 2005). The amplitude of the MMG signal is dependent on the amount of motor unit activation and recruitment along with the strength of the force applied (Gordon 1947; Orizo 2000). This information can be used to further characterize properties of healthy muscles and diseased muscles.

Electromyography (EMG)

Electromyography (EMG) is a measurement of electrical activity when a muscle is stimulated by motor neurons. This is commonly used to diagnose patients and analyze subjects based on the electrical signals created during contraction of muscles by depolarization. EMG can be conducted in vitro or in vivo via surface electrode or a needle penetrating the muscle of interest.

For studies related to analyzing muscles surface EMG (sEMG) is utilized whereas needles are utilized for studies related to pathologies regarding neuromuscular junctions (Merletti and Parker 2005). The signals detected by EMG instruments originates from the action potentials that cause depolarization and repolarization in the sarcolemma (Konrad 2006).

Electromechanical Efficiency (EME)

Electromechanical efficiency (EME) is the ratio of MMG to EMG amplitudes and can provide a measurement of muscle fatigue induced impairment of electrical and mechanical components of muscle contraction and relaxation (Barry et al. 1986). Studies have shown that EME in healthy muscle is impaired because of a buildup of metabolic byproducts such as lactic acid from fatigue that will hinder the electrochemical coupling of actin and myosin during contractionary periods (Hill 2017). EME has the potential to help characterize fatigue related effects on force production that cannot be previously determined from EMG and MMG data alone (Hill 2017).

Applications of EMG, MMG and EME regarding DMD

A subject affected by DMD will have a lack of dystrophin protein and be greatly affected on a basis of muscular strength and endurance because dystrophin is essential for skeletal muscle. With the lack of dystrophin protein, subjects will be impaired in their ability to move their muscles and contract for extended periods of time.

With this knowledge, EMG, MMG and EME can be implemented to better understand and quantify the parameters for healthy muscles and diseased muscles. Even though there are more studies done in vivo with EMG needles, sEMG electrode data has been shown to provide data

with similar trends in vitro (Hogrel 2005). This study will use sEMG to collect EMG data and will be properly complemented with MMG data to better understand the data and analyze the trends discovered.

Initial Study

Initial Protocol

To better understand the references to the initial protocol, it is written below. This is an exact copy of the protocol used by Koilpillai in her study.

Warm Up

6. The subject isometrically contracted at maximum force for 6s followed by 2 min of rest.
7. The subject isometrically contracted at approximately 50% of their maximum force level for 6s followed by 2 min of rest.
8. Repeated for a total of 5 contractions.

Maximal Voluntary Isometric Contraction (MVIC)

4. The subject isometrically contracted at their maximal force level for 6s followed by 2 min of rest.
5. The MVIC was repeated a second time.
6. The contraction with the highest force value was identified. LabScribe was auto- scaled so that the subject could approximate 50% of their maximum force for the following procedure.

Fatiguing Protocol (Sustained Isometric Contraction)

7. The subject isometrically contracted at approximately 50% of their MVIC to exhaustion followed by 15 min of rest.
8. Exhaustion was defined as being unable to maintain a force value within ± 5% of the 50% MVIC.
9. The subjects tracked their force on the LabScribe monitor that showed the force data as it was being acquired.
10. The isometric contraction was repeated for a second time until exhaustion as described in steps 1 and 2.

Understanding the forthcomings of the initial study

In Rehana's thesis in 2021, EME data collected was found to be statistically insignificant. It is yet to be determined the exact cause of this insignificance, but there are predictions for what caused the insignificance. One predication is that a larger sample size is needed, this will be addressed in this study. Another prediction is that the subjects were getting too fatigued in their first fatiguing protocol due to improper warm-up of their muscles. Subjects had longer contraction times in their first fatiguing protocol in comparison to their second fatiguing protocol as seen in the graph below, there was an average of 73.30 seconds of difference. This led to an investigation on understanding the different aspects of muscle physiology that could be affecting the subjects to have inconsistent trials during the fatiguing protocol.

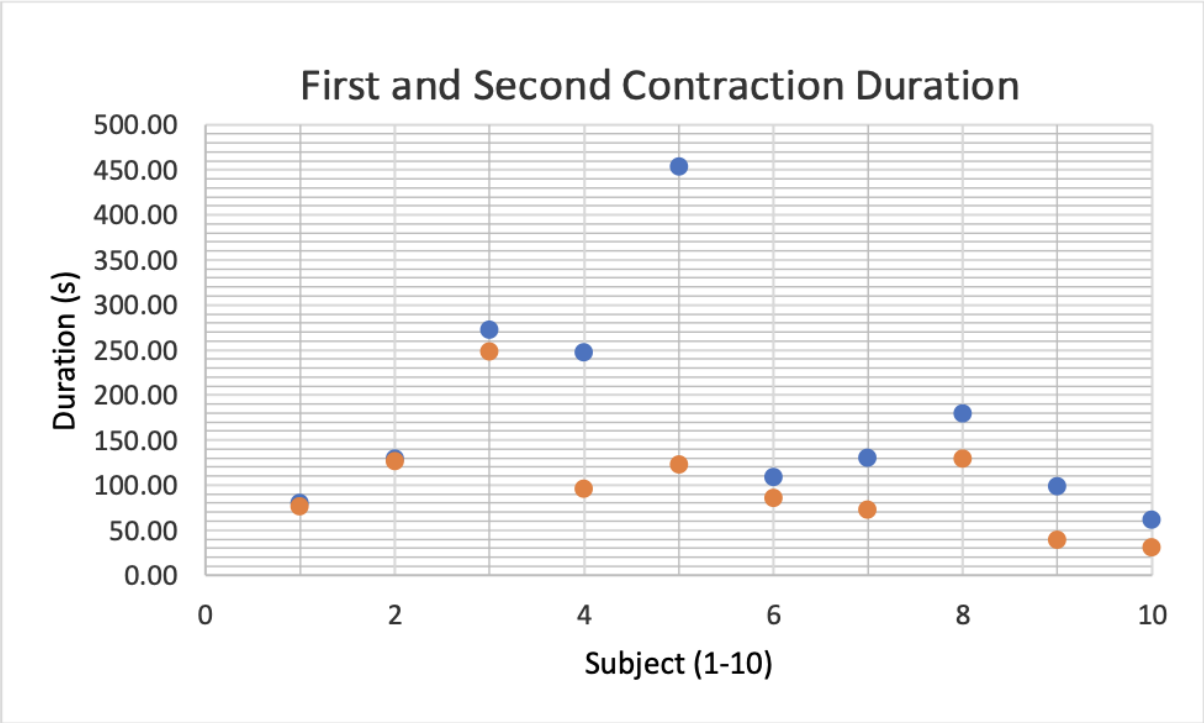

Figure 3: Graphical representation of contraction periods between the first (blue) and second (orange) contraction for all subjects in the old protocol

Another observational issue that could be contributing to the fatigue of the subjects is the MVIC protocol and 50% force level establishment. Since the 50% force level was set based on 50% of the singular highest force level the subject produced across the two MVIC protocols, that singular point came at a great expense of energy to the subject. A remedy to this issue is seen in Stewart's study where instead of a single high force level is selected, the highest one-second average was utilized (Stewart et al. 2003.).

Exploring remedies to the protocol

Proper warm-up

A generalized description of the initial protocol can be simply said as the subjects arrive and contract their muscles. This generalized outlook can also be applied to professional weightlifters as they compete at the highest level in their sport by contracting their muscles for extended periods of time. Before partaking in any weightlifting, a proper warm-up protocol is implemented instead of starting with the heaviest weights that they can lift, since a routine warmup prevents muscular strain (Evans et al. 2002).

This understanding led to the investigation into an implementation of a proper warm-up protocol for the subjects to do before the main fatiguing protocol.

Active vs. Passive warm-up

To implement a proper warm-up in the protocol, it is imperative to understand the difference between active and passive warm-up and analyze which will provide the most benefit to the subjects during the fatiguing protocol. Active warm-up requires movement of the muscular system while doing a light exercise while passive warm-up entails increasing the core temperature of the muscles. In the study conducted by Evans, it was concluded passive warm-up is beneficial in only preventing swelling compared to active warm-up to, otherwise there was no difference in preventing muscle damage (Evans et al. 2002). However, this could have been a result of their protocol for the warm-up which required 100 repetitions of the elbow flexors from an extended position of 170° to a flexed position of 50° (Evans et al. 2002). The Evans group determined that there was no difference between active and passive warm-up but noted

that warm-up in general increased instantaneous maximal power output as shown in the figure below. Extrapolating from this study, in the warm-up part of the new protocol there needs to be a limit on the intensity of the procedure to avoid muscle fatigue before the main fatiguing protocol begins.

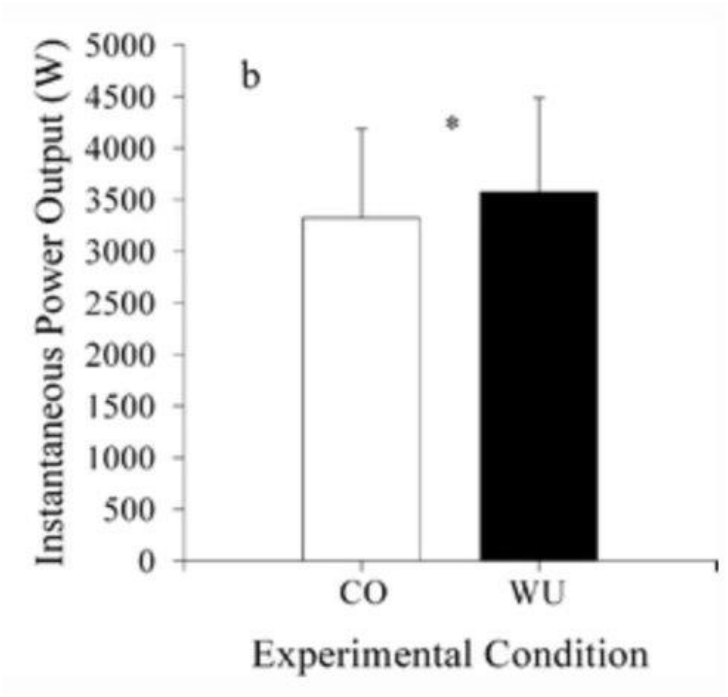

*Figure 4: Graphical representation of instantaneous power output in the different experimental conditions. The control group is noted as CO and the warm-up group is noted as WU, the * represents a statistical significance of $p<0.05$*

Exploration into active warm-up

For the scope of our study, passive warm-up does not seem possible and since Evans showed little difference between passive and active warm-up and Stewart showed an increase in output after an active warm-up, an active warm-up protocol must be investigated (Stewart et al. 2003.). Looking into Stewart's study, there is a discussion regarding the temperature of the muscles. When active warm-up results in an increase in muscular temperature, a similar increase in performance was observed (Stewart et al. 2003.). This can be attributed to the increase in enzymatic processes such as ATPase activity because of the temperature increase which results in the performance increase (Stewart et al. 2003.) It is noted that approximately 15 minutes of active warm-up caused muscle temperature to increase by approximately 3°C (Stewart et al. 2003.). While Stewart used muscle temperature probes, for the purpose of this study, the relationship previously established can be implemented into the protocol to increase the temperature of the muscles.

Understanding warm-up intensity

Establishing the proper intensity of the warm-up protocol is imperative to prevent the onset of muscular fatigue. In the study done by the Tomaras group exploring the amount and intensity of warm-up procedures, they summarized their findings with a common idiom, less is more (Tomras et al. 2011.). Based on their findings that warm up performed

too intensely and for too long of a duration caused fatigue and impaired the athletic ability of the subjects (Tomras et al. 2011).

Lactic Acidosis

When exercise is performed, energy is created in the body by the breakdown of glucose via the Krebs cycle (De Backer 2003). This process is reliant on oxygen, however during exercise when oxygen is unavailable, anaerobic processes take over. This results in the conversion of pyruvate into lactate which can continue to be converted into energy in the form of ATP (De Backer 2003). The excess lactate in the bloodstream causes lactic acidosis. The onset of lactic acidosis is caused when the lactic threshold is crossed, however the lactic threshold is variable from person to person depending on their level of activity and experiences (Faude et al. 2009). To recover from lactic acidosis, there are active measures that will reduce the intensity of lactic acidosis.

Active recovery

To recover from lactic acidosis actively, subjects can take measures such as repeating the motions conducted in a less intensive manner. In the study conducted by Valenzuela's group with climbers, they discovered that by implementing recovery protocol specific to the sport or activity that caused the fatigue enhanced recovery and the removal of lactate (Valenzuela et al. 2015). The protocol that they implemented included a warmup, followed by the fatiguing activity and between the activities the climbers continuously made climbing motions to facilitate recovery and lactate removal

METHODOLOGY

The study was conducted at the University of Central Florida at the Biomedical Acoustics Research Laboratory. This protocol was adapted from the experimental protocol in the study by Koilpillai with an application of a warm-up protocol, extended resting period and active recovery. 10 adult subjects (6 males and 4 females) were studied. With 2 contractions per subject, there is a total of 20 samples which will be compared to the study done by Koilpillai.

Set up

1. The subject will be seated in an upright sitting position as depicted in figure 5. The subject's skin is cleaned with an alcohol wipe to remove any dirt on the surface of the skin.
2. Over the subject's right rectus femoris, on the surface, a surface accelerometer (Model 356A32, PCB Piezoelectronics, Depew, NY) will be attached to the skin at a half-way point between the inguinal crease and the superior aspect of the patella along the femoral axis using medical grade tape.
3. Surface electromyography activity (IX-TA 220, iWire B3G, iWorx, Dover, NH) will be measured using EKG electrodes (REF 2560, Red DotTM Electrodes, 3M Deutschland GmbH Health Care Business, Neuss, Germany). They are attached in three places of the subject as depicted in figure 6. The first two electrodes will be placed 4 cm above and below the surface accelerometer along the femoral axis. The third electrode will be placed on the surface of the patella, this will be utilized as a ground electrode.

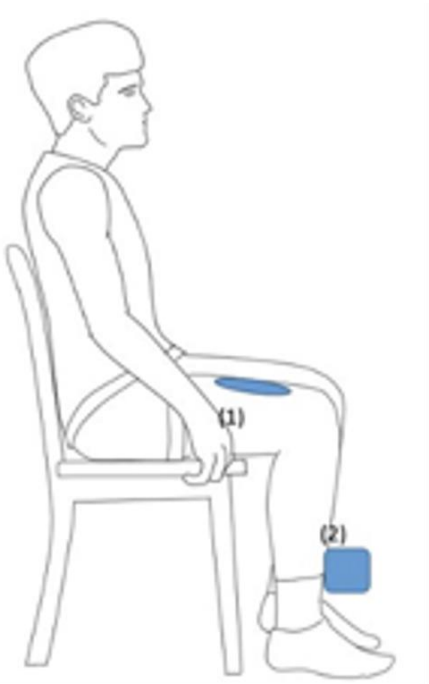

Figure 5: Set up of subject during protocol

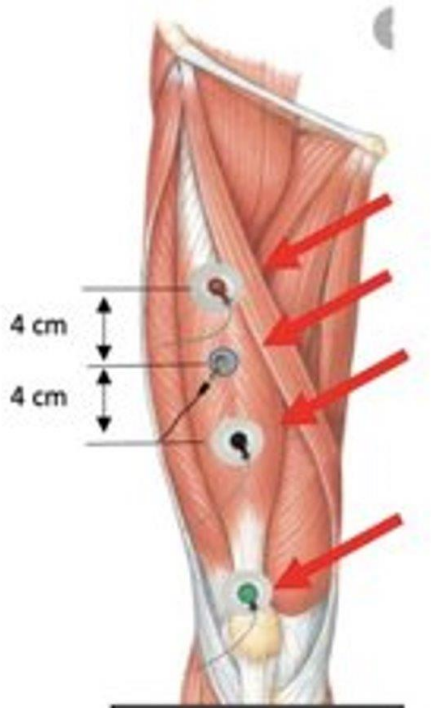

Figure 6: Placement of electrodes on subject's rectus femoris and patella

Protocol

Warm Up

1. The subject will take a light walk for 1 minute
2. The subject is cleaned and set up following the set-up protocol established previously
3. The subject will perform an isometric contraction against the force gauge for 6 seconds at their maximum possible force level and then rest for 5 minutes
    - The experimenter conducting the protocol will find the maximum force level achieved by the subject on LabScribe and adjust the scale to assist the subject in visually understanding their 20% of their maximum force value
4. The subject will perform an isometric contraction against the force gauge for 6 seconds at 20% of their maximum possible force level and then rest for 3 minutes
    - The experimenter conducting the protocol will adjust and scale LabScribe to assist the subject in visually understanding their 33% of their maximum force value
5. The subject will perform an isometric contraction against the force gauge for 6 seconds at 33% of their maximum possible force level and then rest for 3 minutes

Maximal Voluntary Isometric Contraction (MVIC)

6. The subject will perform an isometric contraction against the force gauge for 6 seconds at their maximum possible force level and then rest for 5 minutes
7. The subject will repeat the MVIC for a second time

- The experimenter conducting the protocol will find the highest valued 1 second average force value achieved by the subject on LabScribe and adjust the scale to assist the subject in visually understanding their 50% of their MVIC for the rest of the protocol

Fatiguing Protocol

8. The subject will perform an isometric contraction against the force gauge at 50% of their MVIC level until muscle exhaustion and then rest for 15 minutes
    - Muscle exhaustion is defined by the subject's inability to remain within ± 5% of the determined 50% MVIC level
9. The subject will take a light walk for 1 minute
10. The subject is cleaned and set up again following the set-up protocol established previously
11. The subject will repeat step 8

Analysis

To understand the effectiveness of implementing the warm-up protocol and the other factors that were changed a one-sample t-test will be implemented. A primary indicator is expected to be seen in the difference between the subject's contraction durations. To determine contraction durations, LabScribe was utilized. Unfortunately, some of the data for EMG and MMG were invalid and corrupted due to instrumentation error. Fortunately, the most important data of contraction durations were undisturbed.

RESULTS

Since EMG and MMG data were obscured, only the contraction duration data was analyzed. This will demonstrate the difference in the two protocols that included a warm-up and did not. A side-by-side comparison with summaries of the old and new protocol is present to visually understand the differences in the two protocols. A graphical representation of the differences was plotted for each protocol as well to understand the change in contraction durations between the two protocols. Additionally, the graphs corresponding to the new protocol were adjusted to match the axis dimensions of the old protocol graphs to aid in visual comparison of the differences.

New Protocol vs. Old Protocol

Table 1: New Protocol Summary vs Old Protocol Summary

New Protocol Summary	**Old Protocol Summary**
Warm Up	Warm Up
1. Subject takes a light 1 minute walk	
2. Subject is cleaned and set up	1. Subject is cleaned and set up
3. Subject maximally contracts for 6sec followed by 5min of rest	2. Subject maximally contracts for 6sec followed by 2min of rest
4. Subject contracts at 20% of maximum force for 6sec followed by 3min of rest	3. Subject contracts at 50% of maximum force for 6sec followed by 2min of rest
5. Subject contracts at 33% of maximum force for 6sec followed by 3min of rest	4. Step 3 is repeated for a total of 5 contractions
MVIC	MVIC

6. Subject maximally contracts for 6sec followed by 5min of rest	5. Subject maximally contracts for 6sec followed by 2min of rest
7. Step 6 is repeated once more	6. Step 5 is repeated once more
8. Contraction period with highest 1 second average is identified and used to calculate 50% of MVIC for the rest of the protocol	7. Highest contraction force value is identified and used to calculate 50% of MVIC for the rest of the protocol
Fatiguing Protocol	Fatiguing Protocol
9. Subject contracted at 50% of MVIC until exhaustion followed by 15min of rest	8. Subject contracted at 50% of MVIC until exhaustion followed by 15min of rest
10. Exhaustion is defined as inability to maintain 50% of MVIC within a ± 5% range	9. Exhaustion is defined as inability to maintain 50% of MVIC within a ± 5% range
11. Subject takes a 1min light walk	10. Subject repeats step 8
12. Subject is cleaned and set up again	
13. Subject rests for 15min	
14. Subject repeats step 9	

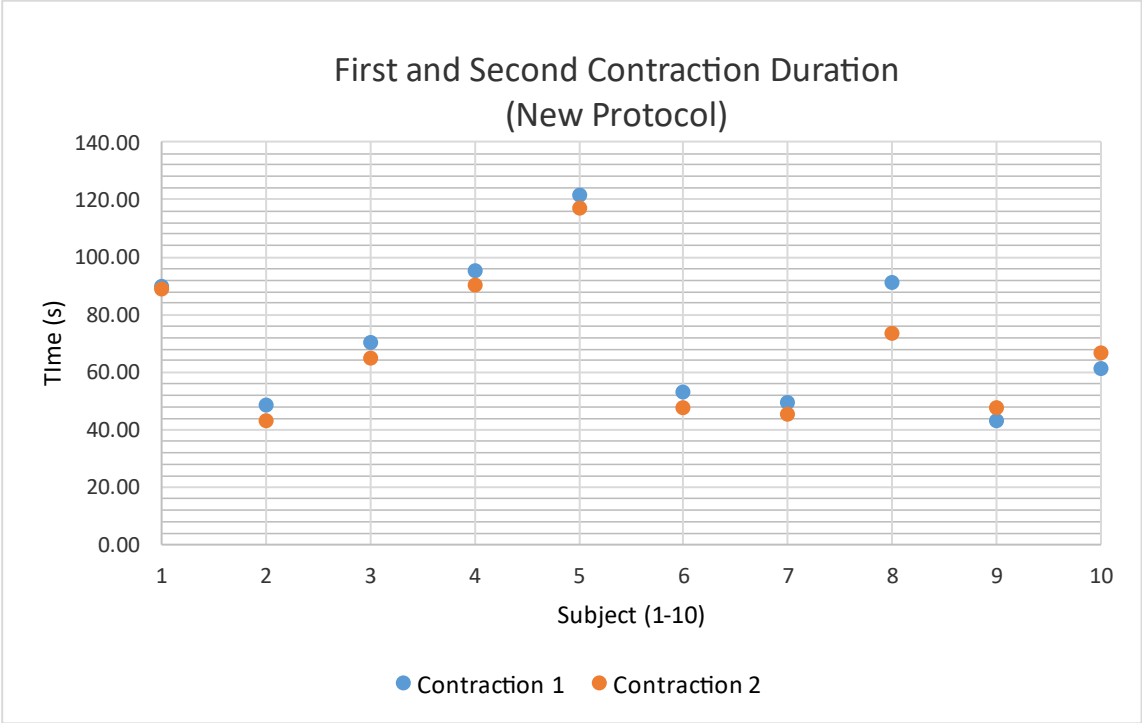

Figure 7: Graphical representation of contraction durations in new protocol

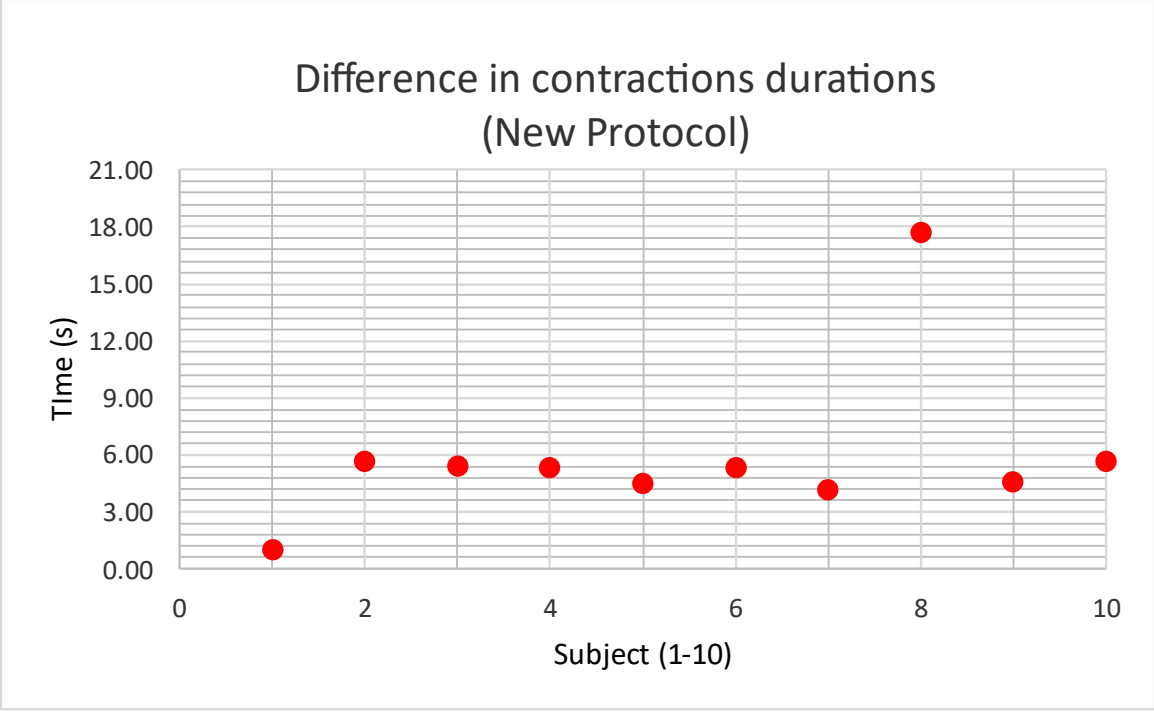

Figure 8: Graphical representation of difference in contraction durations in new protocol

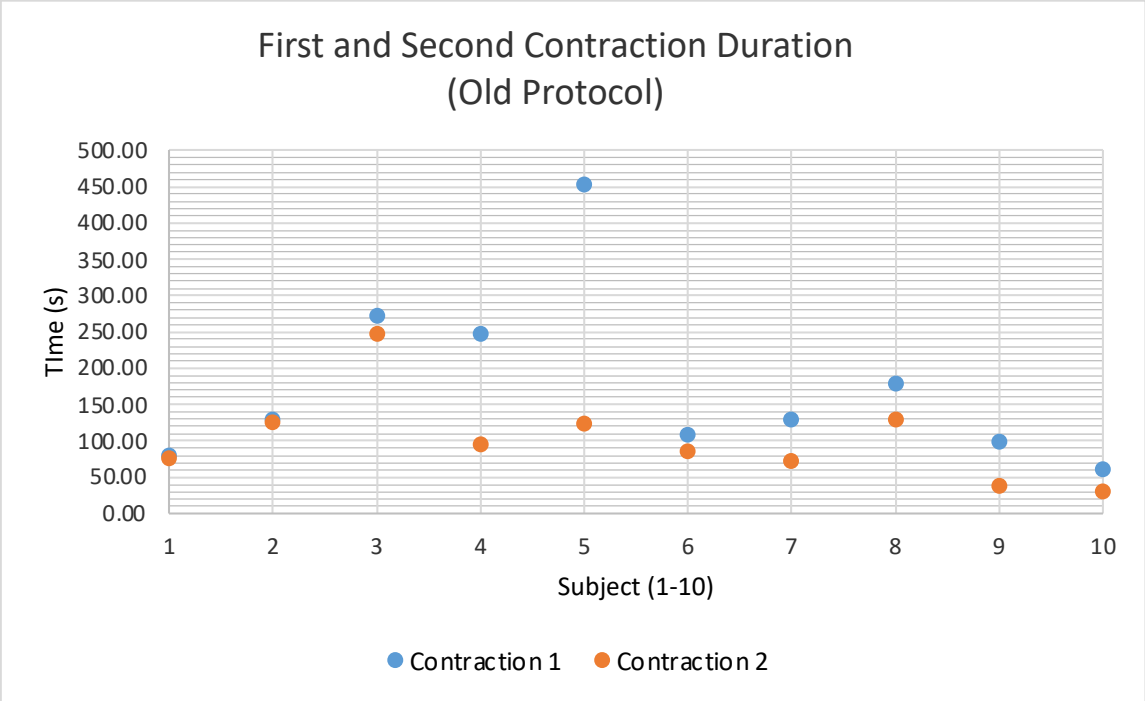

Figure 9: Graphical representation of contraction durations in old protocol

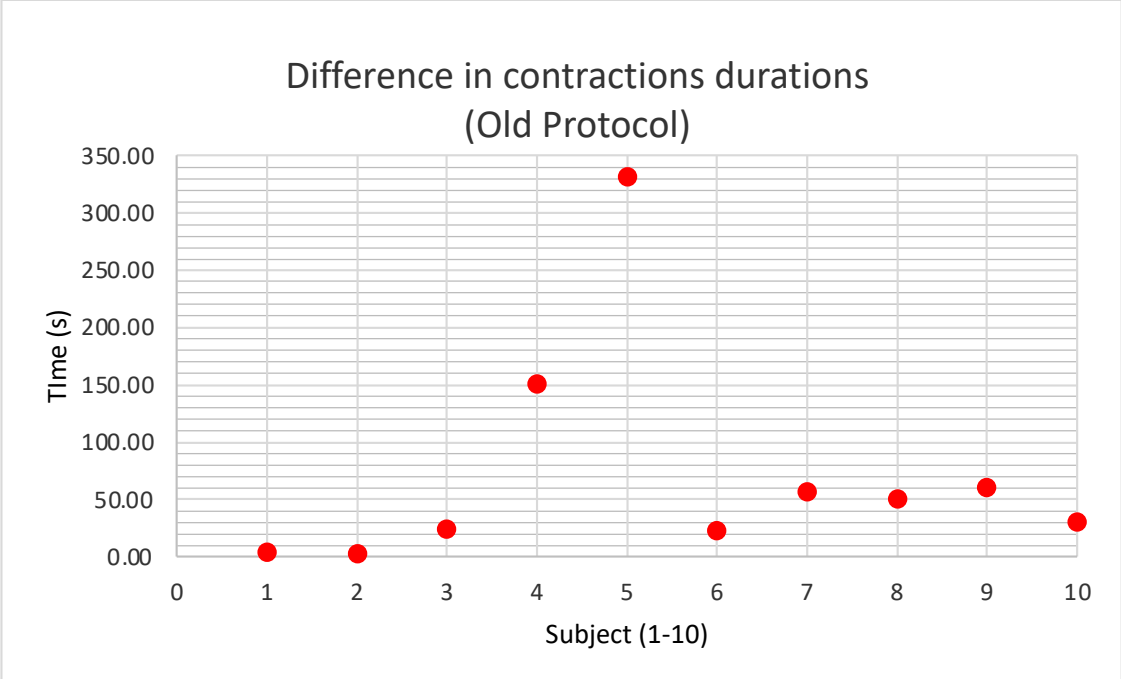

Figure 10: Graphical representation of difference in contraction durations in old protocol

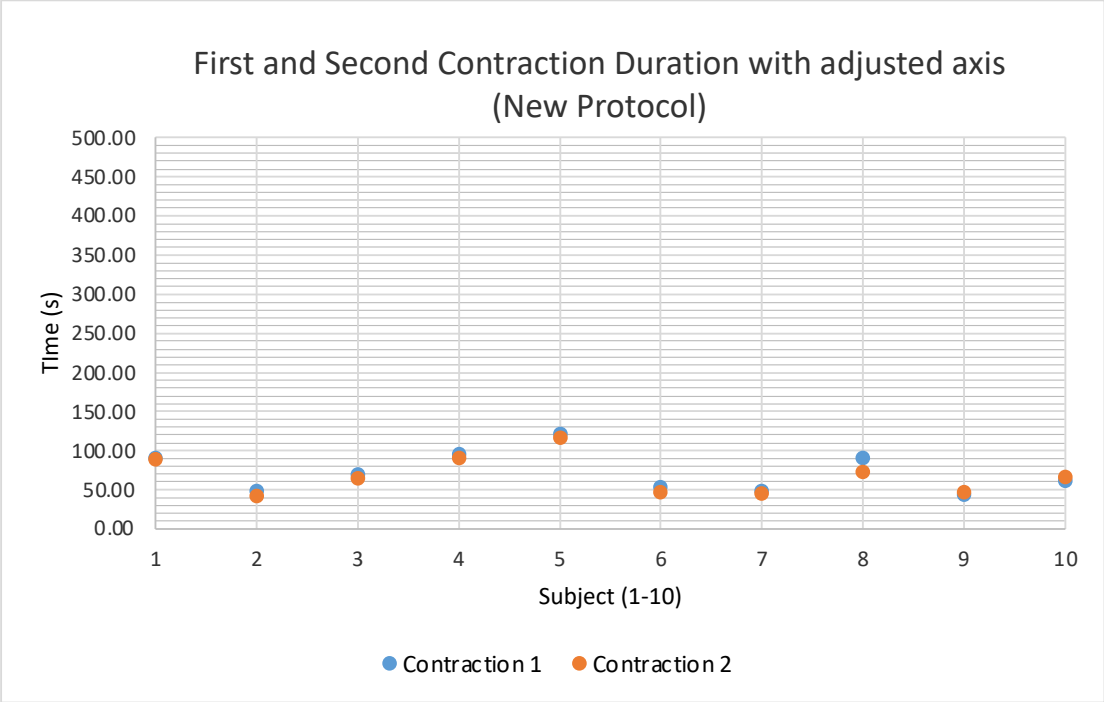

Figure 11: Graphical representation of contraction durations in new protocol with adjusted y-axis to match old protocol graph

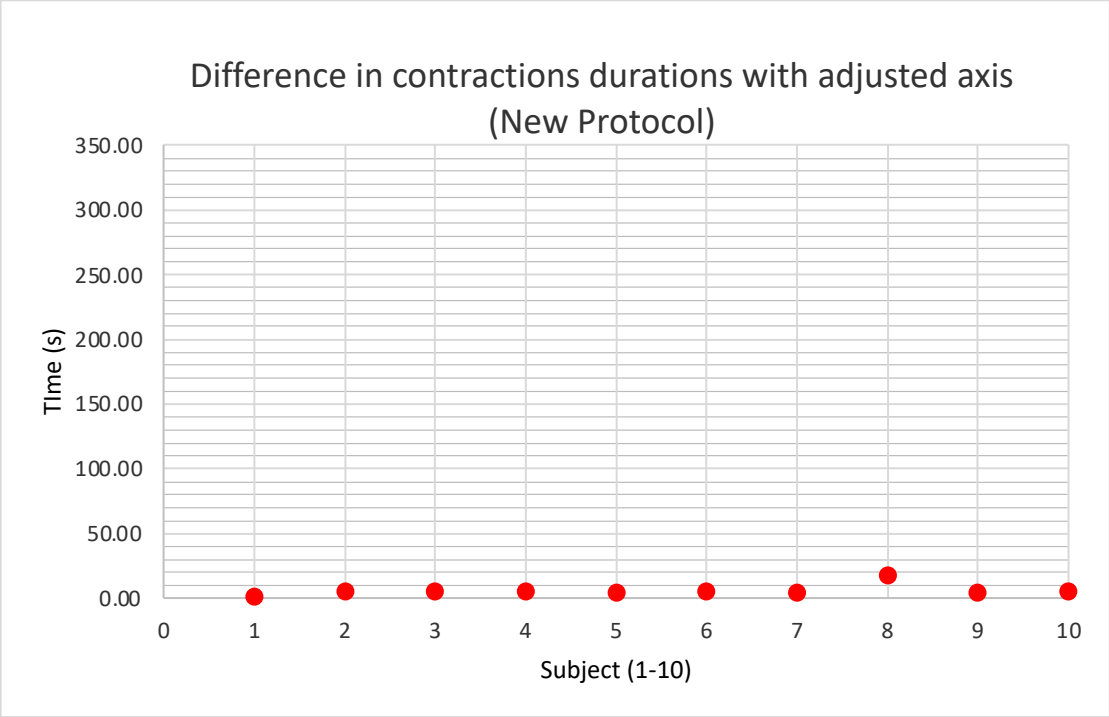

Figure 12: Graphical representation of difference in contraction durations in new protocol with adjusted y-axis to match old protocol graph

DISCUSSION

Based on the results of the study, it can be shown that the changes to the protocol established a significant decrease in the difference between fatiguing contraction durations. The first protocol had an average of 73.30 seconds difference between the first contraction's duration and the second contraction's duration whereas the new protocol had a difference of only 5.94 seconds. This significance is exemplified by the paired one-tailed t-test which gives a p value of 0.001. The subjects also verbally confirmed that they felt the first and second contractions were about equal difficulty. However, something that can be taken into consideration is the psychological factors that could have skewed the data.

Subjects were told about the purpose of the second fatiguing protocol during the rest period between the first and second contractions. A handful of subjects mentioned that they would attempt to match their times and could be visually seen exerting more effort during the second contraction period. This competitive nature is something a few studies have covered. In a study by H V Ulmer, he suggests that subjects are altering the amount of power required to complete the tasks and successfully accomplish their goal to avoid fatigue (Ulmer 1996). This idea does not suit the situation at hand since this would mean subjects knew the objective of the study before hand and as a result adjusted their power output during the MVIC trials or during the first fatiguing protocol as to avoid fatigue and accomplish similar contraction durations in the second contraction period. Alternatively, a study done by the Abbiss group found that during submaximal contractions, fatigue is a caused by neurological factors which reduce the central

drive of the subject (Abbiss 2005). This could explain why subjects are having shorter times during the old protocol for the second contraction.

CONCLUSION

Based on the results of this study, the warm-up and active recovery that was implemented helped reduce muscular fatigue during the fatiguing protocol. A significant difference can be observed between the trials conducted previously without a warm-up and active recovery. This trend is supported by the literature and can be further expanded upon. Future studies can repeat this experimentation to determine if the implementation of warm-up protocols and active recovery changes the results of the previous study (performed without warm-up): no significant trend between EME and MMG frequency. Additionally, by adjusting other parameters regarding the submaximal contractions and observing the trends that subjects produce, it would be interesting to see if the results of this study are consistent over three or four fatiguing contractions. With an understanding of the trends that a warm-up and active recovery provides to muscular fatigue, studies investigating muscular disease can implement these parameters into their investigations to understand the different responses to muscular fatigue.

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