Final Project – Impact of TENS Therapy on Acute Pectoralis Major Recovery

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ABSTRACT

In this study, the effects of transcutaneous electrical nerve stimulation therapy on fatigue recovery in the pectoralis major muscle were explored. The experiment involved one healthy participant who underwent several trials of chest squeeze to induce fatigue, followed by TENS treatment. The EMG data was collected multiple times to examine the impact of the treatment approach on muscle activation. The procedure was repeated twice, using a new EMG device built based on an Arduino circuit, and then with the standard iWorx device. The power distribution of the EMG signal obtained using both devices was compared. The findings revealed that TENS therapy was ineffective in this particular study, as there were no significant differences in the power spectrum. Moreover, the results were deemed unreliable due to methodological limitations. Nevertheless, comparing the Arduino device with the standard device demonstrated that it worked as expected, despite functional constraints and inconsistencies.

I. INTRODUCTION

Electromyography (EMG) is a method of measuring the electrical activity of muscles in response to nerve stimulation. The recording of this activity is known as an electromyogram. EMG is a valuable tool for identifying neuromuscular abnormalities, including chronic denervation or fasciculations in normal muscles, due to its ability to distinguish between myopathic and neurogenic muscle wasting and weakness [1]. By examining the distribution of neurogenic abnormalities, EMG can differentiate between focal nerve, plexus, or radicular pathology, and can provide evidence of the pathophysiology of peripheral neuropathy, such as axonal degeneration or demyelination [1]. Surface EMG (sEMG) is a noninvasive technique that measures the electric potential field produced by active muscle fibers through the undamaged skin [2]. To use this technique, surface electrodes are placed on the skin above the muscle of interest, which then detect the electrical signals produced by the muscle fibers when they contract [2]. The recorded sEMG signal provides information about the timing, amplitude, and duration of muscle contractions. Clinical and research settings commonly use sEMG to evaluate muscle function, diagnose neuromuscular disorders, and monitor physical therapy or rehabilitation programs' progress. It is also frequently used in sports and ergonomics to assess muscle activity during various movements and postures [3].

In the past thirty years, evaluating local muscle fatigue through surface electromyographic (sEMG) signal processing has become a widely used method. Studies have produced quantitative measures for fatigue based on signal analysis, focusing mainly on static tasks but also on dynamic ones [3]. Neuromuscular fatigue results from a sequence of metabolic, structural, and energetic changes in muscles, caused by inadequate oxygen and nutrient supply through blood circulation and changes in the nervous system's efficiency [3]. A standardized method for measuring muscle strength is through maximum voluntary isometric contraction (MVIC or MVC), which occurs when muscle length remains relatively constant as tension is produced [4]. Isometric contraction, despite its low energy cost, can cause local muscle fatigue. This type of fatigue sets in faster when the relative force exerted is over 15-20% of the muscle's MVC and when the duration of the contraction is increased [5]. Continuous monitoring of local muscle fatigue during a specific task is possible by measuring the myoelectric activity of particular muscles through sEMG [3]. The properties of myoelectric signals recorded on the skin surface above the corresponding muscle(s) also reflect the biochemical and physiological changes during fatiguing contractions [3].

The onset of muscle fatigue can lead to a reduction in the skin's ability to sense, the buildup of metabolites in muscle fibers, and a decrease in proper motor control from the motor cortex [6]. Musculoskeletal disorders can also impact muscle tone and stiffness, potentially causing damage. Therefore, it is crucial to appropriately manage muscle fatigue to avoid these negative consequences. Massage therapy is a widely used therapeutic intervention that can effectively alleviate pain, muscle stiffness, and perceived fatigue. Additionally, transcutaneous electrical nerve stimulation (TENS) has been found to reduce muscle fatigue [6]. This is a non-invasive technique that uses pulsed electrical currents to relieve pain by activating the nerves located underneath the skin's surface [7]. Recent research has demonstrated that electrical stimulation can also be beneficial in managing muscle fatigue, particularly when combined with other therapies [8]. The aim of this study is to investigate the effects of TENS treatment on muscle fatigue and recovery. This will be accomplished by analyzing EMG signals from a participant both before and after receiving TENS treatment, as well as after a period of rest for comparison. Additionally, a novel EMG system developed using an Arduino circuit will be evaluated and compared with the standard iWorx device.

II. MATERIALS AND METHODS

A. Building the EMG

Biopotential amplifiers take the weak electric signal and increase its amplitude for recording, processing and display. This is done by rejecting common mode signals (noise) and amplifying the differential signals which carry the muscle activation information. The EMG components and design are discussed below:

1) Components: With inspiration from Advancer Technologies' guide on building an EMG circuit for a microcontroller [9], we chose to breadboard the electronics and read the resulting signals through an Arduino UNO microcontroller. This guide was a great foundation for the construction of the EMG but failed to include many integral details such as raw signal acquisition and microcontroller reading, and included excess signal processing which we did not require. The materials required for building the EMG are listed below:

-Breadboard x1
-Arduino UNO x1
-INA106 Precision Fixed-Gain Differential Amplifier x1 [10]
-TL072 Low-Noise FET-input Operational Amplifier [11]
-9V Batteries x2
-9V Battery Connector x2
-220Ω 1% Resistors x2

-10kΩ 1% Resistor x1
-91kΩ 1% Resistor x1
-150kΩ 5% Resistors x2
-1MΩ 5% Resistors x2
-0.01µF Ceramic Disk Capacitor x1
-USB 2.0 Cable x1
-Wires

2) Circuit Design: The EMG circuit design was modulated into three stages powered by 9V batteries to provide a positive 9V and negative 9V voltage source. A 5V source provided from the arduino was additionally required. The stages of the circuit are outlined below:

Stage 1: Signal Acquisition
The pre-amplification was done using the INA106 Precision Fixed-Gain Differential Amplifier. In Figure 1, this stage is outlined with a blue box with blue numbers representing the pins of the INA106. The acquired electrical current from Electrode 1 and Electrode 2 were passed through the INA106 connected to R1 and R2 to provide a gain of 110.

Stage 2: Amplification & Filtering
To amplify and filter the signal, the TL072 Low-Noise FET-input Operational Amplifier was used. One IC chip contains two operation amplifiers, hence the orange boxes labeled Amplifier 1 and Amplifier 2 in Figure 1 outlined in orange with orange numbers representing the pins of the TL072. The signal from Stage 1 was first passed through an inverting amplifier with a gain of 9.1. This signal was then passed through a coupling capacitor C1 and another inverting amplifier with unity gain. This removes DC-offset and low frequency noise from the signal with a 100Hz high pass filter. The resulting gain from Stage 1 and Stage 2 was 1001.

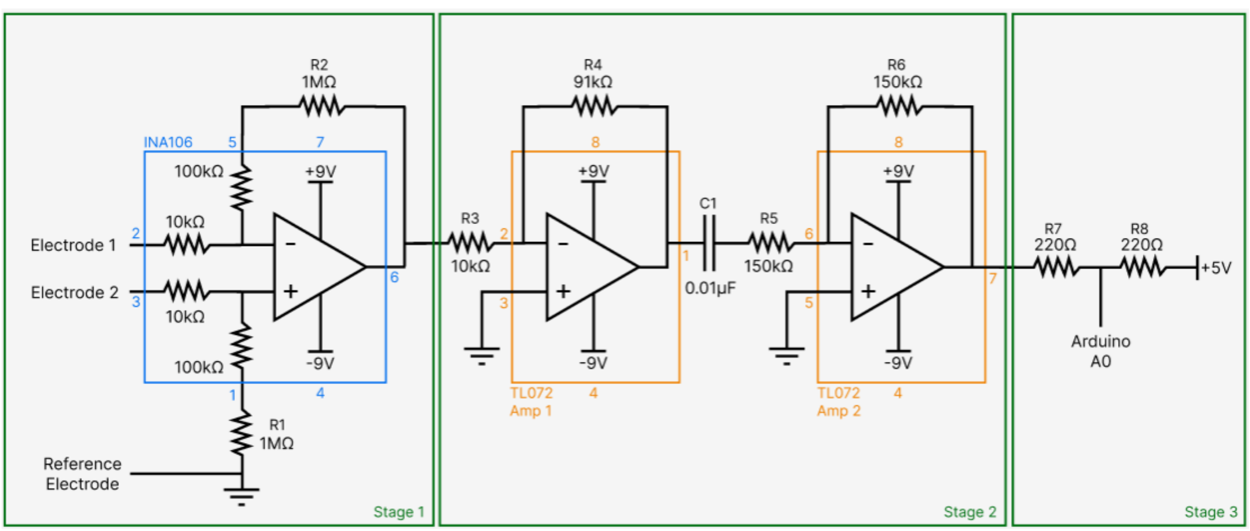

Figure 1. Circuit schematic of EMG signal acquisition, amplification, filtering and recording

Stage 3: Recording

The final stage of the circuit dealt with issues of recording the raw EMG signal. The Arduino UNO analog read pins have capabilities to only read positive voltages. Further, the Arduino is only capable of reading between 0 and 5 volts on a scale from 0 to 1023. To combat these issues, a voltage divider with equivalent resistances R7 and R8 in Figure 1 connected to a positive 5V source was used. This configuration will manipulate the existing signal ranging from -5 to 5V to the processable 0 to 5V. Sadly, this loses signal resolution due to the shrinking of the range, which will be discussed further in the discussion section A. The arduino code can be seen below:

```
int EMGPinRaw = A0;
int EMGValRaw;
unsigned long currentMillis;

void setup() {
  Serial.begin(115200);
}
void loop() {
  currentMillis = millis();
  EMGValRaw = analogRead(EMGPinRaw);
  Serial.print(currentMillis);
  Serial.print(", ");
  Serial.println((EMGValRaw - 512) * 2);
}
```

This arduino program samples the raw EMG signal at 115200 baud (through a 10-bit analog to digital converter.The sampling rate was around 900 Hz. To save the output into the serial port, an SSH client PuTTY [12] was used to record and save the serial output to a CSV text file.

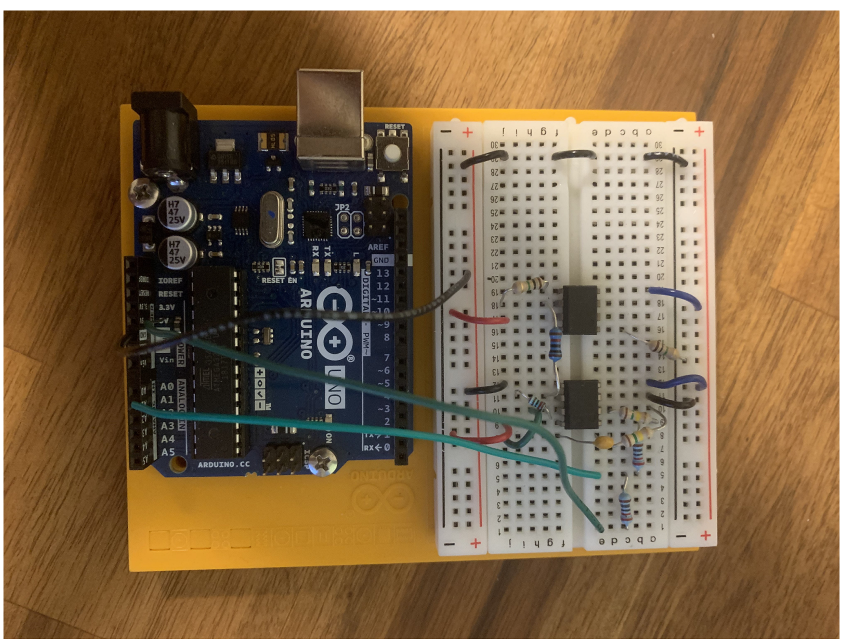

Figure B. Arduino EMG

B. Experimental Protocol

The experimental protocol was designed to highlight the differences in maximal voluntary contraction (MVC) amplitudes between the control and treatment cohorts, and to evaluate how the Arduino-based EMG compares to the conventional iWorx system. In order to have a more focused assessment of MVC, the protocol needed to be designed to include an exercise that was isometric.

The study involved a single participant who underwent a two-day experiment that consisted of signal acquisition using the Arduino EMG and iWorx system on separate days. The iWorx system was configured to acquire EMG signals at a sampling rate of 5000 Hz, employing a high pass filter of 5 Hz and low pass filter of 10000 Hz. Each session began with the participant performing a controlled maximum voluntary contraction (MVC) exercise consisting of an isometric chest squeeze for 10 seconds, while in a seated position with arms extended in front of them. The control MVC was repeated twice to obtain two sets of control MVC EMG signals.

Following the exercise the participant executed two sets of push-ups which consisted of 30 and 20 repetitions respectively. After inducing muscle fatigue with the push-ups, the participant performed the isometric exercise once more to record EMG signals for the MVC after fatigue. Subsequently, the participant was allowed to rest for a two-minute period. For the treatment scenario the participant underwent transcutaneous electrical nerve stimulation (TENS) treatment for the two-minute rest period. Immediately after the rest period, the participant executed the isometric exercise again for 10 seconds, and EMG data was collected to assess the MVC after rest.

C) Data processing

1) Arduino & iWorx Preprocessing
Initial data was extracted and converted to matlab files. Sampling period of MVC was identified, and the rest of the data was discarded. This was only done for the Arduino data. For the iWorx data, the original data was considered to be the “working” data, and no pre-processing was involved. The data collected for both arduino and iWorx contains artifacts and noise at this stage.

2) Signal processing
It is important to get rid of artifacts such as high frequency noise, as well as contaminations from Electrocardiogram (ECG) signals, in order to study relevant muscle units [13]. To get rid of ECG signals, ECG subtraction can be utilized. This requires a referential ECG signal, followed by appropriate filtering and QRS detection [14]. This technique was not utilized in this study, due to EMG signals being generally 100 to 1000 times greater than the ECG signals collected on iWorx. iWorx also had appropriate filtering on ECG data from 0.5-30Hz and 5-10kHz for EMG. As for the arduino, there was no filtering, and due to lack of equipment and leads ECG data could not have been collected.

To generate MVC envelopes, similar techniques as Hof et a.l and Jonkman et al. were followed, the signals for each trial were first rectified and then filtered using a 4th order low pass butterworth filter with a cutoff of 5Hz [13,14]. This allows us to get rid of high frequency content and preserve lower frequency content which is then more closely related to the surface EMG [15]. By doing so we create an envelope for the MVCs. To normalize these envelopes, the peak signal of the first trial was used.

To generate power spectrum for frequency analysis of EMG, the power density was plotted using spectrum on Matlab. This was then used to find the median power frequency. The median power frequency was then compared with all three MVCs.

III. RESULTS

A. Arduino EMG vs. iWorx EMG

Bipolar electrode arrangements used with a differential amplifier essentially subtracts the potential at one electrode for the potential at the other electrode, amplifying the difference. The quality of the EMG signal largely depends on this stage called pre-amplification. There are several important properties to consider in a pre-amplifier which are assessed below:

1) CMRR

The common-mode rejection ratio is a measure of the capability of an op-amp to reject a signal that is common to both inputs [16]. Also known as noise, the goal is to reject these common mode signals and amplify the differential signals. We can measure the CMRR of the Arduino EMG and iWorx EMG to compare this important metric of performance. The Arduino EMG's INA106 was chosen due to its high CMRR, quoted at a minimum of 86dB, typically 100dB. Although iWorx does not disclose the hardware specifications of their IX-BIO 4Ch Biopotential Recorder, we can consider the standard CMRR for EMG's in clinical applications which is 120dB.

2) Input impedance

It is important that EMG preamplifiers have a high input impedance in order to measure the voltage accurately [17]. It should be considerably higher than the impedance at the skin, otherwise the signal will be distorted due to input loading. The INA106 quotes a typical differential input impedance of 10kΩ and common mode impedance of 110kΩ [10]. In comparison, standard clinical EMG pre-amplifiers have input impedances reaching 10GΩ [17]. This design specification favors the iWorx EMG.

3) Distance to signal source

With increased lead lengths, the parasitic capacitance increases and resulting noise increases. Long leads combined with high input impedance can result in lower noise-to-signal ratios [17]. Due to the method of sampling from the electrodes with alligator clips, the length of the Arduino EMG wires were considerably longer than the iWorx EMG. The iWorx leads were measured at 122cm [18] while the alligator clips used for the Arduino were measured at 200cm.

4) Calibration / adjustable gains

In a clinical application, amplitudes of EMG readings will vary based on the muscle group and intensity of contraction. It is important that EMG's have variable gains to be able to maximize the resolution of the measured signal. The Arduino EMG fixed gain of 1001 did not have any capacity to change the gain as there were too many dependencies on the Arduino microcontroller read requirements. The iWorx EMG was chosen to be sampled with a gain of 25,000 offering many other options to customize this value.

5) Safety

Importantly, the EMG device must be safe to handle and apply to the body. As electric current runs through these devices, it is important to have fail-safe measures to protect the patient. The Arduino EMG was safe to use but contained exposed wires and a power source that could be handled directly. These aspects cause some concern for this design.

B. Experimental Results

1) Treatment vs Control

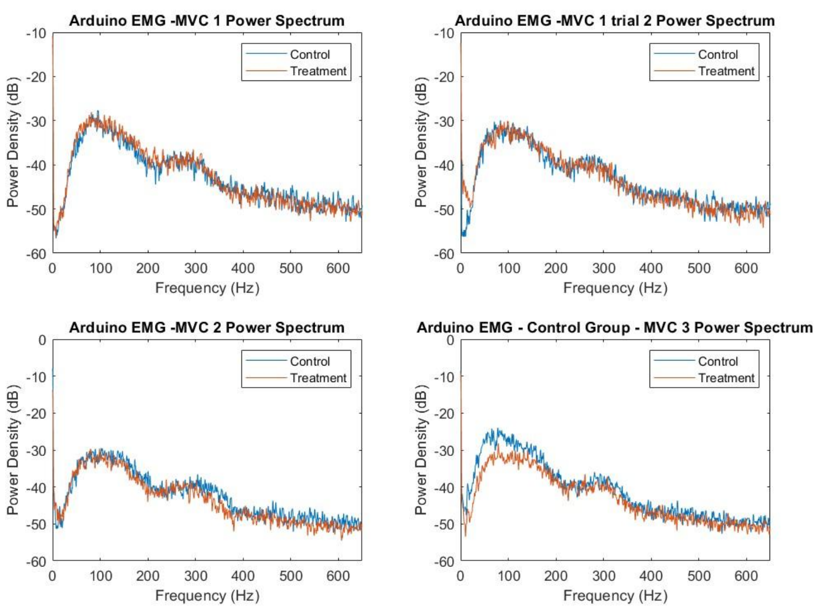

Figure 2. Comparing power distribution in control and treatment settings by examining power spectrum plots of EMG signals obtained using the Arduino system.

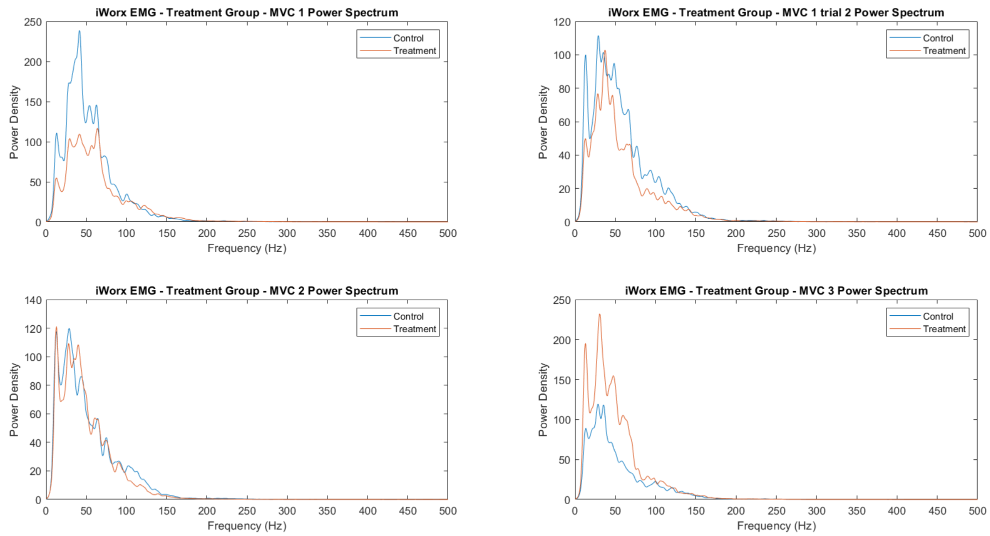

Figure 3. Comparing power distribution in control and treatment settings by examining power spectrum plots of EMG signals obtained using the iWorx system.

2) Comparison Between MVC's

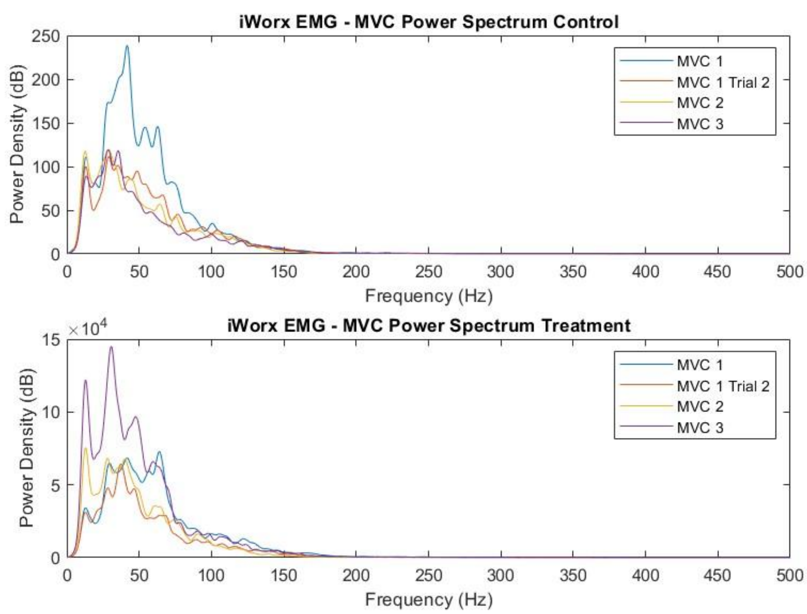

Figure 4. Comparing the power distribution of the different maximal voluntary contractions by examining power spectrum plots of EMG signals obtained using the iWorx system.

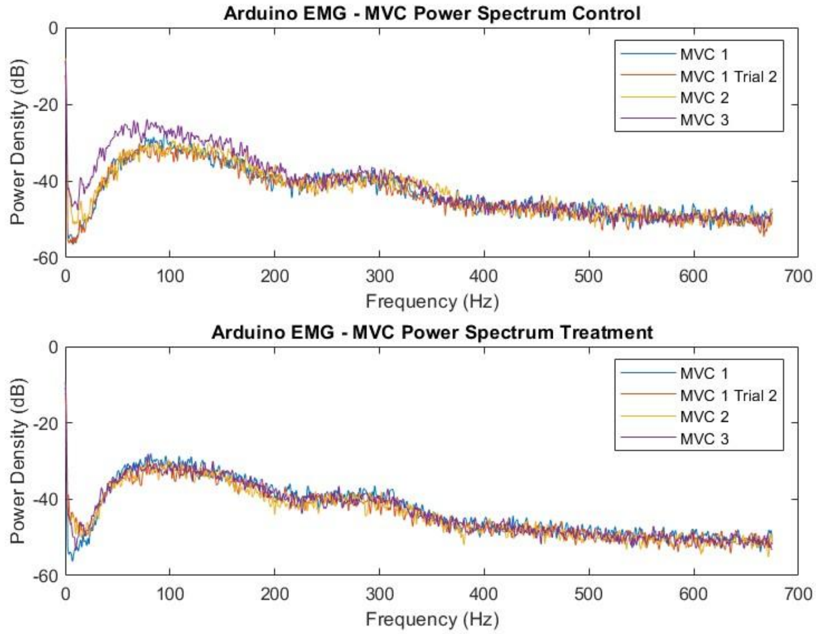

Figure 5. Comparing the power distribution of the different maximal voluntary contractions by examining power spectrum plots of EMG signals obtained using the Arduino system.

Linear Envelopes

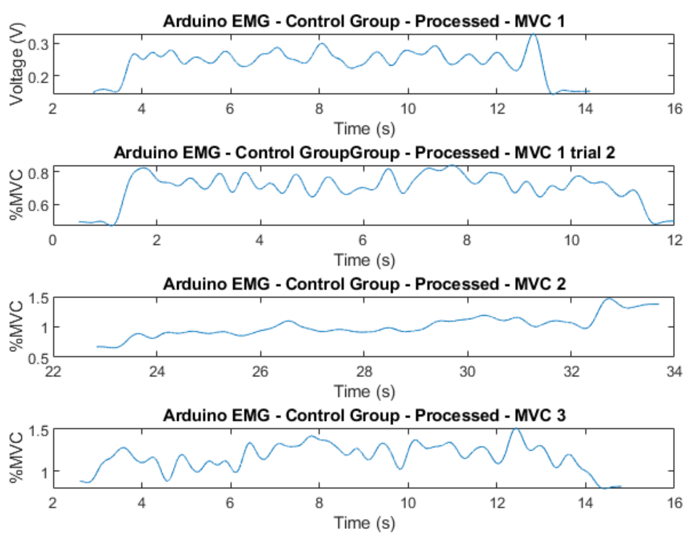

Figure 6. Linear Envelopes of control group experiments with the Arduino system, shown by %MVC of the first trial

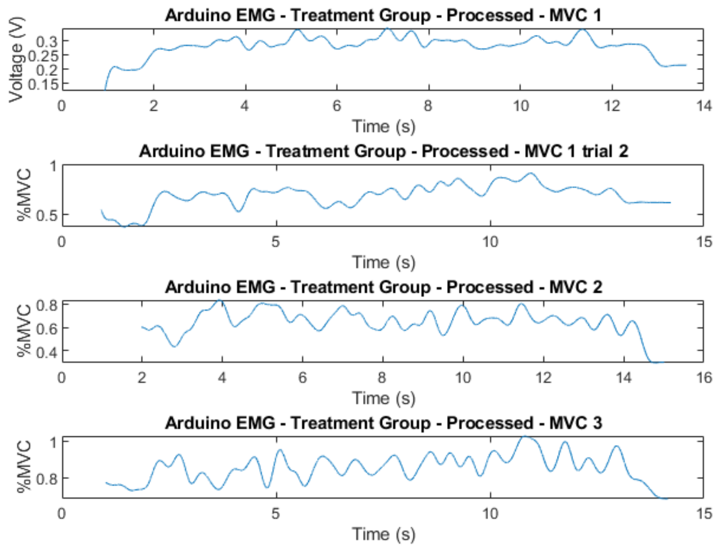

Figure 7. Linear Envelopes of treatment group experiments with the Arduino system, shown by %MVC of the first trial

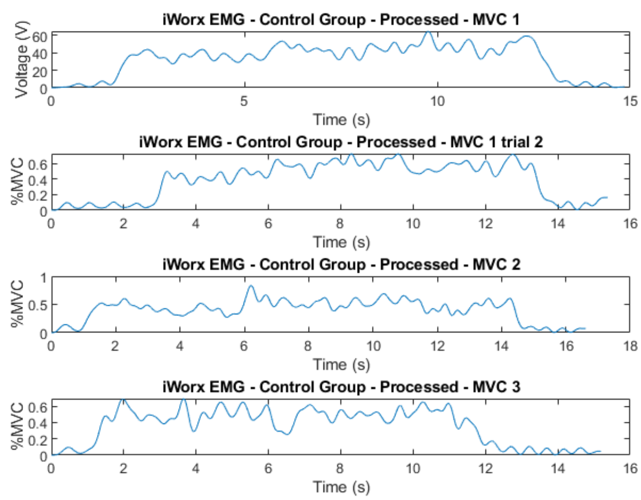

Figure 8. Linear Envelopes of control group experiments with the iWorx system, shown by %MVC of the first trial

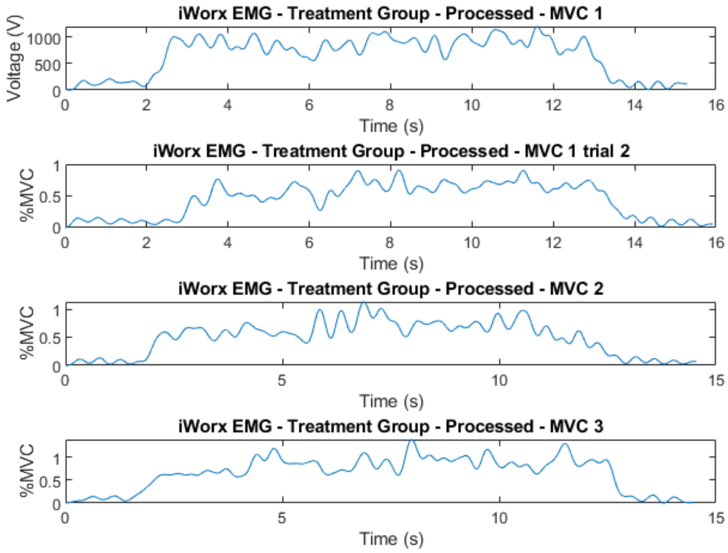

Figure 9. Linear Envelopes of treatment group experiments with the iWorx system, shown by %MVC of the first trial

Table 1. Mean and Median Frequencies from power spectrum analysis of Arduino system

Arduino	Mean Frequency (Hz)	Median Frequency (Hz)
MVC 1 Control	81.2501581529002	57.1632395792897
MVC 1t2 Control	82.9367564042978	58.7891842267273
MVC 2 Control (Fatigue)	84.255379768058	59.8559992823265
MVC 3 Control (Recovery)	81.1171603109183	57.1065840018571
MVC 1 Treatment	82.9788240394506	58.7525667347483
MVC 1t2 Treatment	82.7682490399037	58.5428912833327
MVC 2 Treatment (Fatigue)	81.4647400325879	57.3516667371128
MVC 3 Treatment (Recovery)	84.0082844257119	59.6690485025146

Table 2. Mean and Median Frequencies from power spectrum analysis of iWorx system

iWorx	Mean Frequency (Hz)	Median Frequency (Hz)
MVC 1 Control	53.695	45
MVC 1t2 Control	57.308	48
MVC 2 Control (Fatigue)	54.565	46

MVC 3 Control (Recovery)	53.586	44
MVC 1 Treatment	65.807	58
MVC 1t2 Treatment	58.089	47
MVC 2 Treatment (Fatigue)	54.565	46
MVC 3 Treatment (Recovery)	48.015	38

IV. DISCUSSION

A. Arduino EMG Limitations & Future Perspectives

When considering the limitations of this Arduino EMG design, there are many factors that greatly impacted the quality of the device. Firstly, as the Arduino EMG sample rate is dependent on the number of bits being communicated, as the time increases from 1-digit to 2-digits and 3-digits, etc the sample rate will slow. For example, at a 115200 baud rate (the maximum for arduino), the sample rate will vary as seen in Table 3.

Table 3. Impact of time passed on sample rate

Time (ms)	Sample Rate (Hz)
0-9 (0-0.009 seconds)	1422
10-99 (0.01-0.099 seconds)	1280
100-999 (0.1-0.999 seconds)	1163
1000-9999 (1-9.99 seconds)	1066
10000-99999 (10-99.99 seconds)	984

We can see that this is an inefficient design, but unfortunately could not be worked around due to the constraints of the microcontroller. Additionally, to measure the negative voltages, the signal needed to be scaled and lost resolution. From 0-5V on a scale from 0-1023 bits, there is a resolution of 0.0049V/bit. When scaled, the signal read is from -5 to 5V at the same bit-scale. This means the resolution is halved at 0.0098V/bit. Moving forward, a way to combat these issues could be using an oscilloscope to record and save the EMG signal.

Another issue was the reliability of the breadboarding. Due to the inconsistency of breadboard connections and the fine nature of EMG signals, if components were slightly connected incorrectly, the whole device would not function as intended. Moving forward, a PCB design with soldered components would ensure better connections and a higher reliability.

B. Experimental Discussion of Results

This study aimed to investigate the potential of transcutaneous electrical nerve stimulation (TENS) for muscle recovery by using an isometric chest squeeze to measure the maximum voluntary contraction and to explore the role of muscle fatigue. The way muscle performance usually is evaluated, is by the muscle's ability to generate force during an isometric contraction [19]. The collected data was used to generate power spectrum plots, compare the final MVC between treatment and control, and to observe fatigue between the first and third MVC. These plots provide relevant information on the power distribution over different frequencies, with a general observation of decreased power as frequency increased.

Scaling differences between the Arduino and iWorx devices were noted and could be attributed to the different device configurations. Additionally, although the mean and median frequencies calculated did not provide statistically significant results, mean MVC peaks were also calculated (Table 1 & 2). From these results, an increase in mean peak between the 2nd and 3rd MVC for the treatment scenario was observed for both iWorx and Arduino. However, it is important to note that a slight increase was also noticed between the MVC's for the control scenario as well. Therefore, further statistical analysis would need to be performed to understand its significance. This finding does not strongly support the effectiveness of TENS therapy in promoting muscle recovery in this specific case. Kang et al. similarly found that TENS therapy may help prevent muscle accumulation, but that it does not aid much in muscle recovery from fatigue [20].

Furthermore, when comparing the first or second MVC with the third MVC, the power spectrum for the fatiguing (third) MVC was lower than the others (Figure 4 & 5). This result is consistent with the study's expectations, since this MVC was collected after the pectoralis major muscle was fatigued with push-ups.

V. LIMITATIONS

The study had several limitations, including inconsistencies in the experimental process compared to prior studies with significant findings. The iWorx and Arduino procedures were intended to be performed over two days, each dedicated to each setting. However, both procedures were carried out in a single day with a half-hour break in-between, making the iWorx system data unreliable due to possible fatigue between the two procedures as intended in the original protocol. In addition, the final treatment MVC recorded by the Arduino EMG device was performed twice, which could have impacted the treatment's effects on muscle activation and produced unreliable EMG data. The Arduino circuit also had limitations, such as the sample rate's dependence on the number of transmitted digits, leading to a decrease in sample rate over time. Signal scaling proved to be challenging as it would result in the loss of half of the resolution, and inconsistent connections on the breadboard could easily cause the device to not function properly if any components were incorrectly connected.

VI. CONCLUSIONS

The aim of this study was to investigate the efficacy of TENS therapy in promoting recovery from fatigue in the pectoralis major muscle. The results indicate that TENS therapy may not be effective in this specific case, as the data showed no significant impact. The results were also limited with methodological flaws. Although TENS therapy may help prevent muscle accumulation, it does not seem to aid in muscle recovery from fatigue. It may be beneficial to conduct more high quality and rigorous research on the effects of TENS therapy on exercise-induced pain, chronic pain, or degenerative diseases, as this study does not provide a comprehensive understanding of the treatment's effects on pain. The study also included a comparison between an EMG device built using an Arduino circuit and the standard iWorx device. Despite some limitations in functionality, the Arduino system performed as intended.

VII. RECOMMENDATION

To obtain a more comprehensive understanding of the impact of TENS therapy on recovery, it is recommended to conduct further research with multiple healthy patients, or those suffering from chronic pain. Investigating potential gender differences in muscle activation may also be an interesting area of focus for future research. Additionally, a comparison between the efficacy of alternative pain relief therapies, such as microcurrent therapy, can provide valuable insights into which treatment approach is superior. With regard to the Arduino EMG device, using an oscilloscope to record and store data can resolve the issue of resolution, while opting for a PCB design with soldered components can prevent inconsistent connections and improve the device's reliability. Most importantly, to enhance the quality of trial design and reporting standards in trials, it is recommended that future research follow fundamental guidelines and protocols established in previous studies that have yielded significant findings.

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