Non-invasive Evaluation of Muscle Fatigue Using Mechanomyography and Surface Electromyography – A Pilot Study

A. Benwali[1], Q.R. Ferguson[2], S. Farahat[1], R.H. Sandler[2], E. Hill[3] and H.A. Mansy[1]

1. Dept. of Mechanical and Aerospace Eng., University of Central Florida, Orlando, FL, USA
2. College of Medicine, University of Central Florida, Orlando, Florida, USA
3. School of Kinesiology & Physical Therapy, University of Central Florida, Orlando, FL, USA
{Abdulbaset.Benwali, hansen.mansy, sherif.ahdy, ethan.hill}@ucf.edu,
quinnferguson@knights.ucf.edu, rhsandler@gmail.com

Muscle fatigue is defined as a decline in the ability to maintain a desired force against a load. Muscle fatigue may also be described as a decline in the muscle's maximum force during contraction. In contrast to muscle damage or weakness, characterized by a compromise in the ability of well-rested muscles to generate force, muscle fatigue is generally reversible with rest [2]. In a muscle experiencing fatigue, the nerves cannot sustain the high frequency signal necessary to reach the Maximum Contraction (MC) for a long time, resulting in a decline in muscle force during a sustained contraction. Due to its utility in providing information about nerve signaling and muscle's electrical activity, surface electromyography (sEMG) is currently the dominant method to detect muscle fatigue [2]. Mechanomyography (MMG) can reveal unique information that cannot be derived from the sEMG signal alone about the physiological behavior of muscles during contraction. However, more information may be needed about the ability of MMG to measure changes in muscle's activation patterns and mechanical properties that occur with muscle fatigue. Additionally, investigating the force-dependent characteristics of the MMG signal can provide information about physiological properties such as muscle activation strategies and fiber type distribution, which can be used to explore factors contributing to fatigue responses [1]. The purpose of this study is to examine and analyze the electrical and mechanical muscle responses to submaximal isometric contractions, as well as force-varying trapezoidal contractions in the rectus femoris muscle.

After approval by the University of Central Florida Institutional Review Board, healthy volunteers (n = 16) with no history of neuromuscular disease or intolerance of knee extension were seated in an ergometer (Figure 1). The skin of the anterior thigh over the rectus femoris and over the patella was shaved as necessary to remove hair. The skin was then cleaned with alcohol wipes and a lightweight accelerometer was affixed to a point on the anterior thigh, halfway between the inguinal crease and the patella, as shown in Figure 1. Positive and negative sEMG electrodes were placed on either side of the accelerometer and the ground electrode was placed over the patella. The MMG accelerometer signal was amplified by an ICP sensor amplifier (PCB piezotronics, Depew, NY). The force generated by isometric contraction was measured with a force gauge. The force, sEMG, and MMG signals were digitized by the iWorx-TA recorder (iWorx, Dover, NH) at a rate of 2000Hz.

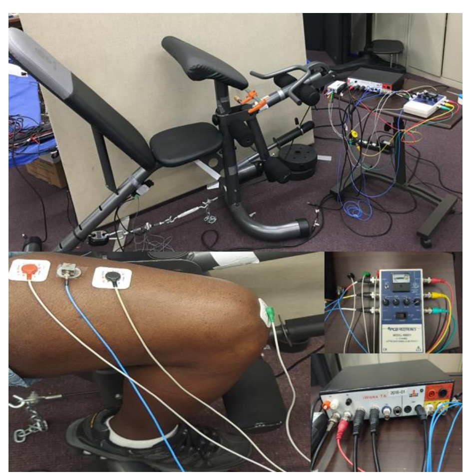


Figure 1. Experimental setup and sensor placement

The data collection protocol is shown in Figure 2 and follows typical loading conditions [1]. After a warm-up period mimicking the trapezoidal contractions, participants performed 2 sets of 5-second maximal isometric contractions to estimate the maximum force generated. Maximal contractions were separated by a 30-second rest period. To study the MMG and sEMG signals at varying force levels, participants then performed a trapezoidal contraction. Trapezoidal contractions consisted of 5 seconds at 5% maximal voluntary contraction (MVC), a 5-second linear

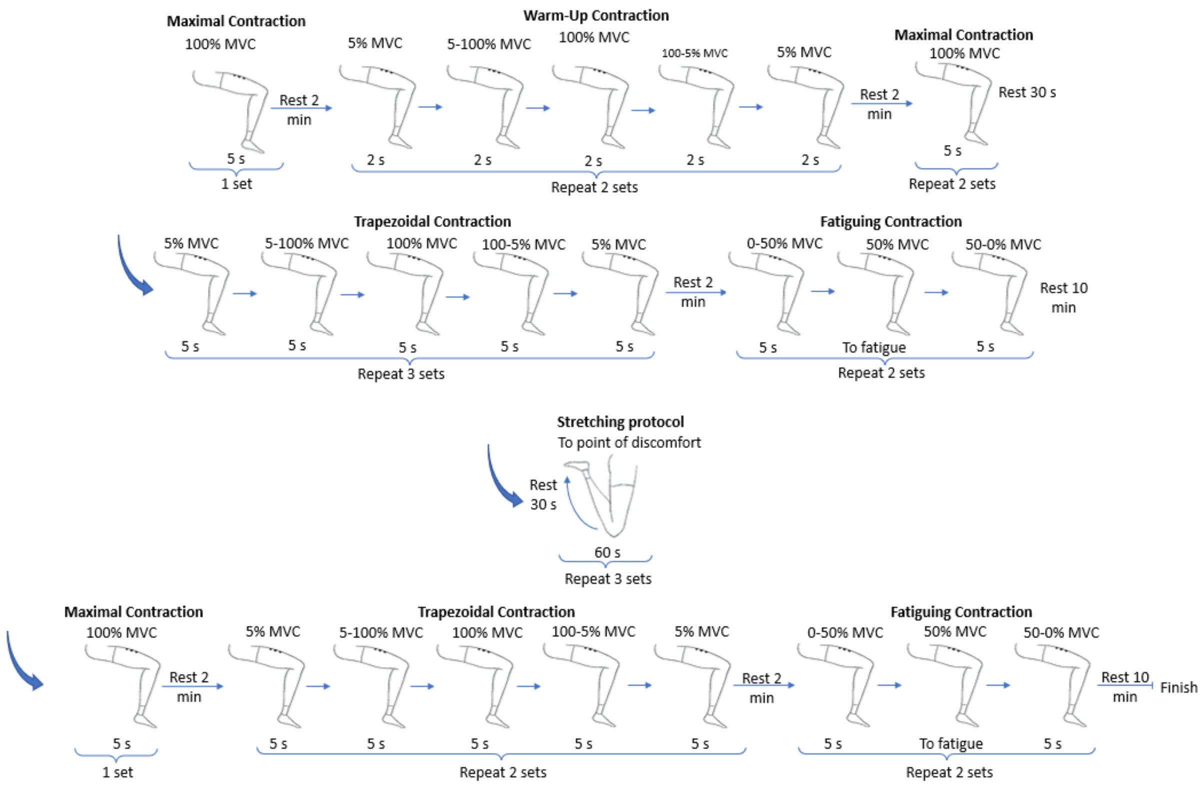


Figure 2. Data collection protocol

increase from 5-100% MVC, a 5-second plateau at 100% MVC, a 5-second linear decrease from 100-5% MVC, and a 5-second isometric contraction at 5% MVC. After the trapezoidal contractions, participants performed two fatiguing isometric contractions at 50% MVC. Participants then performed a stretching protocol consisting of three 60-second passive knee flexions to the point of discomfort, intended to decrease the stiffness of the quadriceps femoris. After stretching, participants then repeated 1 isometric maximal contraction, 3 trapezoidal contractions, and 2 fatiguing contractions, using the same protocols described above.

Pilot data from one subject is shown in Figure 3, suggesting the ability of participants to follow the protocol and technical feasibility of measurements. The pilot data also demonstrates the ability to calculate MMG and sEMG root mean square (RMS) amplitude and mean power frequency (MPF). The channels labeled “MMG X”, “MMG Y”, and “MMG Z” represent the MMG signal in the lateral, longitudinal, and perpendicular directions, respectively. The channel labeled “EMG” corresponds to the sEMG signal, and the channel labeled “Force” corresponds to the measured force. MMG RMS amplitude and MMG MPF for this contraction were both calculated using MATLAB (MathWorks, Natick, MA). MMG MPF during fatiguing contractions is a biologically interesting variable because of its ability to potentially provide unique information about fiber type [1].

Similarly, some studies suggest that force-varying RMS amplitude of the MMG signal can provide unique information on activation strategies [1]. Data analysis of subsequent contractions, both pre- and post-stretching, will include MMG MPF, MMG RMS amplitude, sEMG RMS amplitude, and sEMG MPF. sEMG and MMG may also find future applications in monitoring patients with muscle conditions as well as in informing *in silico* modeling of skeletal muscle function.

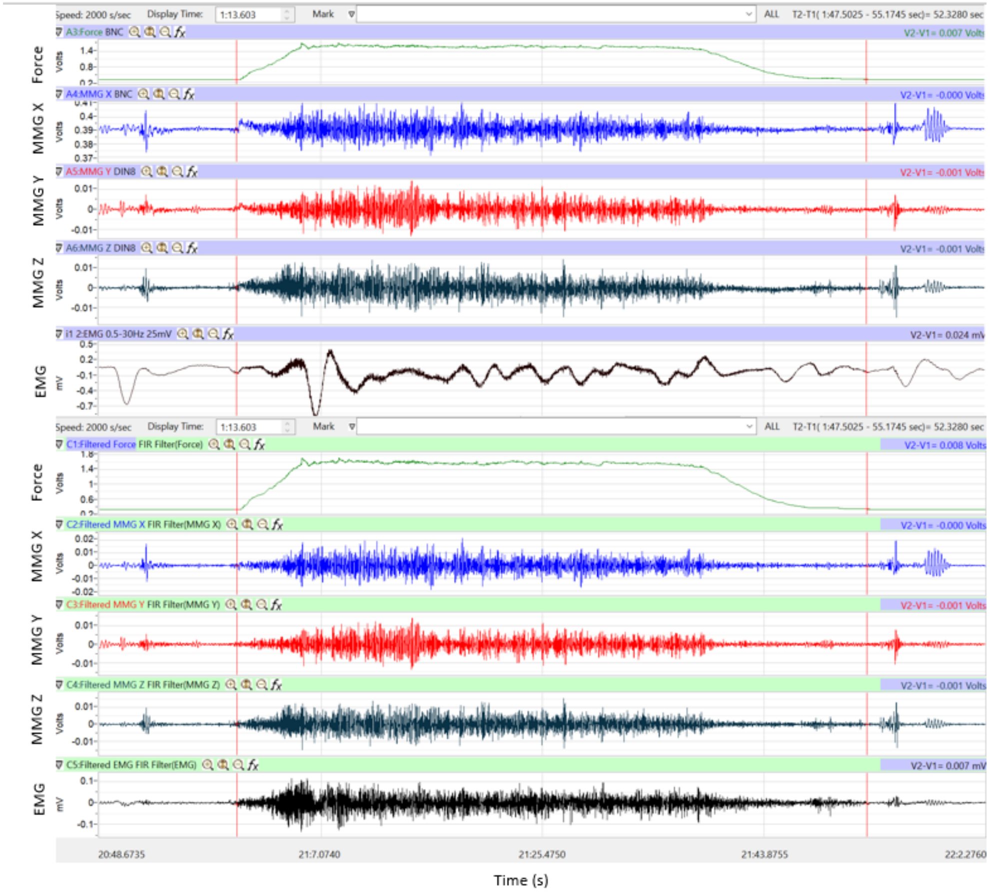
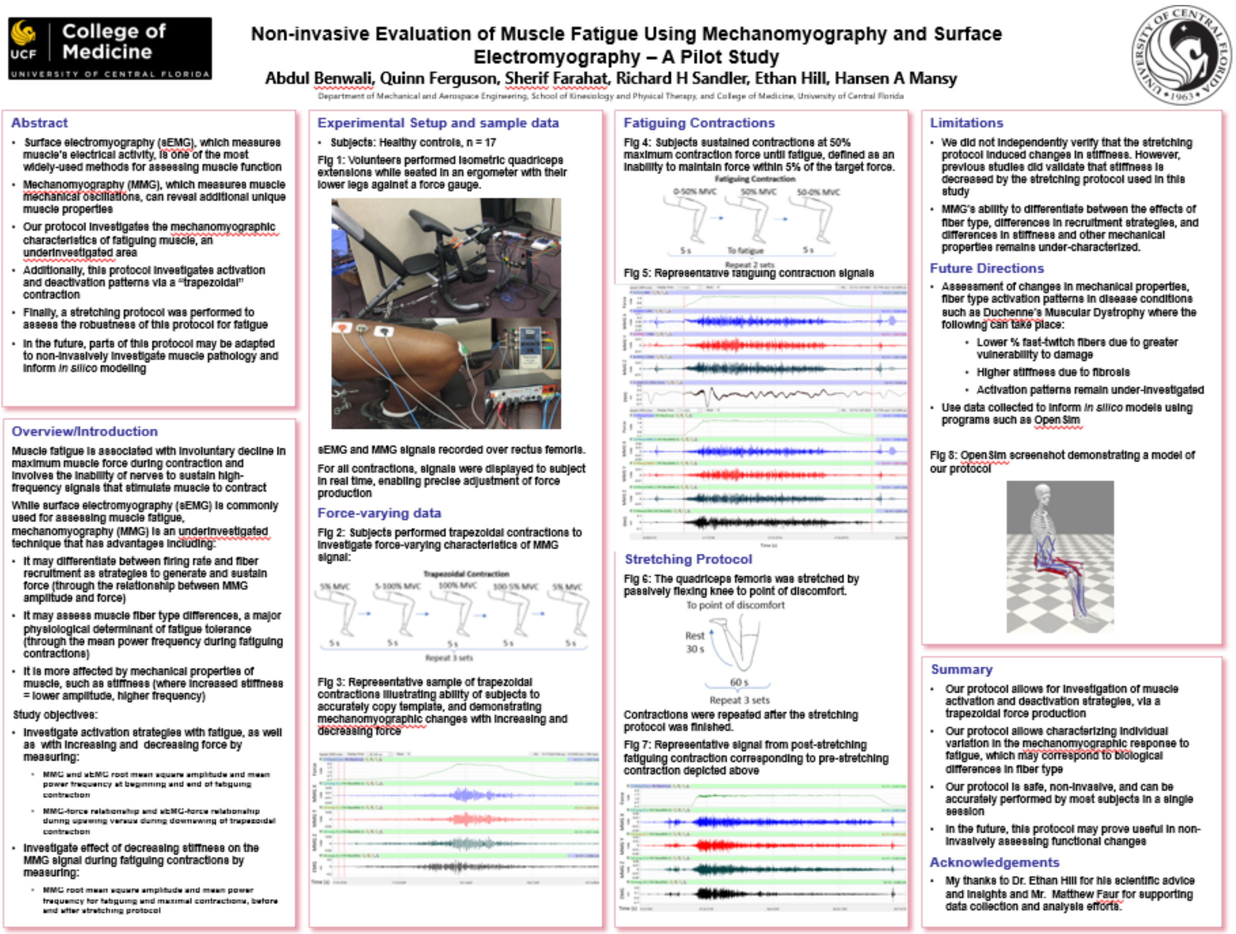


Figure 3. Unfiltered (top) and filtered (bottom) Force, MMG and sEMG

REFERENCES

[1] T.J. Herda, T.J. Housh, A.C. Fry, J.P. Weir, B.K. Schilling, E.D. Ryan, J.T. Cramer, “A noninvasive, log-transform method for fiber type discrimination using mechanomyography,” in Journal of Electromyography and Kinesiology, 2010. pp. 787-7942.

[2] H.A. Yousif, A. Zakaria, N.A. Rahim, A.F. Bin Salleh, M. Mahmood, K.A. Alfarhan, L.A. Kamaruhin, S.M. Mamduh, A.M. Hasan, M.K. Hussain. “Assessment of muscle fatigue based on Surface EMG Signals: A Review”, in IOP Conference Series: Materials Science and Engineering, 2019.


College of Medicine
UCF
UNIVERSITY OF CENTRAL FLORIDA
Non-invasive Evaluation of Muscle Fatigue Using Mechanomyography and Surface Electromyography – A Pilot Study
Abdul Benwali, Quinn Ferguson, Sherif Farahat, Richard H Sandler, Ethan Hill, Hansen A Mansy
Department of Mechanical and Aerospace Engineering, School of Kinesiology and Physical Therapy, and College of Medicine, University of Central Florida
UNIVERSITY OF CENTRAL FLORIDA 1963
Abstract
Surface electromyography (sEMG), which measures muscle's electrical activity, is one of the most widely-used methods for assessing muscle function
Mechanomyography (MMG), which measures muscle mechanical oscillations, can reveal additional unique muscle properties
Our protocol investigates the mechanomyographic characteristics of fatiguing muscle, an underinvestigated area
Additionally, this protocol investigates activation and deactivation patterns via a "trapezoidal" contraction
Finally, a stretching protocol was performed to assess the robustness of this protocol for fatigue
In the future, parts of this protocol may be adapted to non-invasively investigate muscle pathology and inform in silico modeling
Overview/Introduction
Muscle fatigue is associated with involuntary decline in maximum muscle force during contraction and involves the inability of nerves to sustain high-frequency signals that stimulate muscle to contract
While surface electromyography (sEMG) is commonly used for assessing muscle fatigue, mechanomyography (MMG) is an underinvestigated technique that has advantages including:
It may differentiate between firing rate and fiber recruitment as strategies to generate and sustain force (through the relationship between MMG amplitude and force)
It may assess muscle fiber type differences, a major physiological determinant of fatigue tolerance (through the mean power frequency during fatiguing contractions)
It is more affected by mechanical properties of muscle, such as stiffness (where increased stiffness = lower amplitude, higher frequency)
Study objectives:
Investigate activation strategies with fatigue, as well as with increasing and decreasing force by measuring:
MMG and sEMG root mean square amplitude and mean power frequency at beginning and end of fatiguing contraction
MMG-force relationship and sEMG-force relationship during upswing versus during downswing of trapezoidal contraction
Investigate effect of decreasing stiffness on the MMG signal during fatiguing contractions by measuring:
MMG root mean square amplitude and mean power frequency for fatiguing and maximal contractions, before and after stretching protocol
Experimental Setup and sample data
Subjects: Healthy controls, n = 17
Fig 1: Volunteers performed isometric quadriceps extensions while seated in an ergometer with their lower legs against a force gauge.
sEMG and MMG signals recorded over rectus femoris.
For all contractions, signals were displayed to subject in real time, enabling precise adjustment of force production
Force-varying data
Fig 2: Subjects performed trapezoidal contractions to investigate force-varying characteristics of MMG signal:
Trapezoidal Contraction
5% MVC
5-100% MVC
100% MVC
100-5% MVC
5% MVC
5 s
Repeat 3 sets
Fig 3: Representative sample of trapezoidal contractions illustrating ability of subjects to accurately copy template, and demonstrating mechanomyographic changes with increasing and decreasing force
Fatiguing Contractions
Fig 4: Subjects sustained contractions at 50% maximum contraction force until fatigue, defined as an inability to maintain force within 5% of the target force.
Fatiguing Contraction
0-50% MVC
50% MVC
50-0% MVC
5 s
To fatigue
5 s
Repeat 2 sets
Fig 5: Representative fatiguing contraction signals
Stretching Protocol
Fig 6: The quadriceps femoris was stretched by passively flexing knee to point of discomfort.
To point of discomfort
Rest 30 s
60 s
Repeat 3 sets
Contractions were repeated after the stretching protocol was finished.
Fig 7: Representative signal from post-stretching fatiguing contraction corresponding to pre-stretching contraction depicted above
Limitations
We did not independently verify that the stretching protocol induced changes in stiffness. However, previous studies did validate that stiffness is decreased by the stretching protocol used in this study
MMG's ability to differentiate between the effects of fiber type, differences in recruitment strategies, and differences in stiffness and other mechanical properties remains under-characterized.
Future Directions
Assessment of changes in mechanical properties, fiber type activation patterns in disease conditions such as Duchenne's Muscular Dystrophy where the following can take place:
Lower % fast-twitch fibers due to greater vulnerability to damage
Higher stiffness due to fibrosis
Activation patterns remain under-investigated
Use data collected to inform in silico models using programs such as Open Sim
Fig 8: Open Sim screenshot demonstrating a model of our protocol
Summary
Our protocol allows for investigation of muscle activation and deactivation strategies, via a trapezoidal force production
Our protocol allows characterizing individual variation in the mechanomyographic response to fatigue, which may correspond to biological differences in fiber type
Our protocol is safe, non-invasive, and can be accurately performed by most subjects in a single session
In the future, this protocol may prove useful in non-invasively assessing functional changes
Acknowledgements
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