Real time detection of muscle fatigue using arduino based surface EMG frequency and amplitude measurements

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Abstract

Impacting millions of people globally, tendonitis leads to pain and reduces everyday work efficiency. To prevent tendonitis, detecting tendon and muscle fatigue is crucial. This study uses a portable, low-cost surface electromyography (sEMG) device and an Arduino processor to monitor subjects who are engaged in physical therapy by evaluating electromyography amplitude and frequency data. The device was successful in identifying several potential indications of muscle fatigue in testing.

1.0 Introduction

Between 150-400 million people globally experience symptoms of tendonitis each year. In the United States, over 40 million people have musculoskeletal disorders (Manheim, L. M. 1995). Musculoskeletal complaints account for 10% to 20% of all primary care and emergency visits in the US every year (Houston, T. K. et al. 2004) (Miller, A. N. 2016). These symptoms can include pain and the inability to use muscles. In 2015, 30% of patient visits to healthcare providers for musculoskeletal issues were related to tendonitis and tendon tears (Andarawis-Puri et al., 2015). One particularly debilitating form of tendonitis occurs in the wrist and can lead to tendon injury and long-term pain (Andarawis-Puri & Flatow 2011). If proper recovery procedures are not instituted, severe pain could be permanent or require surgical repair.

There is no precise way to detect tendon fatigue (which can eventually lead to tendonitis). However, tendon fatigue always happens with muscle fatigue (Andarawis-Puri & Flatow 2011) since tendons transmit the contractile force of muscle tissue (Curzi, D. et al., 2012). Therefore, if muscle fatigue is detected in people with tendonitis, they can be advised to rest before the tendon is further damaged. Using a low cost detection device will allow more people to get access to tendon protection.

1.1 Background

1.1.1 Tendonitis

Tendons are fibrous connective tissues that connect muscles to bones. Overuse of tendons or muscles can cause damage to the tissue. For muscles, every time the muscle is stretched or contracted, small tears are created, and the repair of these tears is what leads to new muscle development. The movement of muscles involves movement of tendons, and muscle stretching can increase tendon stress (Witvrouw, E. et al., 2007). Repeated tendon strains can produce scars which lead to inflammation of the tendon and the sheath that protects it as tendon stress accumulates. This inflammation is known as tendonitis and is a normal part of the body's healing process. Inflamed tendons are painful, and the pain gets worse with exercise since overuse of muscles worsen tendonitis (Shepherd & Screen, 2013). Long-term tendon inflammation can lead to more severe tendon tears, requiring surgery.

Most tendinitis can be alleviated with rest, ice, anti-inflammatory drugs, physical therapy, and medication However, tendonitis can be avoided by regularly observing muscle use and adjusting exercise schedules to avoid further injuries (Karamanidis & Epro. 2020).

1.1.2 Muscle Fatigue

Muscle fatigue is defined as a decrease in the largest force the muscle can exert at the start of exercise, which is called maximal force. Fatigue onset happens when the person can no longer apply the same maximal force. In the case of repetitive movements, muscle forces are often submaximal. In these cases, muscles become fatigued before the submaximal force decreases (Karagiannopoulos et al., 2020). This suggests fatigue is a gradual process instead of a sudden decrease in output of force since the onset of fatigue does not immediately limit the ability to perform a task.

1.1.3 Muscle Anatomy

In order for a muscle to contract, neural signals in the form of action potential are sent from the brain to the neuromuscular junction. The signals cause the release of the neurotransmitter acetylcholine (ACh) (Squire J. 2019). This molecule binds with the receptor at the junction, opening the sodium(Na+) ion channels(see Figure 1A). The voltage-gated sodium ion channels located on the membrane of the muscle fiber will be depolarized as Na+ flows into the membrane (shown in Figure 1B). As more Na+ flows in, the polarity of the membrane will eventually be reversed (i.e. more positive ions inside the membrane than outside). As a result, voltage-gated potassium(K+) ion channels will open up and allow K+ ions to flow out (Figure 1C), returning the voltage back to its resting state and repolarizing the membrane (McKennaet al., 2008). ATP helps to reset the balance of Na+ and K+ after each contraction (Figure 1D) by releasing the used and bringing in new Na+ and K+ ions. Ions are lost during every contract and stretch and when ions and energy cannot rebalance fast enough to support further movement, the muscle becomes fatigued.

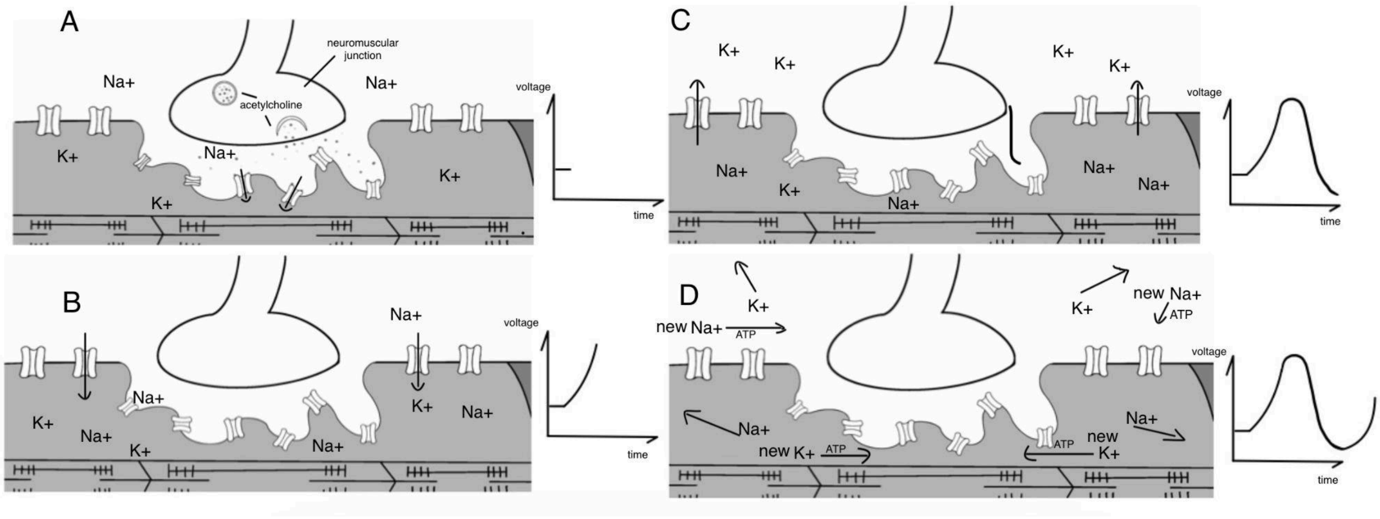


Figure 1: Different stages of muscle contraction physiology and action potentials

1.1.4 Measurement of muscle contraction

Electromyography (EMG) measures the difference of electric potentials or voltage between two different positions on a muscle. The voltages for different muscle contraction stages of a single EMG fluctuation are shown in Figure 1. 1A shows a small voltage because Na+ are starting to transit through the ion channels. In 1B, the voltage increases because more Na+ are passing through the ion channels into the membrane. Finally, in 1C, K+ starts to leave the membrane, decreasing the amount of positive charged ions inside the membrane. Muscle movement follows this cycle, resulting in voltage measurements that are constantly fluctuating from which can be derived two important measurements: Amplitude and Frequency of the voltage fluctuations.

According to a study done by Enoka & Duchateau (2008), when muscles are fatigued, the EMG amplitude increases and frequency decreases. This finding is useful because though specific voltage values vary based on health factors, the trend of voltage measurements during muscle fatigue will remain constant. Figure 2 illustrates how EMG amplitude and frequency vary, specifically showing an amplitude increase and frequency decrease in the case of muscle fatigue. The average percentage change in the frequency for half-maximal force was 44% (± 41%). Therefore a change in frequency around 44% should suggest muscle fatigue is occuring (Fuglevand et al., 1999).

Force Output	**EMG Amplitude**	**EMG Frequency**
Force Increase	Increase	Increase
Force Decrease	Decrease	Decrease
Fatigue	Increase	Decrease
Recovery	Decrease	Increase

Figure 2: Relationship between EMG Amplitude, Frequency and Muscle Force Output

1.2 Lit Review

According to Raez et al. in 2006, EMG technologies are well developed and understood. However, given the complex principles of rotation and synchronization of motor units during sustained muscle contraction, fatigue onset can be reflected inaccurately by the EMG. When the muscle is contracted, groups of fibers called motor units are activated in different sequences, which is called motor unit recruitment. As more force is needed, the larger and faster motor units are activated, which is called rotation. If the contraction is sustained like holding a weight, the initial small units that are activated before the big units will get fatigued first. When this happens, the EMG is expected to show an increase in amplitude and decrease in frequency. However, instead of letting the small units fatigue completely until they lose their ability to sustain the contraction, they relax and other units are activated, which is called synchronization. Units coordinate by firing together, so many units are active simultaneously. This synchrony makes the overall EMG signal look smoother rather than showing signs of fatigue. As a result, reading the EMG alone can miss signs of fatigue since it obscures fatigued units. This makes it challenging to directly link a raw EMG reading to fatigue level at times. However, fatigue can be detected by the EMG, when the majority of the small units are not contributing to contraction. The ability to identify fatigue processes makes it possible to stop exercise at the first sign of fatigue onset is a wise solution to prevent further damage of the tendon.

A study done by Tosovic, D., Than, C., & Brown, J. M. in 2016 confirmed the sEMG frequency & amplitude response of fatigued muscles using Mechanomyography (MMG). Unlike EMG, which measures electrical activity, MMG measures the physical, low-frequency, lateral oscillations of active skeletal muscle fibers. MMG signals can be used to indicate the degree of muscle activation and to monitor muscle fatigue in situations where sEMG cannot be applied, such as long-term implantation or adverse environments contaminated by electrical noise (Tarata, M.T. 2003). With the accumulation of fatigue, Tosovic et al. showed the MMG amplitude increases and the average muscle oscillation frequency decreases. A slower contraction of muscle fibers predicts strength loss, allowing for early detection of fatigue-related injury risks. These MMG findings validate the connection between fatigue and muscle activation frequency and amplitude changes. Detecting similar changes with sEMG can provide a widely available and cost-effective way to gain similar insights of what is detected from the MMG.

1.3 Project Statement

The movement of muscles involves movement of tendons, and muscle stretching can increase tendon stress. Repeated tendon strains can produce scars which lead to inflammation of the tendon called tendonitis. People with tendonitis need a way to detect real-time muscle fatigue in repetitive exercise to prevent overuse of muscle that may cause long-term pain and inflammation, further tendon damage, and reduce joint durability. To detect muscle fatigue in real time, a low cost, portable EMG will be developed based on the Arduino platform. Software analysis of the EMG signal will allow users to be alerted when the muscle is fatigued to let them pause for recovery in order to prevent further muscle and tendon damage.

2.0 Methods

2.1 Software Algorithm

EMG voltage measurements will be done with an arduino device from Myoware™ that is able to detect raw EMG signal. To make the measurements meaningful, voltage amplitude values are calculated using RMS and dominant frequencies using a FFT library (Condes, E., 2024). Real time graphing can be observed using the arduino plotter. A sampling rate of 64 data points was the highest value usable within the memory limitation of the arduino.

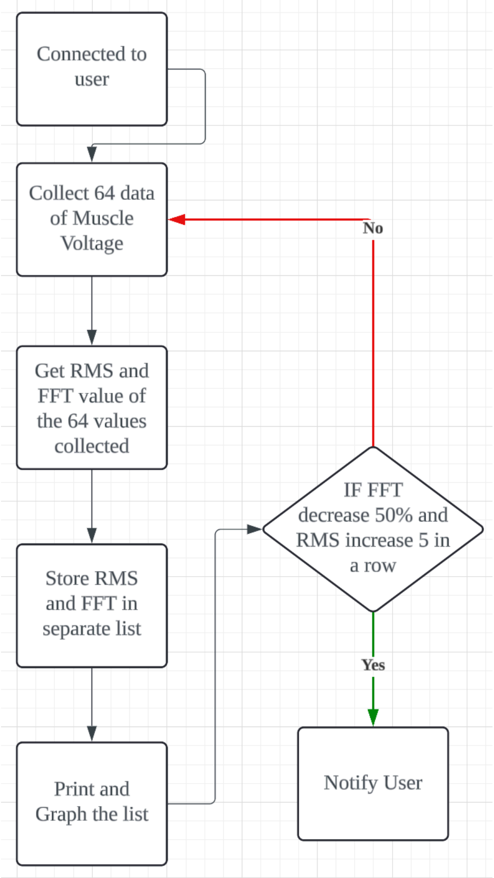


Figure 3: Software Algorithm of sEMG Arduino device

2.2 Software Validation

The RMS and FFT algorithms will be validated by generating simulated data sets of sine waves with known frequency and amplitude. This simulated data will be input into both algorithms separately, allowing comparison of known and calculated results. The full validation process detail is shown in Appendix.

2.3 Force Test

To test for muscle fatigue, a force grip test was combined with the sEMG real time device attached on the participant’s forearm. The goal of the test is to identify the process of fatigue and to utilize the real time sEMG as an objective reference for fatigue onset.

An experiment stopping point of 1/3 maximal force was determined after several subject tests. Stopping earlier results in insufficient depiction of the fatigue process as the force of the participant is not experiencing a second decline. In this case, the fatigue process is not shown completely, impacting the precision of identifying the whole fatigue process.

3.0 Results

Though duration and relative forces differ, all force tests show a stage1 decline, stage 2, plateau, and stage 3 decline, as shown in both participant 1 and 2 (Figure 4 and 5).

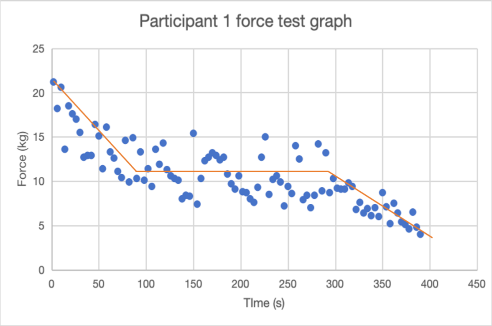


Figure 4: Maximum Grip force of Participant 1 with fatigue showcased by the trend line

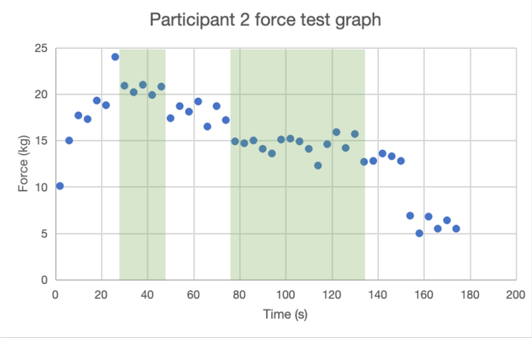
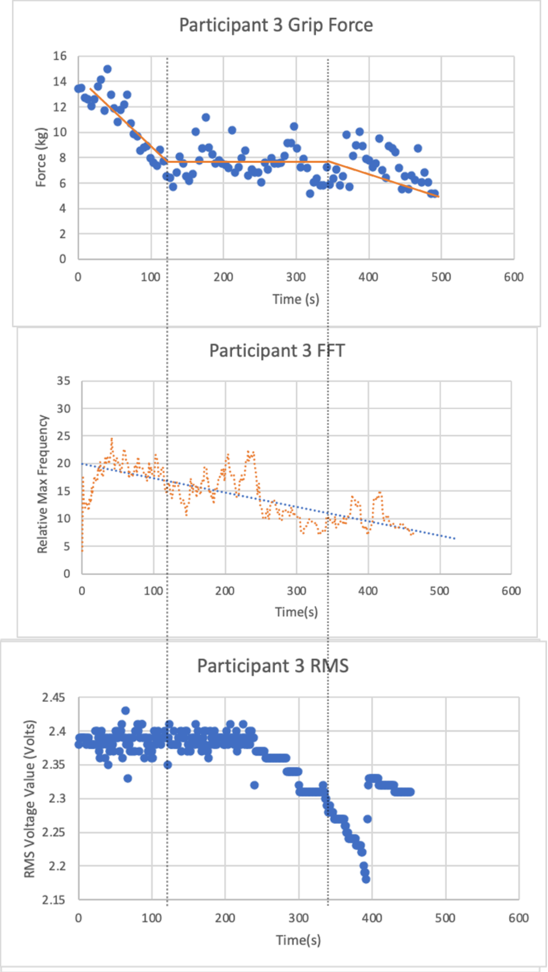


Figure 5: Maximum Grip force of participant 2 with plateau highlighted

Figure 6 shows the full maximum grip force graph for Participant #3, aligned with RMS and FFT data from the same test. Inflection points from the force graph are extended to all three graphs. When the force graph shows the first transition from decline to plateau, a steady decline is reflected in the FFT graph. During the plateau stage, variations are observed in the FFT graph as well as the RMS. During the transition from the plateau stage to the second declining stage of the force graph, the FFT increased, but soon decreased more than before. The RMS showed the opposite, it decreased and then increased.



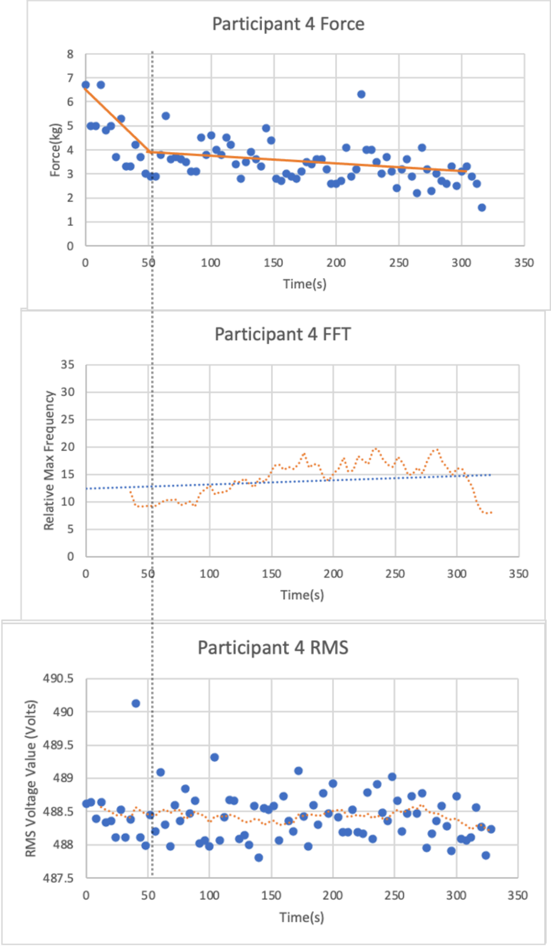


Figure 6: Relationship between maximum grip force and sEMG's FFT and RMS value over time of Participant 3

Figure 7: Relationship between maximum grip force and sEMG's FFT and RMS value over time of Participant 4

Figure 7 shows the same graphs for a different participant (#4). In this case, steady decline in force output is reflected on the FFT graph as an increase in frequency. And relatively constant RMS.

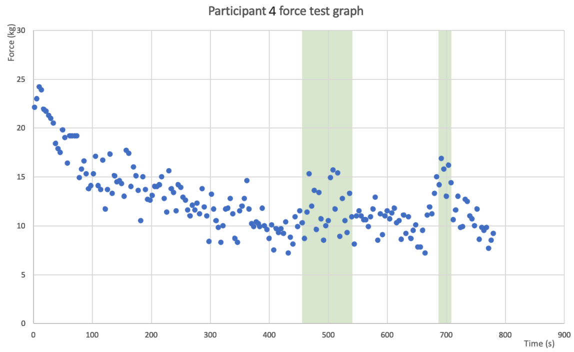


Figure 8: Emotions reflected on force graph

Figure 8 shows the data from Participant #4, which helps to understand external elements of the participant's ability to sustain muscle force in a repetitive exercise. The highlighted green sections indicate when the participant was having emotional changes (e.g. expressed anger at muscle pain) and showed a temporary increase in muscle force. This short term increase in force was not sustainable over time. As time increases, the participant's ability to hold the increased level of force decreases.

4.0 Discussion

The graphs of the force data show an initial decline, a plateau, and a second decline (figure 4&5). Participant 3 (figure 6) shows the same pattern and the start of the second decline corresponds to a 50% drop in maximum frequency (which is consistent with the 44% drop described by Fuglevand(et al., 1999). Based on the correlation of these two events, we suggest the start of the second force decline is a potential indicator of muscle fatigue. Participant 4 does not show the same force trend. In this case, we believe the plateau is too short to be identifiable. If we assume the subject's second decline starts at the end of the first decline, the inflection point correlates with the maximum frequency drop predicted. A short plateau is consistent with observations of the participant during testing, who seemed to reach fatigue quickly.

As we gained experience with the testing procedure, the force test procedure improved as did the understanding of the graph. In Figure 5, the participant did not start with maximal force. This is common among other participants as their maximal grip does not always start on initial attempts. The muscle undergoes a “warm-up” period before the force starts to decline.

More testing will increase confidence in the clear cycle of decline-plateau-decline as shown in green highlights in Figure 5. However, to fully understand the pattern of how long each stage lasts, what each stage means, and whether the duration of each stage depends on the muscle strength of the participant, more research is needed.

Supporting the fact that the fatigue definition allows for continued sub-maximal force even after fatigue, many participants reported tiredness verbally in their first 10-20 grips. However, as shown in their force graphs, they still have muscle strength to complete the task and most participants never reached zero in their muscle force output. This indicates that most muscle damage is avoided by a self perception of fatigue which leads to natural rest far before the point when muscle damage is at risk. A person's feeling about their muscle state is inaccurate and they need assistance in determining fatigue, showing the utility of this device.

Furthermore, emotions can be an important factor in the muscle’s ability to sustain repetitive work. As participants tire mentally, the frequency of asking to stop increases. When frequently mentioned requests could not be fulfilled, participants showed signs of anger. This was also reflected on the force graph as shown in the green parts of Figure 8. Maximum force spikes appear, but the participants' ability to sustain the level of force gets shorter as they are more fatigued.

The process of data collection is still in development and there are significant differences in every participant. Since the frequency and amplitude interpretation of the two participant tests are different, a wider range of participant data is needed to increase confidence in the ability of this algorithm to be generally useful. For example, the RMS for participant 3 decreased instead of increasing. The cause of this difference is uncertain. At that point, to make sure this is not an exception or an random error, future applications could include experimentation with the same participant again and a wider range of participants is needed to understand the uncertainties.

Once the EMG signals can reliably detect fatigue, the next addition will be to add notification. For example, a user in a rehabilitation session would be notified that they are reaching a level of fatigue that could result in reinjury of their tendons. The device would collect real-time muscle voltage and display sound and LED light when the maximum frequency drops by 50% as determined by the Arduino algorithms.

5.0 Conclusion

Trying to prevent people with tendonitis from further muscle and tendon damage from repetitive movements of tendon and muscle, this project used sEMG to detect muscle fatigue. Measuring electromyography amplitude and frequency and conducting force grip tests, this project successfully identified the process of muscle fatigue and determined the stop point through the pattern of decline, plateau, and secondary decline in force output to prevent the overuse of muscle and tendon. Emotions and further understanding of individual variations can help to make more precise analysis of the data sets.

In order to further understand muscle fatigue, further research on individual differences is necessary. The existing method of identifying fatigue needs to be generalized so the force data is no longer part of the process. Conducting experiments with a wider range of participants to understand uncertainty and variation would help this project identify the amplitude and frequency parameters that can identify fatigue and notify users when fatigue levels are reached.

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7.0 Appendices

Test and Validation process worksheet

What are you testing (highlight): Sensors [✓ Component] System

Describe the purpose of this test:
Determine if the FFT program is functioning correctly

How will you perform the test:

1. Design and store 3 kinds of frequency sine wave (1.low frequency, 2 high frequency, 3.mixed frequency)
2. Read the files to make sure they are stored correctly
3. Note the difference in the raw data
4. Compare their difference in the FFT value
5. If their FFT value is correct, compare them with each other.
6. Change the parameters (ex. Sampling frequency, # of samples, range of data) to see the limit of the fft

What are the success criteria:

1. FFT value is reasonable and correct
2. FFT value is comparable and meaning is understood
3. The range of our device is enough for muscle detection

Results:

…Insert Data Table…

Fake Data	FFT Value(expected)	FFT value(actual)
Original	x	1.7
Quadruple	4x	6.5
Two frequency	First x then 4x	1.69->1.64->6.5
Two frequency (opposite)	4x to x	6.56->1.69

When run out of value 0.0 is detected and FFT value significantly decreases to less than 1.