IMPACT OF VIBRATION

AND STOCHASTIC RESONANCE ELECTRICAL STIMULATION

ON MUSCLE CONTRACTION

By

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Abstract:

Motivated by possible applications in pain management and improved prognosis, this study looks into the different methods of potential intervention methods to reduce joint contact forces in the upper and lower extremities. This research looks at both vibration and stochastic resonance electrical stimulation as intervention methods. To avoid invasive procedures, a custom torque sensor measurement device and electromyography (EMG) measurements were used as surrogates for joint contact forces. A preliminary study with 6 male research participants age 18-30 was completed to determine the reliability of EMG measurements when vibration was introduced through a custom vibration sleeve. These tests were analyzed in both frequency and time domain and statistical analysis was used to determine if the presence of vibration caused any change in muscle activity. The second and third studies looked at the effects of vibration and stochastic resonance electrical stimulation on muscle force. In these studies, torque sensor measurements were used as surrogates for joint contact forces. This study was tested on 20 research participants age 18-30 (10 males and 10 females). These tests were statistically analyzed to determine how the muscle forces would be affected. These studies will collectively be used to advance research of the different components of creating a wearable rehabilitation device that could reduce the impacts of knee Osteoarthritis.

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INTRODUCTION

1.1 Motivation

The Centers for Disease Control and Prevention claims that an estimated 78 million adults in the United States (US) are projected to have doctor diagnosed arthritis by the year 2040 [14]. The most prevalent form being Osteoarthritis (OA) which accounts for 30 million adults in the US [15]. According to an epidemiology study from 2010, 10 % of men and 13 % of women aged 60 years or older in the US exhibit symptomatic knee OA [52]. The number of people affected by knee OA is expected to increase with the aging populations and the obesity epidemic [13, 16, 8]. With the number of people affected by knee OA increasing, more research on potential intervention methods are needed. Knee braces, neuromuscular retraining, and application of different stimulation patterns, are a few examples of intervention methods that are being developed to address pain and disease progression in knee OA [10, 3, 37].

1.2 Review of Literature

The progression of knee OA is thought to be caused by the laxity and destabilization of the knee joint due to higher muscle co-contraction [21, 27] which consequentially increases the joint contact forces [45, 28]. The connection between co-contraction and the progression of knee OA is not clear [44], but there is evidence of increased co-contraction in individuals with medically diagnosed OA and those that are at high risk for OA [28, 44, 48, 42, 32, 37]. While the connection between joint contact forces and progression of knee OA is also not clear, some studies have shown that in individuals who were at high risk for knee OA after anterior cruciate ligament injury [45] and [28] found there was higher co-contraction and high tibiofemoral contact forces. Whereas in other studies in [41] and [50], found there were lower tibiofemoral contact forces. Evidence of an increased duration of co-contraction being correlated to increased progression of knee OA had been found in study [22]. These results are an indication that more co-contraction studies and intervention devices targeted at reducing co-contraction at the knee joint are needed.

Motivated by the results found in [37], where it was demonstrated that a reduction in co-contraction and an associated reduction in the Western Ontario and McMaster Universities Arthritis Index (WOMAC) pain score could be obtained in individuals with knee OA using neuromuscular re-education targeted at reduction of muscular co-contraction. The focus of the study was on developing co-contraction reduction techniques that can later be implemented in wearable devices. Any effort at reduction of co-contraction needs to be cognizant of the fact that increased co-contraction of the knee muscles is widely believed to be

a stabilizing response to counter the joint instability caused by knee OA [27, 5]. In [44] there is evidence that counteracting the process of co-contraction may decrease the stability of the knee which reduces the ability to walk correctly. Decreasing the stability of the joint is an issue that raises other questions about what types of stimulation could cause a large enough reduction in stability to counteract any positive outcomes from reducing co-contraction. Because the affects of different types of stimulation, duration, and their effects on muscle force or joint stability are not fully understood, this thesis examines all three of these phenomena to determine what types of stimulation strategies are feasible for reduction in co-contraction.

There has been evidence in literature to suggest that vibration applied to the leg muscles can have a significant impact on locomotion [24] and low frequency local vibration applied to a muscle can induce muscular relaxation [23, 35]. Vibration has been shown to have both facilitatory and suppressive effects on muscle spindle output, which both effect the altered motor output [2]. Both the frequency and the duration of vibration and have been shown to affect muscle output in different ways. In [40] a frequency of 70-100 Hz has been shown to alter the Ia afferent nerve fibers which can significantly alter how quickly a muscle stretch changes. The impact of vibration is seen to have a suppressive effect on muscle spindle activity when applied for 30 seconds or longer [39]. This suppressive effect on muscle spindle activity resulted in a decrease in maximal strength of 7-30 % [6, 19, 25, 26, 31, 43, 47]. On the contrary, it has been observed that brief vibration (2 to 25s), has resulted in additional excitation to the motor neuron pool which ultimately enhances force production [7, 17]. However, [36] found that brief vibration did not have a statistically significant increase. Since the results for brief duration vibration have not been consistent, this thesis examines

the effects on short (3-6s) duration and prolonged (9s) vibration on maximal bicep contraction. Shorter duration stimulation can be used to simulate a potential strategy for wearable devices that can be worn and triggered to apply stimulus at different phases during the gait cycle. The typical duration of a male gait cycle is 0.98-1.07s [34] which further encourages the exploration of shorter duration vibration as a mechanism to reduce co-contraction.

Similar to the impact of vibration on muscle co-contraction, there is evidence to suggest that stochastic resonance stimulation can effectively reduce muscular co-contraction at the knee joint [9]. Stochastic resonance (SR) may help slow disease progression by decreasing impulsive an improper muscle activation. SR is a concept in which low-level noise improves a given system's sensitivity to weak stimuli. Different applications in subsensory SR stimulation has demonstrated improvement in tactile sensation [11], muscle spindle output [12], balance control [18, 38], and joint position sense [10]. Previous work has shown that a knee sleeve/brace can improve proprioception [4, 3, 20]. Thus, by combining SR stimulation with a knee sleeve, greater improvements in proprioception may result. With an enhancement in the sensory system, proprioceptive improvements may alter gait, resulting in reduced joint loading, thus possibly delaying onset and/or slowing progression of knee OA. Although SR can act as a way to increase the sensitivity of weak signals, it is also said to increase the muscle spindle output, which could potentially increase muscle force production [30]. This increase in muscle spindle output could cause counteractive effects for applying SR at the knee joint. Since the research regarding the effect of SR on muscle force is inconclusive, this thesis examines the effect of SR on maximal voluntary contraction of the bicep. These results will be used to determine if increased muscles spindle output could cause counteractive

effects in attempt at reducing co-contraction.

1.3 Summary of Objectives

The primary object of this thesis is to investigate potential stimulation mechanisms that can be used to reduce muscle force. The participants are asked to perform maximum voluntary contraction (MVC) of the bicep by pushing up against an immovable platform and electromyography (EMG) or torque sensor measurements are recorded and are used as a surrogates for joint contact forces. Investigation of duration, type of stimulation, and stimulation frequencies are used to determine which strategies are most effective in reducing muscle force. The experiments in this thesis are performed on the upper extremities because the equipment that is used does not have the capability to record higher forces produced by the lower extremities.

1.4 Statistical Test Assumptions

The statistical tests used in this thesis are the two-tailed and one-tailed t-tests and the analysis of variance (ANOVA) test. The tests are used to determine whether there are statistically significant differences in participant responses to various stimuli. The statistical tests use a predetermined set of assumptions. The assumptions for each test are shown in Table 1 [29, 46]. A discussion on the validity of using these assumptions for the data in this thesis is in Chapter 5.

t-test	**ANOVA**
The data are continuous	The means for each type of stimulation have a normal probability distribution
The means of the data sets collected from each participant are from a normal probability distribution	The distributions for all of the participants data have the same variance
The variances for the sensor recordings of the two data sets are equal	The participants data are independent of one another
The data points within each participants data sets are independent of one another	
Both sets of data from sensor readings are simple random samples of MVC.	

Table 1: Statistical test assumptions table. First column is the assumptions for the t-test and the second column is for the ANOVA test.

Chapter II

STUDY OF THE EFFECT OF VIBRATION ON MUSCLE ACTIVITY

Using muscle activity measured via electromyography (EMG) signals, as surrogates for forces produced by the muscle, this chapter analyzes the effect of vibration on muscle force.

2.1 Experimental Setup

For the preliminary data collection trials, each research participant was equipped with a custom vibration motor sleeve. The sleeve included 8 DC vibration motors, equally spaced, and sewn into an adjustable elastic arm strap. The motors were wired together and powered by a common 6V DC voltage source. The DC motors were running for various durations of time during the participant's maximum voluntary contraction (MVC). A block diagram of the wiring is shown in Figure 1.

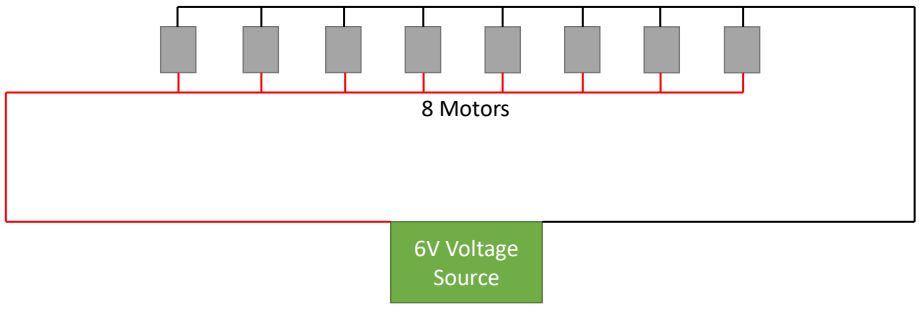

Figure 1: Block diagram of the 8 DC motors wired to a 6V voltage source

The results in [1], found that the most accurate bicep muscle readings from EMG were obtained by placing the EMG electrodes directly on the middle (or belly) of the bicep muscle. Using this information, the participants were instructed to place the EMG Electrodes on the middle of the bicep muscle. Once the electrodes were attached, tape was used to secure the wireless sensor for the electrodes on the opposite side of the participants arm.

A plastic shield was placed underneath the motor sleeve to prevent the motors from pressing into the skin. The plastic shield was easy to disinfect, and as such, also helped maintain hygiene when switching the sleeve between participants. Lastly, tape was used to secure the sleeve on the plastic shield to prevent any slipping from occurring. Images of the motor sleeve and placement of the sleeve on a participant's arm are shown in Figure 1 and Figure 2.

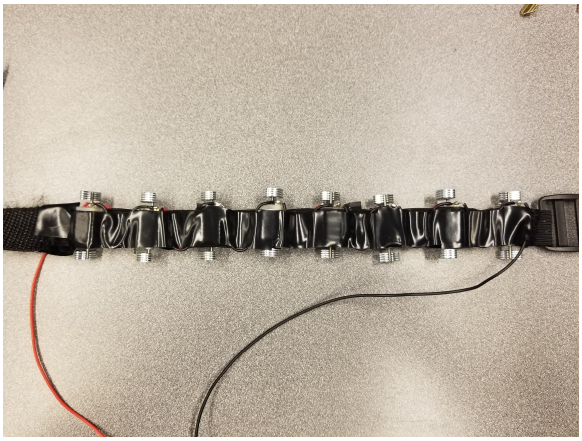

Figure 2: The vibration motor sleeve with 8 DC vibration motors all wired together to a common 6V voltage source.

Figure 3: A research participant with the plastic shield, vibration sleeve, tape securing the sleeve, and the EMG electrodes placed on the bicep.

2.2 Frequency Analysis

A preliminary test was conducted to determine the effect of vibration on EMG recordings. These results were used to determine if the EMG measurements were distorted by the vibration. Four trials were repeated with vibration ON with the research participants arm in a resting condition. A fast Fourier transform (FFT) of the EMG signals is shown in Figure 4.

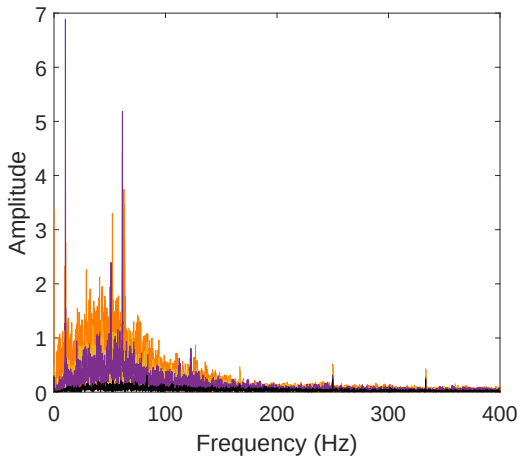

Figure 4: Graph of the FFT for the vibration tests. The black line indicates the test performed with a resting arm with NO vibration. All of the other colors represent repeated trials with vibration ON.

The results showed that the vibration from the sleeve created a disturbance in the EMG measurements in the 0-100 Hz frequency band. The typical frequency band for muscle activation is between 50-100 Hz [33], which overlaps with the frequency band of the vibration-induced disturbance. Since there was crossover between muscle electrical activity and the vibration-induced disturbance, determining if the vibration affected the EMG signal proved difficult. After repeated tests on a resting arm, it was determined that the EMG amplitude increased by an average of 14 μV when vibration was introduced. To offset this increase, 14

μV was subtracted from the EMG signals for all of the trials.

2.3 Experimental Procedure

The objective for this experiment was to determine if the custom vibration motor sleeve was capable of reducing muscle activity. Another objective was to further understand if the duration of vibration has an impact on muscle activity, which was why different vibration durations were tested in the trials.

Six male research participants from ages 18-30 were recruited and 5 different test scenarios were recorded. The participants were either resting or performing maximal voluntary bicep contraction for a duration of 6 seconds. Each test scenario included a different flex type (flexing or resting) and a different vibration type (ON or OFF or 3 seconds ON 3 seconds OFF). The data collection scenarios for the preliminary EMG test are shown in Table 2.

Scenario	Flex Type	Vibration Type
Scenario 1	No Flex	OFF
Scenario 2	Flex	OFF
Scenario 3	Flex	ON
Scenario 4	Flex	ON/OFF
Scenario 5	Flex	OFF/ON

Table 2: Preliminary data collection scenarios

2.4 Data Analysis

The data from each of the 6 research participants were processed for each of the different scenarios. The data processing included rectifying the signal to the positive portion of the EMG recording, trimming any excess data that exceeded the 6 second duration, and

computing the root mean squared (RMS) values for each portion of the data. The ON/OFF and OFF/ON scenarios were split into two separate RMS values, to determine if there was a difference with and without vibration. Graphs of the processed data for an individual research participant are shown in Figures 5-9.

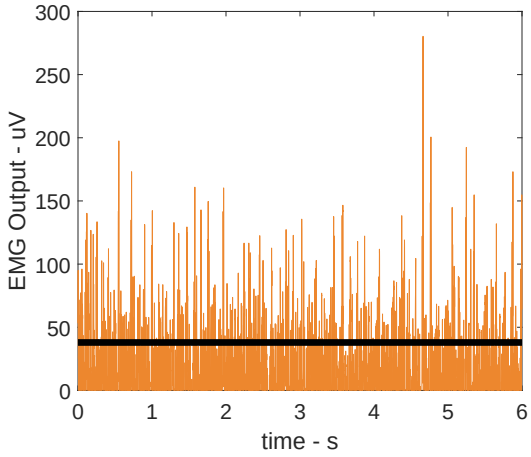

Figure 5: Processed plot of EMG activity versus time. The plot is for data scenario 1 (NO flex with vibration OFF). The black line indicates the RMS value.

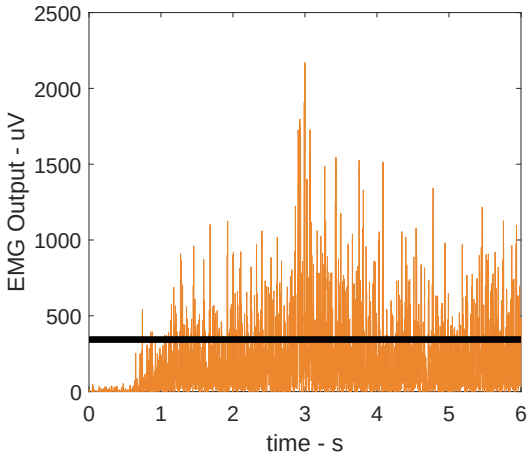

Figure 6: Processed plot of EMG activity versus time. The plot is for data scenario 2 (Flex with vibration OFF). The black line indicates the RMS value.

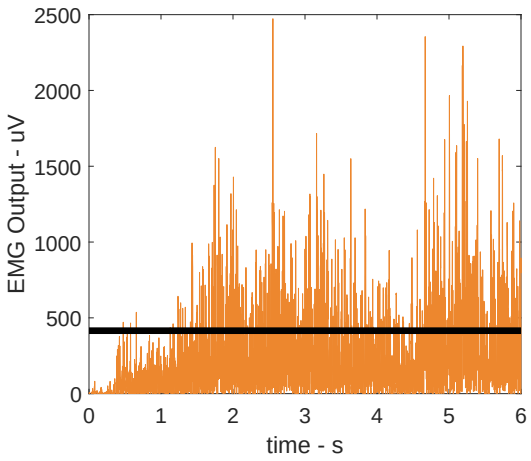

Figure 7: Processed plot of EMG activity versus time. The plot is for data scenario 3 (Flex with vibration ON). The black line indicates the RMS value.

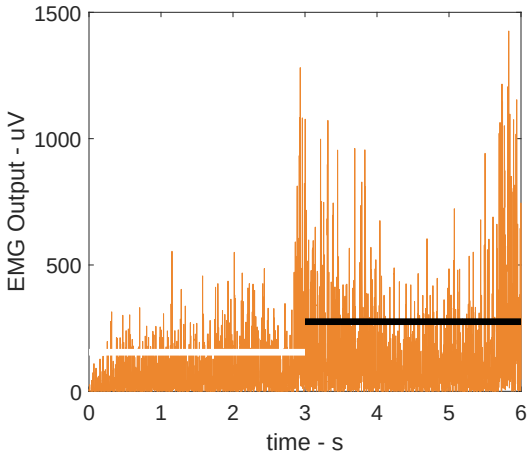

Figure 8: Processed plot of EMG activity versus time. The plot is for data scenario 4 (Flex with vibration ON 3s/OFF). The white line indicates the RMS value for the first half of data and the black line indicates the RMS value for the second half.

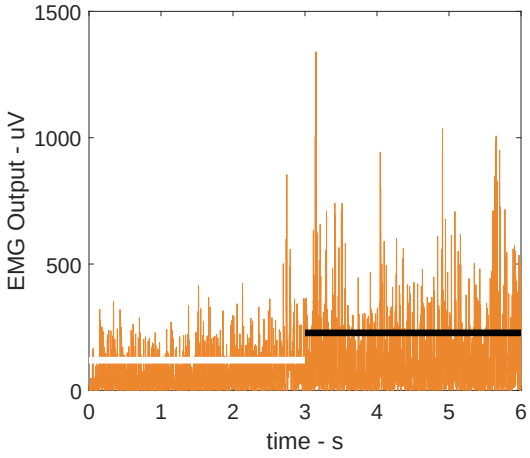

Figure 9: Processed plot of EMG activity versus time. The plot is for data scenario 5 (Flex with vibration OFF/ON 3s). The white line indicates the RMS value for the first half of data and the black line indicates the RMS value for the second half.

The calculated RMS values for each of the research participants for each collection scenario are shown in Table 3.

Subject	RMS FNV	RMS FV	RMS OFF	RMS ON	RMS ON	RMS OFF
1	151.135	222.955	128.833	142.565	188.495	210.672
2	343.280	415.283	119.470	227.588	154.697	275.575
3	103.810	102.105	96.307	87.387	123.319	110.563
4	527.818	537.753	428.417	490.990	503.301	566.526
5	107.094	86.965	39.033	53.153	54.045	54.322
6	798.295	953.378	156.022	485.201	838.281	941.676

Table 3: RMS data for each of the research participants. FNV denotes flex with no vibration, FV denotes flex with vibration and the last four columns are for the 3 seconds OFF/ON and ON/OFF scenarios.

2.5 Statistical Analysis

A statistical test was used to analyze the effects of vibration on muscle activity. A two-tailed t-test was used to determine if the means of the EMG signals recorded in two different scenarios were unequal. A level of significance of $\alpha = 0.05$ was used for each test. The null hypothesis for the t-test was that the means were equal and rejecting the null hypothesis means that if the means were equal, the data we observed would be statistically unlikely. The data that were compared were flex with no vibration and flex with vibration, flex with vibration OFF/ON (first half of the data compared with the second half) and flex with vibration ON/OFF (first half of data compared with the second half). A summary of the results of the statistical tests is shown in Table 4.

Subject	RMS FNV vs RMS FV	RMS OFF vs RMS ON	RMS ON vs RMS OFF
1	Reject	Reject	Reject
2	Reject	Reject	Reject
3	Fail to Reject	Fail to Reject	Reject
4	Fail to Reject	Reject	Reject
5	Reject	Reject	Fail to Reject
6	Reject	Reject	Reject

Table 4: Preliminary vibration study summary table of statistics for a two-tailed t-test for each individual research participant.

2.6 Results

From the collected data, the results were inconclusive. Out of the 18 possible outcomes, 4 were statistically inconclusive, 9 were statistically different for higher EMG recordings with vibration ON, and 5 were statistically different for lower EMG recordings with vibration ON. Possible reasons for the variability in the data are research participant fatigue, vibration interference with EMG recordings, sleeve tightness, EMG electrode placement, and overall variation in participant skin interaction with the EMG electrodes (muscle/fat composition).

Fatigue can cause a research participants EMG amplitude to vary greatly due to loss in muscle strength throughout the multiple tests which would make it difficult to determine if vibration was the actual cause of amplitude reduction. To counter the effects of fatigue, more rest can be given between trials. Vibration interference with the EMG recording creates a similar difficulty in determining whether the EMG amplitude was increasing because of vibration induced distortion or because of actual muscle activity increase. This ambiguity makes it difficult to attribute any change in muscle activity to the vibration being applied. Sleeve tightness could also affect EMG recordings due to the potential for sleeve slipping. Sleeve slipping was difficult to prevent due to the nature of the vibration device on a plastic

shield, and tape was used in an attempt to prevent this. EMG electrode placement can cause different readings based on the placement of the electrodes on the bicep, and since the research participants were instructed to place them, themselves, the placement could lead to variability. A potential way to reduce variability due to electrode placement is to have the research assistant place the electrodes, which can only be done if COVID-19 safety precautions are taken. Lastly, variation in participant skin interaction with the EMG electrodes can cause variability due to the way the EMG signals are distributed through the tissue to the surface where they are recorded by the electrodes. A potential option to reduce the variability of these issues, is to include an exclusion criteria for all participants who do not meet a specific BMI or body fat percentage.

2.7 Conclusion

Since it was found that the vibration sleeve causes an increase in EMG amplitude, it was difficult to determine if muscle activity decreased when vibration was introduced. One possible solution for mitigating the effects of vibration on EMG recordings would be to filter the vibration frequencies out using a notch filter. However, this solution would potentially interfere with recording of the actual muscle activity since the muscle activation frequency range was also within the range of the motor vibration frequency. As a result, we concluded that the likelihood of getting any conclusive results from EMG measurements was very low. In the next chapters, we use direct torque measurements to get a more reliable measurement of muscle force.

Chapter III

STUDY OF THE EFFECT OF VIBRATION ON MUSCLE FORCE

When applied for 30 seconds or longer, the impact of vibration is seen to have a suppressive effect on muscle spindle activity [39]. This suppressive effect on muscle spindle activity resulted in a decrease in maximal strength of 7-30 % [6, 19, 25, 26, 31, 43, 47]. On the contrary, it has been observed that brief vibration (2 to 25s) enhances force production [7, 17]. However, [36] found that brief vibration did not have a statistically significant increase in force production. Because the results from brief duration vibration studies have not been consistent, we are motivated to get conclusive results on the effects of brief vibration on maximum voluntary contraction. This chapter discusses the experimental set up, experimental procedure, data analysis, statistical analysis and results for testing the effects of brief vibration on maximum voluntary contraction (MVC) of the bicep muscle.

3.1 Motivation

Filtering vibration-induced distortion in EMG recordings was found technically infeasible in the vibration study. To remedy the vibration-induced distortion in EMG recordings, this experiment utilizes torque sensor measurements to examine the effects vibration has on maximum voluntary contraction of the bicep.

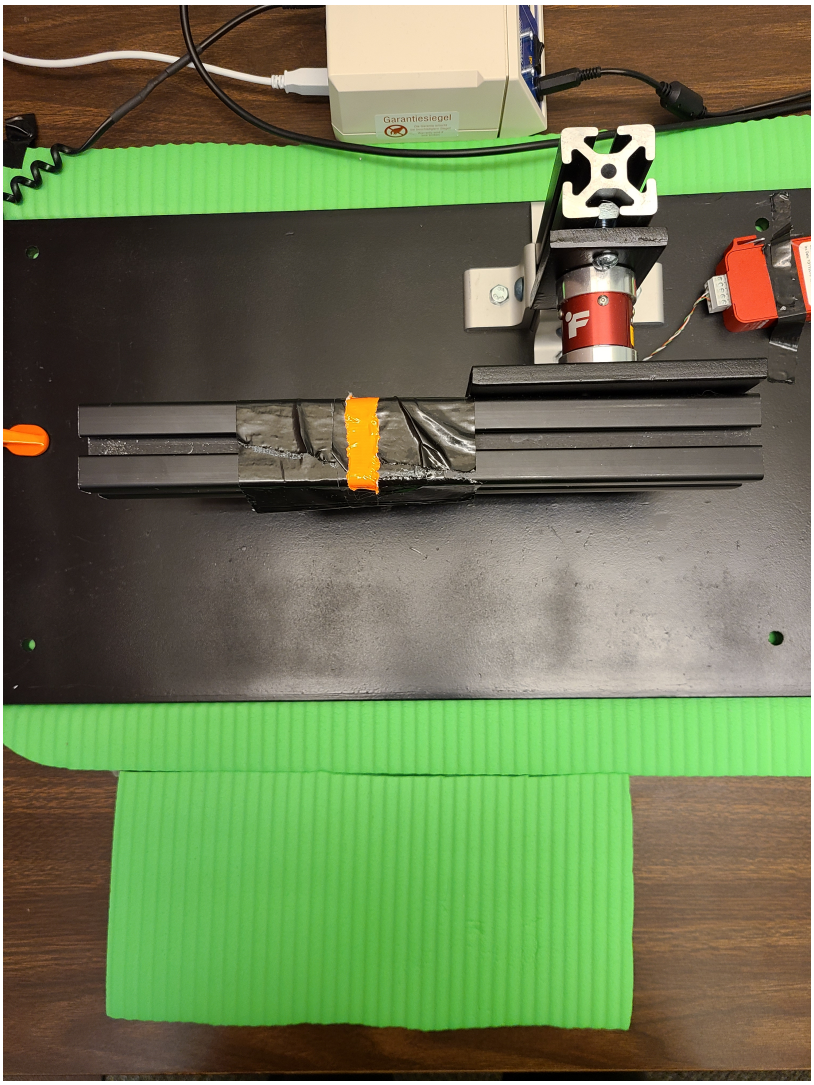

Figure 10: A Futek reaction torque sensor attached to the aluminum 40 mm x 40 mm lever arm on the active end of the sensor and mounted to a vertical 40 mm x 40 mm aluminum piece to the base plate. (Top view)

3.2 Experimental Setup

The torque sensor set up was custom made for this project and is shown in Figure 10 and Figure 11. The torque sensor set up was designed to allow participants to push up against the sensor with maximum voluntary contraction, avoid exceeding the maximum capacity of the sensor which is 1300 in-lbf, and to synchronize the timing of the torque sensor measurements with that of the vibration stimulus.

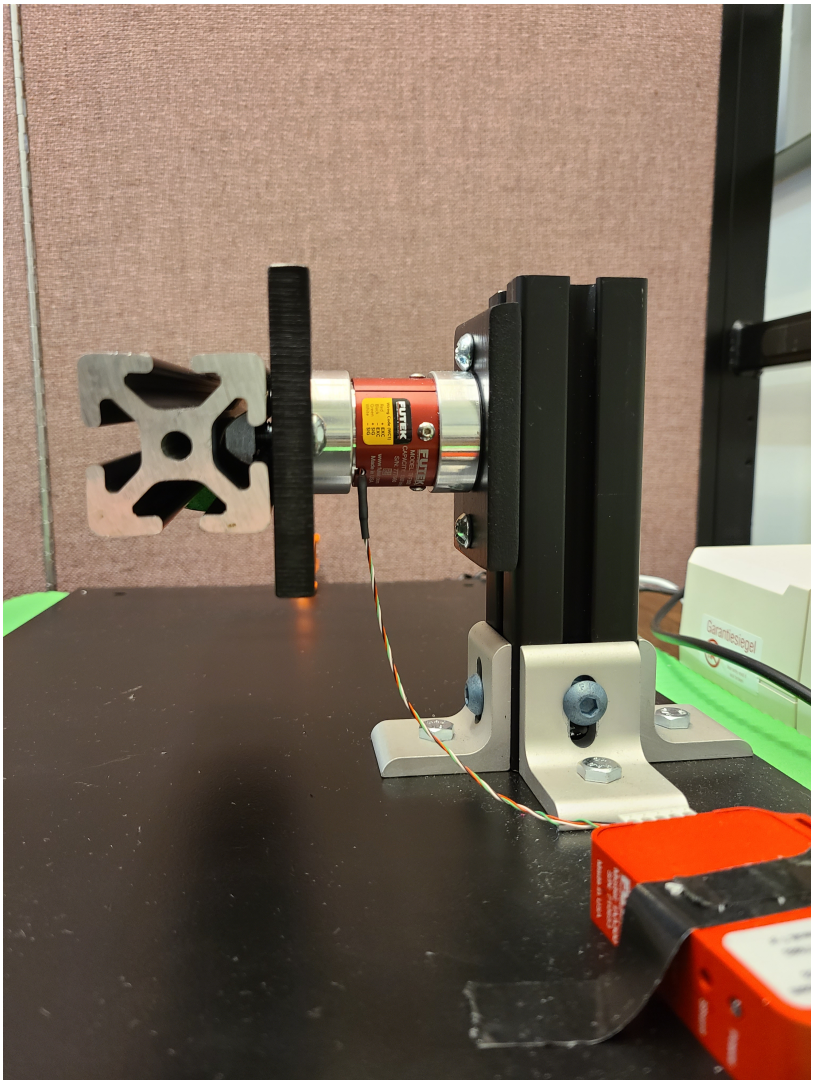

Figure 11: A Futek reaction torque sensor attached to the aluminum 40 mm x 40 mm lever arm on the active end of the sensor and mounted to a vertical 40 mm x 40 mm aluminum piece to the base plate. (Side view)

The base plate for the set up is made out of 3/8 in thick steel and all other torque sensor attachment pieces were cut from the 1 foot by 2 foot steel plate. The handle is made out of a 6 in piece of 40 mm x 40 mm aluminum with t-slots. The handle is mounted to the active end of the torque sensor by a connection with steel piece that is bolted using self aligning roll in t-nuts with spring leafs. This connector piece is directly connected to the active end of the torque sensor using steel bolts. The fixed end of the sensor is bolted to another steel connector plate which is bolted to the vertical aluminum 40 mm x 40 mm using the same self aligning t-nuts with spring leafs. The vertical aluminum piece is mounted to the base plate with 4 brackets. The entire set up is placed on top of a memory foam mat to provide research participants with a comfortable place to rest their elbow while applying maximum voluntary contraction.

The torque sensor is connected to a Futek IAA300 analog amplifier. This amplifier is wired to a 15V power supply and the output signal is wired to a Quanser Q8-USB data acquisition device. The data acquisition device is also used to control an Arduino Mega 2560 with a DFRobot motor driver shield attached to power the vibration sleeve. The motor driver provides 6V to the motors to induce vibration. This motor sleeve is the same sleeve used in chapter 2. The Quanser board is connected to the simulation laptop via USB and a simulink model is used to power the motors at the correct time and also to collect the data from the torque sensor and send the data to the MATLAB workspace.

3.3 Experimental Procedure

In this study, 20 research participants (10 male and 10 female) ages 18-30 were recruited and the following procedures were used to determine the effects of vibration on maximum voluntary contraction. For each data collection session, each research participant was brought into the lab and was required to sign four voluntary consent forms which include a COVID-19 safety measures form for each experiment, and a consent form for vibration and stochastic resonance stimulation. These consent forms and procedures are approved by the Oklahoma State University Institutional Review Board.

After signing all of the consent forms, the participants were assigned a number, to be used as the only participant identifier other than gender. The research assistant then fastened a plastic shield around the participants right bicep muscle just above where the elbow bends. The motor sleeve was then placed on top of the plastic shield and was tightened until it was flush against the plastic shield. The sleeve was then taped at 3 or 4 different places to ensure that no slipping would occur when the vibration was turned on. After the sleeve was fully taped, the research assistant ran a motor test to ensure that the motors were spinning properly and there was no slipping of the sleeve. The participants were instructed by the research assistant to place their hand underneath the sensor and push upward on the lever arm as hard as they could for the duration of the 5 different scenarios. An image showing the experimental set up is shown in Figure 12 and the five different data collection scenarios are shown in Table 5. After each data collection scenario was complete, the data were saved from the MATLAB workspace into a folder for each individual. Each participant was asked

to return once more for a repeat trial.

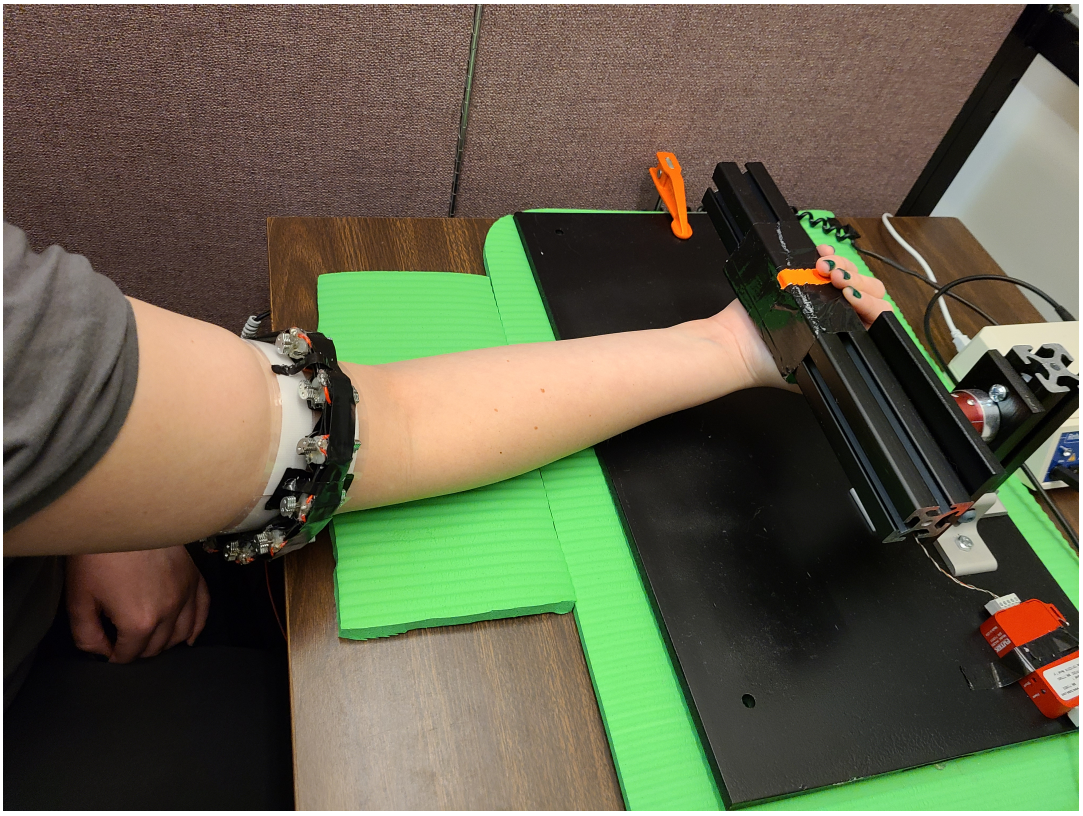

Figure 12: Experimental set up for vibration tests. The participant was equipped with the plastic shield and sleeve which was held in place with tape. The participant places their hand underneath the level arm of the sensor and pushes up on the lever for each different stimulation scenario.

Scenario	Vibration Duration	Vibration Type
Scenario 1a	9s	ON
Scenario 1b	6s	ON
Scenario 2	0s	OFF (control)
Scenario 3	3s	ON/OFF
Scenario 4	3s	OFF/ON

Table 5: Torque sensor data collection scenarios for vibration experiment. Scenario 1a is 9s total duration vibration, but only 6s of maximum voluntary contraction

The different stimulation scenarios for vibration durations were chosen to determine if short (3-9s) duration vibration has the potential to decrease force production. Since the ultimate objective of this research is to create wearable devices to apply stimulation during the loading or stance phase of the gait, which lasts for less than 1s, analysis of brief vibration as a possible intervention method is well-motivated [34]. Scenario 1a is used to simulate a potential strategy to vibrate the muscle prior the the stance phase which is why the participants are relaxed for the first 3s. Scenario 1b is used to determine if 6 seconds of vibration can cause any decrease in force for a MVC of 6 seconds. And Scenarios 3 and 4 were designed to determine if 3s vibration causes any decrease in force for a MVC duration of 6 seconds.

3.4 Data Analysis

After all of the data were collected, the raw voltage signal from the torque sensor was used to calculate the corresponding load in in-lbf. The load values were interpolated from the manufactures calibration sheet. Graphs showing the load vs time for each of the five different scenarios for Trial 1 are shown in Figures 13-17.

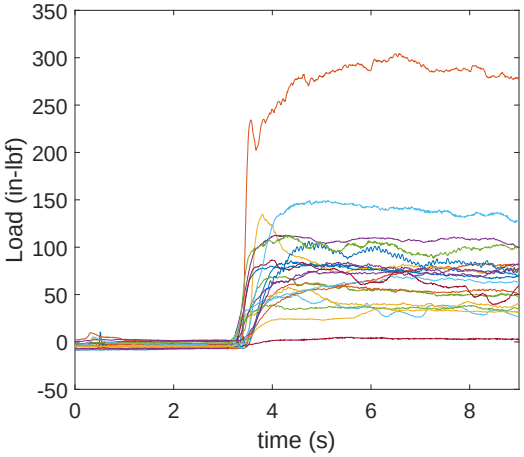

Figure 13: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with vibration applied for a 9s duration (Scenario 1a)

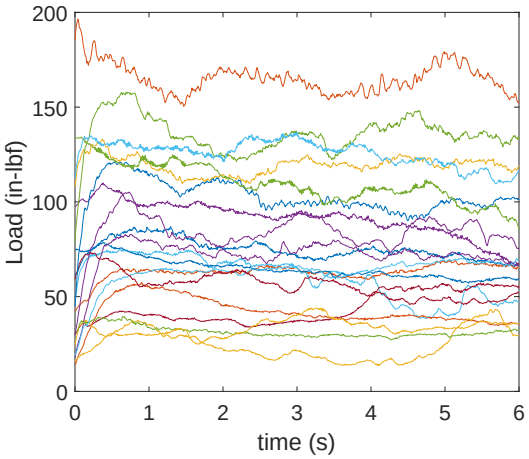

Figure 14: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with full 6s duration vibration applied (Scenario 1b)

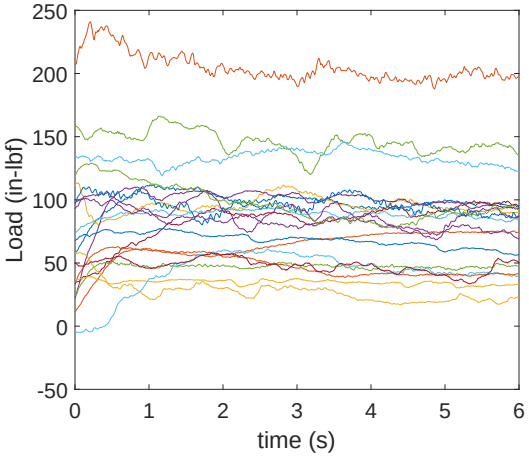

Figure 15: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with no vibration applied (Scenario 2)

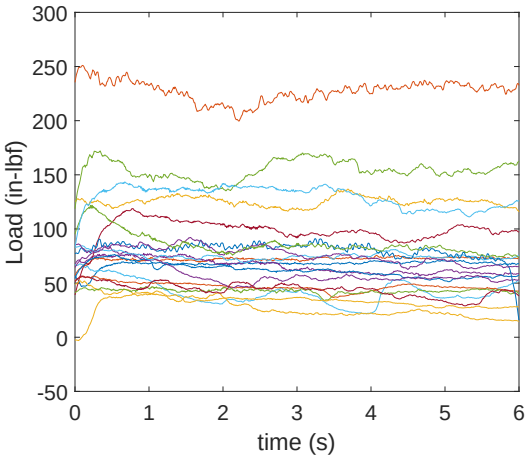

Figure 16: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with 3s duration vibration applied on the first half of the test (Scenario 3)

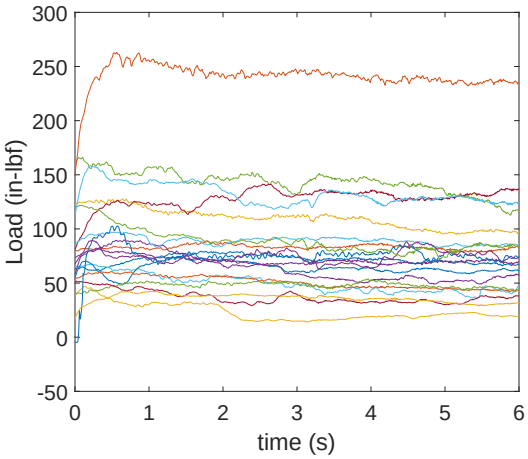

Figure 17: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with 3s vibration duration applied on the second half of the test (Scenario 4)

3.5 Statistical Analysis Trial

Question	Hypothesis	Test
Are the means of prolonged vibration equal to the means of acute?	$H_0 : \mu_p = \mu_a$, $H_a : \mu_p \neq \mu_a$	two-tailed
Are the means of prolonged vibration equal to the means of control?	$H_0 : \mu_p = \mu_c$, $H_a : \mu_p \neq \mu_c$	two-tailed
Are the means of acute vibration equal to the means of control?	$H_0 : \mu_a = \mu_c$, $H_a : \mu_a \neq \mu_c$	two-tailed
Are the means of acute vibration less than or equal to the means of control?	$H_0 : \mu_a = \mu_c$, $H_a : \mu_a \leq \mu_c$	one-tailed
Are the means of prolonged vibration less than or equal to the means of control?	$H_0 : \mu_p = \mu_c$, $H_a : \mu_p \leq \mu_c$	one-tailed

Table 6: Statistical test results summary table for vibration. This table includes the question to be answered, the Hypothesis for that question, and which type of test is used to check that hypothesis. μ_p denotes the mean of prolonged stimulation, μ_a denotes the mean of acute stimulation, and μ_c denotes the mean of control condition.

A series of different statistical tests were conducted in order to analyze the effects of vibration on muscle force. A summary of the hypothesis in each of the tests is shown in Table 6. Both two-tailed and one-tailed t-tests were used on each set of scenario data for each individual research participant. The data were first checked for a significant statistical

difference in the overall means of the torque sensor readings using two-tailed tests. The null hypothesis in the 2-tailed tests is that the means are equal and rejecting the null hypothesis means that if the means were equal, the data we observe would be statistically unlikely. Next, the data were analyzed using a one-tailed test to check the hypothesis if the means of the torque sensor readings with vibration applied were smaller than those without vibration. For these tests, the alternate hypothesis is that the means for the vibration tests are less than the means for the control tests, so rejecting the null hypothesis means the data favors the alternative hypothesis. For each of the tests, a level of significance of α=0.05 is used. Detailed per-participant results of the two-tailed t-tests are available in Tables 25-27 in the Appendix.

From the 2-tailed tests, we can conclude that the different scenarios likely produce different means for the 3 compared conditions. A summary of the results from Tables 25-27 from the Appendix is shown in Table 7.

Comparison	Reject	Fail to Reject
Prolonged vs Acute	20	0
Prolonged vs Control	18	2
Acute vs Control	19	1

Table 7: Two-tailed t-test results for vibration summarizing the outcomes of each test

Now that it is confirmed that the means are unlikely to be equal, a one-tailed tests is used to test against the alternate hypothesis that the vibration mean is less than the control mean. Detailed per-participant results of the one-tailed t-tests are available in Table 28 and Table 29 in the Appendix.

Tables 28-29 from the Appendix are summarized in Table 8. Table 8 indicates that 70% of the research participants produced a decrease in average torque when acute vibration is introduced and 75% produced a decrease in average torque for prolonged vibration.

Comparison	Reject	Fail to Reject
Acute Vibration vs Control	14	6
Prolonged Vibration vs Control	15	5

Table 8: One-tailed t-test results for vibration summarizing the outcomes of each test

Question	Hypothesis	Test
Are the first 3 seconds with vibration means equal to the next 3s without vibration?	$H_0 : \mu_{o1} = \mu_{f2}$, $H_a : \mu_{o1} \neq \mu_{f2}$	two-tailed
Are the first 3 seconds without vibration means equal to the next 3s with vibration?	$H_0 : \mu_{f1} = \mu_{o2}$, $H_a : \mu_{f1} \neq \mu_{o2}$	two-tailed
Are the first 3 seconds with vibration means less than or equal to the next 3s without vibration?	$H_0 : \mu_{o1} = \mu_{f2}$, $H_a : \mu_{o1} \leq \mu_{f2}$	one-tailed
Are the first 3 seconds without vibration means greater than or equal to the next 3s with vibration?	$H_0 : \mu_{f1} = \mu_{o2}$, $H_a : \mu_{f1} \geq \mu_{o2}$	one-tailed

Table 9: Statistical test results summary table for ON/OFF and OFF/ON scenarios for vibration. This table includes the question to be answered, the Hypothesis for that question, and which type of test is used to check that hypothesis. μ_{o1} denotes the ON portion of ON/OFF scenario, μ_{f2} denotes the OFF portion of ON/OFF scenario, μ_{f1} denotes the OFF portion of OFF/ON scenario, and μ_{o2} denotes the ON portion of OFF/ON scenario.

The last data that need to be analyzed belonged to Scenario 3 (ON/OFF Vibration) and Scenario 4 (OFF/ON Vibration), in order to determine if even shorter duration vibration (3s) would produce any difference in force/torque production. A summary of the hypothesis in each of the tests is shown in Table 9. A 2-tailed test was used to determine if the average of the first 3 seconds of the data was different than the next three seconds of data. Then, a one-tailed test was used to determine if the torque with vibration is less than the torque

when there is no vibration. Rejecting the null hypothesis for the two-tailed case would mean that if the means of each half of the data were equal, the data we observe would be statistically unlikely. Rejecting the null hypothesis for the one-tailed case would mean that the data favor the alternate hypothesis. For each of these tests, a level of significance of α=0.05 was used. Detailed per-participant results for the two-tailed t-test are available in Table 30 and Table 31 in the Appendix and the results for the one-tailed t-tests are available in Table 32 and Table 33 in the Appendix.

From the two-tailed tests, it is clear that there is a significant difference in the means for Scenario 3 and 4. However, the results from the one-tailed test show that Scenario 3 does not show that vibration decreases the force/torque, but scenario 4 shows that vibration does cause a decrease in force/torque for the 3s of vibration. Tables 10 and 11 summarize the results in Tables 30-33 from the Appendix.

Comparison	Reject	Fail to Reject
ON/OFF	19	1
OFF/ON	18	2

Table 10: Two-tailed t-test results summarized for Scenarios 3 and 4 for vibration

Comparison	Reject	Fail to Reject
ON/OFF	5	15
OFF/ON	17	3

Table 11: One-tailed t-test results summarized for Scenarios 3 and 4 for vibration

Trial 2 was analyzed using the same statistical tests as Trial 1 and the results are in Table 12.

Comparison	Type	Reject	Fail to Reject
Prolonged Vibration vs Acute vibration	2 Tail	18	2
Prolonged vs Control	2 Tail	19	1
Acute Vs Control	2 Tail	20	0
Prolonged vs Control	1 tail	13	7
Acute Vs Control	1 tail	8	12
ON/OFF	2 tail	19	1
OFF/ON	2 tail	19	1
ON/OFF	1 tail	1	19
OFF/ON	1 tail	16	4

Table 12: One-tailed and two-tailed t-test results summarized for Trial 2 for vibration

With the exception of a few participants, the results of Trials 1 and 2 were found to be consistent.

3.6 Results

Instead of comparing the effect of vibration on MVC per individual, to get an idea on the effects on the entire group, a repeated measures ANOVA test was preformed for prolonged vs control, acute vs control, first half of ON/OFF data vs second half, and the first half of the OFF/ON data vs the second half for both Trial 1 and Trial 2. A significance level $\alpha = 0.05$ was used to determine strong statistical significance and a significance level of $\alpha = 0.1$ was used to determine weak statistical significance. The results for these tests are shown in Table 13.

Comparison	Trial	p value	statistical significance
Prolonged Vibration vs Control	1	0.053591	Weak
Acute Vibration vs Control	1	0.09779875	Weak
ON/OFF	1	0.000834187	Strong
OFF/ON	1	0.000337	Strong
Prolonged Vibration vs Control	2	0.050089	Weak
Acute Vibration vs Control	2	0.513045	None
ON/OFF	2	0.000648	Strong
OFF/ON	2	0.001213	Strong

Table 13: Repeated measures ANOVA results for trial 1 and trial 2 for vibration.

The results of the ANOVA tests show that both Trial 1 and Trial 2 resulted in the same statistical significance other than Acute vs Control vibration. Since the results only show if the means for each research participant are different for a different type of stimulation scenario, it was difficult to determine if there was an increase or a decrease on force/torque production when vibration is applied.

Combining these results with the individual one-tailed and two-tailed t-tests, it can be concluded that prolonged vibration has more of an effect of force decrease than acute vibration. The results for prolonged vibration are consistent amongst multiple trials, so it is likely for prolonged vibration to be the cause of force/torque reduction. Since the results for the acute vibration varied from Trial 1 to Trail 2 it is likely that vibration may not be the cause for force reduction. For the 3 second stimulation scenarios, the OFF/ON scenario produced a decrease in force, while the ON/OFF scenario produced the opposite. The results of the 3 second stimulation make it clear that shorter 3 second vibration is probably not what causes the decrease in force for each research participant. A potential cause for this difference in the 3 second trial decrease for the OFF/ON scenario could be research participant fatigue or a learned strategy from performing the tests multiple times. The learned strategy could result from the research participants knowing their 6 second force production trial is almost up, so this could cause the participant to start decreasing their force prematurely. Although both of these results can not be directly confirmed, they offer a good explanation for why 3 second vibration results may be opposite of one another.

In order to test the validity of the claim of fatigue, statistical tests were done on the ON/OFF and OFF/ON data sets. The statistical tests compared the front end of the ON/OFF data with the tail end of the OFF/ON data. And the other test compared the tail end of the ON/OFF data with the front end of the OFF/ON data. A one-tailed t-test was preformed to test the alternate hypothesis of the ON/OFF data being greater than the OFF/ON data. The reason for testing them in this way is because the ON/OFF scenario was preformed before the OFF/ON scenario. Comparing the two data sets between scenario

Comparison	trial	Reject	Fail to Reject
OFF vs OFF (Tail end $\leq$ Front end)	Trial 1	17	3
ON vs ON (Front end $\geq$ Tail end)	Trial 1	13	7
OFF vs OFF (Tail end $\leq$ Front end)	Trial 2	13	7
ON vs ON (Front end $\geq$ Tail end)	Trial 2	15	5

Table 14: One-tailed t-test results for comparing the front end of the ON/OFF data the the tail end of the OFF/ON data and the tail end of the ON/OFF data to the front end of the OFF/ON data.

3 and scenario 4 will determine if fatigue takes place when there is not enough break in between scenarios. Similarly, comparing the front end to tail end and tail end to front end of the data determines if fatigue is within the 6 seconds of MVC. This test can confirm if fatigue does cause the opposite results from the previous tests, but it will not confirm if between scenario fatigue, within MVC fatigue, or a combination of the two is what causes the opposite results. Table 14 summarizes the results from Tables 34- 37 from the Appendix.

From these results, it is confirmed that fatigue is causing a decrease in the participants MVC. Comparing the front end off the ON/OFF data to the tail end of the OFF/ON data and the tail end of the ON/OFF data to the front end of the OFF/ON data resulted in an average of 73% rejection when testing if the front end is greater than the tail and the tail end is less than the front end. Determining if these results are caused by fatigue from within the 6 seconds trials or between different 6-second scenarios is difficult, but in either case, future studies need to build in safeguards to prevent fatigue from affecting results.

Chapter IV

STUDY OF THE EFFECT OF STOCHASTIC RESONANCE ELECTRICAL STIMULATION ON MUSCLE FORCE

In literature, it has been proven that SR can act as a way to increase the sensitivity of weak signals, which has demonstrated improvement in tactile sensation [11], muscle spindle output [12], balance control [18, 38], joint position sense [10], and when combined with a knee brace/sleeve, has increased proprioception. Since it said to increase the muscle spindle output, SR stimulation could potentially increase muscle force production [30]. This increase in muscle spindle output could cause counteractive effects for applying SR at the knee joint in attempt to decrease co-contraction. Since the research regarding the effects of SR on muscles force is inconclusive, this chapter discusses the experimental set up, experimental procedure, data analysis, statistical analysis and results for testing the effects of stochastic resonance (SR) electrical stimulation on maximum voluntary contraction (MVC) of the bicep muscle.

4.1 Experimental Setup

The torque sensor set up for this experiment was the same as the set up used in Chapter 3. The torque sensor is connected to a Futek IAA300 analog amplifier. This amplifier is wired

to a 15V power supply and the output signal is wired to a Quanser Q8-USB data acquisition device. The data acquisition device is also used to control the clock of the RehaStim V 1.3 electrical stimulation device. The Rehastim electrical stimulation device is connected to two output channels which both connect to a pair of 1 inch round Axelgaard PALS conductive cloth neurostimulation electrodes. The Quanser board and Rehastim are connected to the simulation laptop via USB and a simulink model is used send the correct stimulation frequency, current and pulse-width to the electrodes. For the data collection Trails, the pulse frequency is fixed at 200 Hz and the current is fixed at 40 mA. Stochastic resonance stimulation is implemented using a varying pulse-width which is randomly generated in a range from zero to 75% of the research participants threshold for detection. The threshold for detection is determined by increasing the pulse-width in increments of 0.25 μs until the research participant can feel the presence of electrical stimulation on their bicep muscle.

The level of 75% of the threshold for detection and 200 Hz pulse frequency is used to replicate the effects used in [9]. 75% is considered to be the level of SR stimulation that can improve proprioception which potentially decreases unwanted co-contraction around the knee during gait. Replicating these effects will determine how an increase in proprioception effects maximum voluntary contraction during stationary contractions. A pulse frequency of 200 Hz is used to mimic the 0-1000 Hz bandwidth Gaussian white noise stimulation frequency used in [9]. A value of 200 Hz is the highest pulse frequency the Rehastim stimulation device was capable of producing.

4.2 Experimental Procedure

In this study, 20 research participants (10 male and 10 female) ages 18-30 were recruited and the following procedures were used to determine the effects of SR stimulation on maximum voluntary contraction. For each data collection session, each research participant was brought into the lab and was required to sign four voluntary consent forms which include a COVID-19 safety measures form for each experiment, and a consent form for vibration and stochastic resonance stimulation. These consent forms and procedures are approved by the Oklahoma State University Institutional Review Board.

After signing all of the consent forms, the participants were assigned a number, to be used as the only participant identifier other than gender. The research assistant then instructed each participant to clean the area around their bicep muscle with an alcohol wipe and then explained where to place the stimulation electrodes. The electrodes used for the trials were one inch round electrodes with one pair placed above the bicep muscle and one pair placed below the bicep. The research assistant would then turn on the electrical stimulation and increase the pulse-width until the research participant could feel the presence of the stimulation. Once the threshold value was determined, the stimulation was turned off and a calculated 75% of this value was used for the remaining tests. The participants were instructed to place their hand underneath the sensor and push upward on the lever arm as hard as they could for the duration of the 5 different scenarios. An image showing the electrode placement is shown in Figure 18 and an image of the experimental set up is shown in Figure 19. The five different scenarios that were performed are shown in table 15.

After each data collection scenario was complete, the data were saved from the MATLAB workspace into a folder for each individual. Each participant was asked to return once more for a repeat trial.

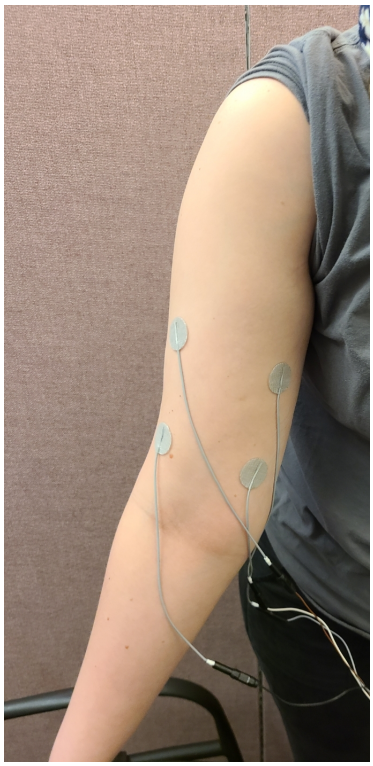

Figure 18: Electrode placement for SR experiment. The channel A electrodes are placed below the participants bicep muscle and channel B electrodes are placed above the bicep muscle.

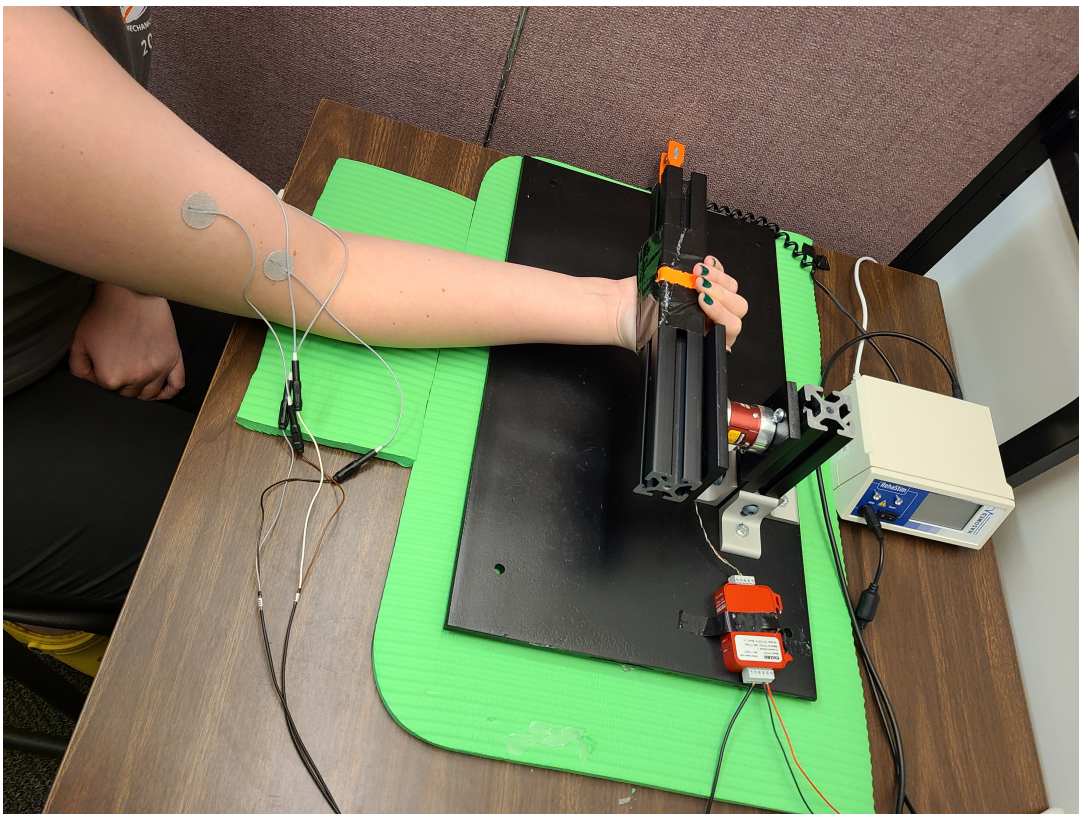

Figure 19: Experimental set up for SR tests. The participant is equipped with the 2 sets of electrodes placed above and below the bicep. The participant places their hand underneath the lever arm of the sensor and pushes up on the lever for each different stimulation scenario.

Scenario	Stimulation Duration	Stimulation Type
Scenario 1a	9s	ON
Scenario 1b	6s	ON
Scenario 2	0s	OFF (control)
Scenario 3	3s	ON/OFF
Scenario 4	3s	OFF/ON

Table 15: Torque sensor data collection scenarios for SR experiment. Scenario 1a is 9s total duration stimulation, but only 6s of maximum voluntary contraction.

The different stimulation scenarios for SR stimulation durations were chosen to determine if short (3-9s) duration SR stimulation has the potential to decrease force production. These scenarios were chosen to mimic those in Chapter 3.

4.3 Data Analysis

After all of the data was collected, the raw voltage signal from the torque sensor was used to calculate the corresponding load in in-lbf. The load values were interpolated from the manufactures calibration sheet. Graphs showing the load vs time for each of the five different scenarios for Trial 1 are shown in Figures 20-24.

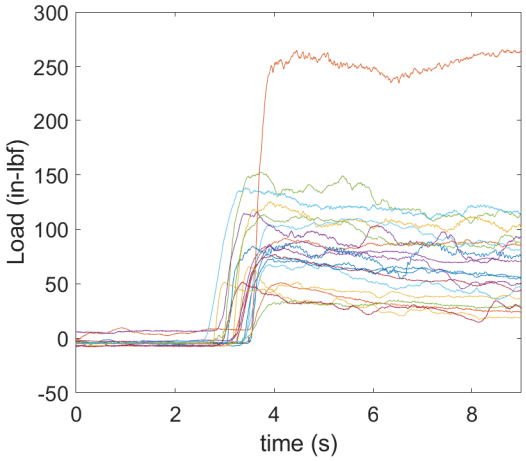

Figure 20: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with stimulation applied for a 9s duration (Scenario 1a).

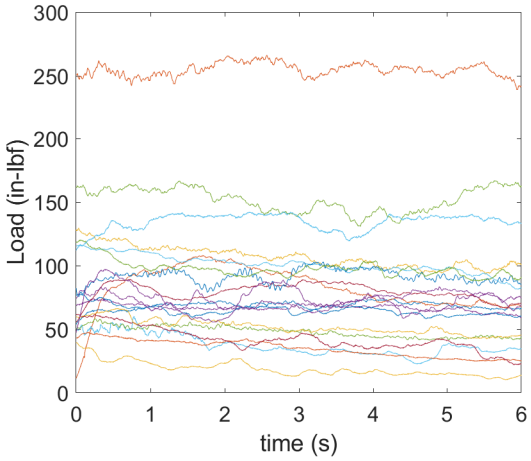

Figure 21: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with full 6s duration stimulation applied (Scenario 1b).

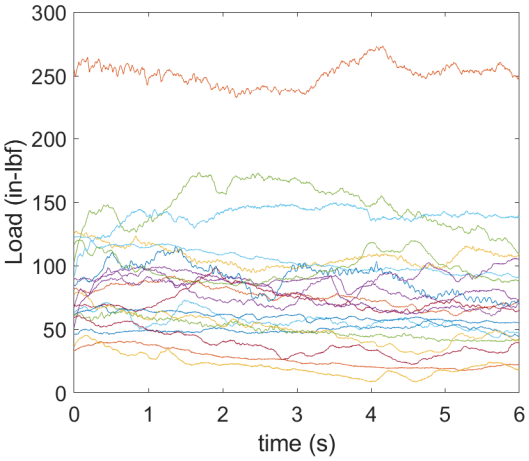

Figure 22: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with no stimulation applied (Scenario 2).

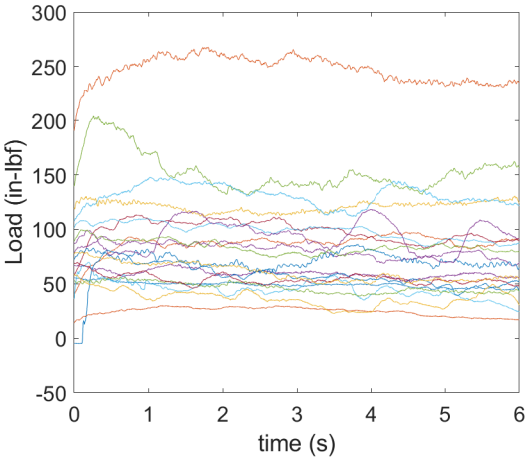

Figure 23: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with 3s duration stimulation applied on the first half of the test (Scenario 3).

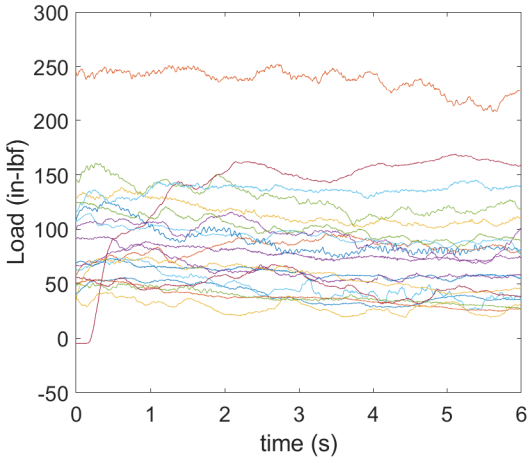

Figure 24: Graph of torque load vs time. The different colors represent each of the individual research participants data. This graph shows the load with 3s stimulation duration applied on the second half of the test (Scenario 4).

4.4 Statistical Analysis

Question	Hypothesis	Test
Are the means of prolonged SR equal to the means of acute?	$H_0 : \mu_p = \mu_a$, $H_a : \mu_p \neq \mu_a$	two-tailed
Are the means of prolonged SR equal to the means of control?	$H_0 : \mu_p = \mu_c$, $H_a : \mu_p \neq \mu_c$	two-tailed
Are the means of acute SR equal to the means of control?	$H_0 : \mu_a = \mu_c$, $H_a : \mu_a \neq \mu_c$	two-tailed
Are the means of acute SR less than or equal to the means of control?	$H_0 : \mu_a = \mu_c$, $H_a : \mu_a \leq \mu_c$	one-tailed
Are the means of prolonged SR less than or equal to the means of control?	$H_0 : \mu_p = \mu_c$, $H_a : \mu_p \leq \mu_c$	one-tailed

Table 16: Statistical test results summary table for SR stimulation. This table includes the question to be answered, the Hypothesis for that question, and which type of test is used to check that hypothesis. μ_p denotes the mean of prolonged stimulation, μ_a denotes the mean of acute stimulation, and μ_c denotes the mean of control condition.

A series of different statistical tests were completed in order to analyze the effects of electrical stimulation on muscle force. A summary of the hypothesis in each the tests is shown in Table 16. Both two-tailed and one-tailed t-test were used on each set of trial data for each individual research participant. The data were first checked for a significant statistical difference in the overall means of the torque sensor measurements using two-tailed tests. The null hypothesis in the 2-tailed tests were that the means were equal and reject-

ing the null hypothesis means that if the means were equal, the data we observed would be statistically unlikely. Next, the data were analyzed using a one-tailed test to check the hypothesis if the means of the torque sensor measurements with electrical stimulation applied were smaller than those without electrical stimulation. For these tests, the alternate hypothesis was that the means for the electrical stimulation tests were less than the means for the control tests, so rejecting the null hypothesis confirms that the results favor the alternate hypothesis. For each of the tests, a level of significance of α=0.05 is used. Detailed per-participant results of the two-tailed t-tests are available in Tables 38-40 in the Appendix.

From the 2-tailed tests, we can conclude that the different scenarios produce different means for the 3 compared interventions. Tables 39 and 40 from the Appendix are summarized in Table 17.

Comparison	Reject	Fail to Reject
Prolonged vs Acute	20	0
Prolonged vs Control	20	0
Acute vs Control	18	2

Table 17: Two-tailed t-test results for SR stimulation summarizing the outcomes of each test.

Now that it is confirmed that the means are unlikely to be equal, a one-tailed tests was used to test against the alternate hypothesis that the SR stimulation mean is less than the control mean. Detailed per-participant results of the one-tailed t-tests are available in Table 41 and Table 42 in the Appendix.

Tables 41 and 42 from the Appendix are summarized in Table 18. Table 18 indicates

that 40% of the research participants produced a decrease in average torque when acute SR stimulation was introduced and 75% of the research participants saw a decrease when prolonged SR stimulation was introduced.

Comparison	Reject	Fail to Reject
Acute Stimulation vs Control	8	12
Prolonged Stimulation vs Control	15	5

Table 18: One-tailed t-test results for SR stimulation summarizing the outcomes of each test

Question	**Hypothesis**	**Test**
Are the first 3 seconds with SR means equal to the next 3s without SR?	$H_0 : \mu_{o1} = \mu_{f2}$, $H_a : \mu_{o1} \neq \mu_{f2}$	two-tailed
Are the first 3 seconds without SR means equal to the next 3s with SR?	$H_0 : \mu_{f1} = \mu_{o2}$, $H_a : \mu_{f1} \neq \mu_{o2}$	two-tailed
Are the first 3 seconds with SR means less than or equal to the next 3s without SR?	$H_0 : \mu_{o1} = \mu_{f2}$, $H_a : \mu_{o1} \leq \mu_{f2}$	one-tailed
Are the first 3 seconds without SR means greater than or equal to the next 3s with SR?	$H_0 : \mu_{f1} = \mu_{o2}$, $H_a : \mu_{f1} \geq \mu_{o2}$	one-tailed

Table 19: Statistical test results summary table for ON/OFF and OFF/ON scenarios for SR stimulation. This table includes the question to be answered, the Hypothesis for that question, and which type of test is used to check that hypothesis. μ_{o1} denotes the ON portion of ON/OFF scenario, μ_{f2} denotes the OFF portion of ON/OFF scenario, μ_{f1} denotes the OFF portion of OFF/ON scenario, and μ_{o2} denotes the ON portion of OFF/ON scenario.

The last data that needed to be analyzed belonged to Scenario 3 (ON/OFF SR stim-

ulation) and Scenario 4 (OFF/ON SR stimulation), to determine if even shorter duration SR stimulation (3s) would produce any difference in force/torque production. A summary of the hypothesis in each of the tests is shown in Table 19. A 2-tailed test was used to determine if the average of the first 3 seconds of the data was different than the next three seconds of data. A one-tailed test was used to determine if the torque with SR stimulation is less than the torque when there is no SR stimulation. Rejecting the null hypothesis for the two-tailed case would mean that if the means of each half of the data were equal, the data we observe would be statistically unlikely. Rejecting the null hypothesis for the one-tailed case would mean that the data favor the alternate hypothesis. For each of these tests, a level of significance of α=0.05 was used. Detailed per-participant results for the two-tailed t-test are available in Table 43 and Table 44 in the Appendix and the results for the one-tailed t-tests are available in Table 45 and Table 46 in the Appendix.

From the two-tailed tests, it is clear that there was a significant difference in the means for Scenario 3 and 4. However, the results from the one-tailed test show that Scenario 3 does not show that SR stimulation decreases the force/torque, but Scenario 4 shows that SR stimulation does causes a decrease in force/torque for the 3s of SR stimulation. Tables 20 and 21 summarize the results in Tables 43-46 from the Appendix.

Comparison	Reject	Fail to Reject
ON/OFF	20	0
OFF/ON	20	0

Table 20: Two-tailed t-test results summarized for Scenarios 3 and 4 for SR stimulation.

Comparison	Reject	Fail to Reject
ON/OFF	3	17
OFF/ON	17	3

Table 21: One-tailed t-test results summarized for Scenarios 3 and 4 for SR stimulation.

Trial 2 was analyzed using the same statistical tests as Trial 1 and the results are in Table 22.

Comparison	Type	Reject	Fail to Reject
Prolonged Vibration vs Acute vibration	2 Tail	19	1
Prolonged vs Control	2 Tail	20	0
Acute Vs Control	2 Tail	20	0
Prolonged vs Control	1 tail	11	9
Acute Vs Control	1 tail	9	11
ON/OFF	2 tail	20	0
OFF/ON	2 tail	19	1
ON/OFF	1 tail	6	14
OFF/ON	1 tail	16	4

Table 22: One-tailed and two-tailed t-test results summarized for Trial 2 for SR stimulation

With the exception of a few participants, the results of Trials 1 and 2 were found to be consistent.

4.5 Results

Instead of comparing the effect of SR stimulation on MVC per individual, to get an idea on the effects on the entire group, a repeated measures ANOVA test was preformed for prolonged vs control, acute vs control, first half of ON/OFF data vs second half, and the first half of the OFF/ON data vs the second half for both Trial 1 and Trial 2. A level significance level of $\alpha = 0.05$ was used to determine strong statistical significance and a significance level of $\alpha = 0.1$ was used to determine weak statistical significance. The results for these tests

are shown in Table 23.

Comparison	Trial	p value	statistical significance
Prolonged SR stimulation vs Control	1	0.001354	Strong
Acute SR stimulation vs Control	1	0.866619	None
ON/OFF	1	7.02E-05	Strong
OFF/ON	1	0.003171	Strong
Prolonged SR stimulation vs Control	2	0.31909	None
Acute SR stimulation vs Control	2	0.713474	None
ON/OFF	2	0.089973	Weak
OFF/ON	2	0.000185	Strong

Table 23: Repeated measures ANOVA results for trial 1 and trial 2 for SR stimulation

The results of the ANOVA tests show that both Trial 1 and Trial 2 resulted in differences for Prolonged SR stimulation vs control and ON/OFF collection scenarios. Since the results only show if the means for each research participant are unequal for a different type of stimulation scenario, it was difficult to determine if there is an increase or a decrease of force/torque when SR stimulation was applied.

Combining these results with the individual one-tailed and two-tailed t-tests, it can be concluded that prolonged SR stimulation has more of an effect on force decrease than acute SR stimulation. Since the results for acute SR stimulation are consistent with no statistical significance, it appears that acute SR stimulation does not effect force production. The prolonged SR stimulation for Trial 1 showed a strong statistical significance, while Trial 2 showed none. This could mean that other factors outside of SR stimulation caused the changes in force. For the 3 second stimulation scenarios, it appears as though the OFF/ON scenario produced a decrease in force, while the ON/OFF scenario produced the opposite. The results of the 3 second stimulation make it clear that shorter 3 second SR stimulation

is probably not what causes the decrease in force production for each research participant. A potential cause for this difference in the 3 second trial decrease for the OFF/ON scenario could be research participant fatigue or a learned strategy from performing the tests multiple times. The learned strategy could result from the research participants knowing their 6 second force production trial is almost up, so this could cause the participant to start decreasing their force prematurely. Although both of these phenomena can not be directly confirmed, they offer a good explanation for why 3 second SR stimulation results may be opposite of one another.

In order to test the validity of the claim of fatigue, statistical tests were done on the ON/OFF and OFF/ON data sets. The statistical tests compared the front end of the ON/OFF data with the tail end of the OFF/ON data. And the other test compared the tail end of the ON/OFF data with the front end of the OFF/ON data. A one-tailed t-test was preformed to test against the alternate hypothesis of the ON/OFF data being greater than the OFF/ON data. The reason for testing them in this way is because the ON/OFF scenario was preformed before the OFF/ON scenario. Comparing the two data sets between scenario 3 and scenario 4 will determine if fatigue takes place when there is not enough break in between scenarios. Similarly, comparing the front end to tail end and tail end to front end of the data determines if fatigue is within the 6 seconds of MVC. This test can confirm if fatigue does cause the opposite results from the previous tests, but it will not confirm if between scenario fatigue, within MVC fatigue, or a combination of the two is what causes the opposite results. Table 24 summarizes the results from Tables 47- 50 from the Appendix.

Comparison	trial	Reject	Fail to Reject
OFF vs OFF (Tail end $\leq$ Front end)	Trial 1	16	4
ON vs ON (Front end $\geq$ Tail end)	Trial 1	13	7
OFF vs OFF (Tail end $\leq$ Front end)	Trial 2	16	4
ON vs ON (Front end $\geq$ Tail end)	Trial 2	16	4

Table 24: One-tailed t-test for SR stimulation results for comparing the front end of the ON/OFF data the the tail end of the OFF/ON data and the tail end of the ON/OFF data to the front end of the OFF/ON data

From these results, it is confirmed that fatigue is causing a decrease in the participants MVC. Comparing the front end off the ON/OFF data to the tail end of the OFF/ON data and the tail end of the ON/OFF data to the front end of the OFF/ON data resulted in an average of 76% rejection when testing if the front end is greater than the tail and the tail end is less than the front end. Determining if these results are caused by fatigue from within the 6 seconds trials or between different 6-second scenarios is difficult, but in either case, future studies need to build in safeguards to prevent fatigue from affecting results.

Chapter V

CONCLUSIONS AND FUTURE WORK

5.1 Validity of Statistical Test Assumptions

Chapter 1 discusses the assumptions that are used for each statistical test used in this thesis. For the t-tests, the assumption of the data being continuous is valid because each participants torque production can be any value within a range. The assumption of each participants mean of MVC data points coming from a normal distribution for the t-tests would be valid if the samples are independent, because the central limit theorem applies, which indicates that the number of samples must be greater than 30 in order to have the distribution of the sample means be approximately normally distributed. Because we are comparing measurements dependent on each subjects ability to produce force, the torque data measurement may not be independent due to fatigue and one participants own muscle dynamics. A potential way to remove the dependency of fatigue is by using a detrending technique as discussed in [49] or to model fatigue similar to [51] and find a way to remove the effect of fatigue from statistical testing. For data sets that are not normally distributed, a MANN Whitney test, which does not require normality could be used. The assumption of population variances being equal was assumed to be reasonable due to the measurement coming from the same sensor throughout all trials. To find out whether the equal variance

assumption had a significant impact on the results, a Welch's t-test was performed. The results from Welch's t-test were consistent with the results from the regular t-test, confirming the validity of the equal variance assumption. The last assumptions for t-tests of the samples being simple random samples from their populations, may be invalid due to all of the samples being from college students ages 18-30. However, for our study, we do not expect factors such as age group or occupation would affect the results. The assumption of independent data for the ANOVA tests is valid because each ANOVA sample comes from a different individual. For the ANOVA tests, because we are comparing participant averages, assuming normal distribution would be similar to claiming that if we had a very large number of people participate in this study, their MVC would be normally distributed due to the dynamics of the bicep muscle for each participant being similar. This is because if the data are samples of normally distributed random variables, then the samples means are normally distributed, regardless of the number of samples. In a similar way, claiming the variance is equal would mean the variance between participants MVC could vary equally.

5.2 Conclusions

From the collected data and the statistical analysis, there is not a clear answer on whether or not vibration and stochastic resonance electrical stimulation directly effect force/torque production. Both OFF/ON and ON/OFF scenarios have been disregarded from the discussion on conclusive results due to fatigue impacting the data.

From the results of the ANOVA for vibration, prolonged vibration had a weak statistical significance for both trial 1 and trial 2. Since this is the only type of vibration that re-

mained consistent between the two trials other than the OFF/ON and ON/OFF scenarios, prolonged stimulation is identified as the most promising intervention method. In one-tailed t-tests for trial 1, 70% of research participants saw a decrease in force production for acute vibration and 75% of participants saw a decrease in for production for prolonged vibration when compared to the control condition. For trial 2, 65% of participants had a force decrease for prolonged vibration, and only 40% for acute vibration, when compared to the control condition. Since prolonged vibration had a higher percentage for both trials and the percentages for acute vibration were very different, the t-tests supports the results of the ANOVA test. Since the results are consistent for both ANOVA and the one-tailed t-test, it can be concluded that prolonged vibration had the largest impact on force reduction for the participants.

One factor that could have caused variability in the data for the vibration trials is plastic shield/sleeve tightness. Depending on how tight the plastic shield and sleeve are placed for each participant, one participant may have more vibration interaction on their muscles than another, which would cause the impacts of the vibration to be less consistent between research participants.

From the results of the ANOVA test for SR stimulation, there were no scenarios other than ON/OFF and OFF/ON stimulation, in which the results of trial 1 agreed with trial 2. In one-tailed t-tests for trial 1, 40% of research participants saw a decrease in force production for acute SR stimulation and 75% of participants saw a decrease in for production for prolonged SR stimulation when compared to the control condition. For trial 2, 55%

of participants had a force decrease for prolonged SR stimulation, and only 45% for acute SR stimulation, when compared to the control condition. Since both acute SR stimulation comparisons produced a low percentage of participants who saw a decrease in force production and prolonged stimulation percentages were very different from trial 1 to trial 2, these varying percentages confirm the results of the ANOVA test. Since the results of ANOVA and the one-tailed t-test are consistent, this statistical analysis confirms that there is not a consistent change in force production when SR stimulation is applied to the bicep muscle during maximum voluntary contraction.

One potential cause of variability in SR data is SR electrode placement. Muscle response to stimulation can change based on how the electrodes are placed on the bicep, and since the research participants are instructed to place the electrodes themselves, difference in electrode placement can cause more variability for between subject comparison.

Some factors that can cause variability in data for all of the experiments could be fatigue, stimulation frequencies and amplitudes, bandwidth of the signals, electrode placement, and participant muscle/fat composition. Fatigue can cause a research participants force/torque production to vary greatly due to loss in muscle strength throughout the multiple scenarios which would make it difficult to determine if the stimulation applied is the actual cause of force reduction. This is why the ON/OFF and OFF/ON scenarios have been discarded from the discussion on stimulation impacts. For both vibration and SR stimulation, stimulation frequencies, amplitudes and bandwidth can potentially change the outcome of each experiment, so exploring a range of values for both frequency and amplitude, may be another way

to explore the effectiveness of these types of stimulation. Lastly, variation in participant skin interaction with the stimulation electrodes or vibration sleeve can cause variability due to the way the stimulation is dissipated through the various tissues to the muscles.

The results from the vibration tests show promise because of the consistency between trials and consistent decrease observed for most research participants when prolonged vibration is introduced. However, incorporation of prolonged vibration in a wearable rehabilitation device may not be practical because the loading phase of the gait cycle appears for less than 1 second. This means vibration would need to be applied before the loading phase, which could potentially decrease overall knee stability during other phases of the gait cycle. Another issue with using vibration as a mechanism to reduce co-contraction is finding the proper motors or vibration device to apply stimulation. Incorporating vibration motors in a knee brace could require smaller motors. The motors that were used for the sleeve in this experiment were small enough to be easily made into a wearable device, and were also producing frequencies high enough to cause a potential decrease in muscle force due to being able to alter how quickly muscle stretch changes [40]. Since both size and frequency produced by the device must be specific, it may be difficult to find motors that are smaller than the ones used in this experiment that are also capable of producing the same frequencies of vibration.

The stochastic resonance electrical stimulation results show less promise in causing a decrease in muscle force production because results were not consistent between the two trials. The methods used in [9] apply stochastic resonance electrical stimulation as a way

to increase proprioception during the gait. Since the effects of stochastic resonance stimulation on maximal contraction are still not known, SR could potentially cause an increase or decrease in co-contraction and could potentially cause undesired effects during gait due to over/under contraction of the muscles surrounding the knee joint. Since there was not a big difference in muscle force production with stochastic resonance stimulation applied, stochastic resonance stimulation may still be a good way to increase proprioception without causing any alterations to gait.

5.3 Future Work

Since the results of both tests were not entirely conclusive, some future tests can be conducted with the same experimental set up but with additional test conditions. One of the conditions that can be added is multiple repeated tests for each different scenario to ensure the research participants are producing consistent maximum voluntary contractions. For the issue of plastic shield/sleeve tightness for the vibration studies, there may be a way to leave off the plastic shield, and make alterations to the vibration sleeve to accomplish the same purpose of the shield. Another addition to the vibration tests would be to change the orientation of the motor sleeve or add more motors around the bicep muscle. The issues with consistent electrode placement for the SR stimulation can be avoided by having the research assistant place the electrodes, which can only be done if COVID-19 safety precautions are taken. For both vibration and electrical stimulation trials, different stimulation frequencies, amplitudes, and bandwidths of the signals should be tested for a difference in muscle contraction. To counter the effects of within experiment or between scenario fatigue, more rest

can be given between scenarios, and the SR experiments and vibration experiments can be conducted on different days. Another potential method for mitigating the effect of fatigue on MVC during the 6 seconds trials is by incorporating a force tracking graph. In [2], the researchers used a method in which research participants were given live torque feedback on a display with a torque curve template for the participants to follow. This template is used as a guide for the participants to follow so that the data remain more consistent. Lastly, an option for solving the issue of variation in muscle/fat composition is by including an exclusion criteria while recruiting for all participants who do not meet a certain BMI or body fat percentage.

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APPENDICES

Statistics Tables from Chapter 3

Subject	Gender	Prolonged Vibration vs Acute Vibration	p value
1	M	Reject	3.39217E-12
2	M	Reject	0.022589625
3	M	Reject	5.0791E-204
4	F	Reject	9.0423E-13
5	M	Reject	0
6	F	Reject	3.8079E-236
7	M	Reject	0
8	F	Reject	3.7916E-06
9	F	Reject	4.07289E-08
10	M	Reject	7.2771E-102
11	F	Reject	1.00784E-05
12	M	Reject	1.97145E-08
13	F	Reject	1.99159E-20
14	F	Reject	6.45169E-11
15	M	Reject	3.70825E-83
16	M	Reject	4.2654E-150
17	F	Reject	8.52148E-46
18	F	Reject	2.92061E-93
19	F	Reject	3.1865E-50
20	M	Reject	0.03849026

Table 25: Two-tailed t-test for vibration comparing the last 6 seconds of scenario 1a (prolonged vibration) vs scenario 1b (acute vibration)

Subject	Gender	Prolonged Vibration vs Control	p value
1	M	Reject	5.8173E-131
2	M	Reject	0.008723776
3	M	Reject	1.22082E-58
4	F	Fail to Reject	0.361530351
5	M	Reject	0
6	F	Reject	9.91493E-27
7	M	Reject	0
8	F	Fail to Reject	0.548396801
9	F	Reject	0.018187872
10	M	Reject	3.70084E-82
11	F	Reject	1.64458E-59
12	M	Reject	6.9427E-209
13	F	Reject	9.4577E-284
14	F	Reject	2.11649E-54
15	M	Reject	6.80718E-53
16	M	Reject	2.02016E-60
17	F	Reject	3.59027E-79
18	F	Reject	2.5027E-130
19	F	Reject	0.000409951
20	M	Reject	4.44417E-10

Table 26: Two-tailed t-test for vibration comparing the last 6 seconds of scenario 1a (prolonged vibration) vs scenario 2 (Control)

Subject	Gender	Acute Vibration vs Control	p value
1	M	Reject	0
2	M	Fail to Reject	0.238126633
3	M	Reject	0
4	F	Reject	1.22756E-27
5	M	Reject	9.64438E-73
6	F	Reject	3.30179E-86
7	M	Reject	0
8	F	Reject	3.67297E-27
9	F	Reject	1.13611E-38
10	M	Reject	0.000282639
11	F	Reject	6.0039E-106
12	M	Reject	0
13	F	Reject	0
14	F	Reject	8.81218E-95
15	M	Reject	8.4386E-43
16	M	Reject	0
17	F	Reject	1.95441E-16
18	F	Reject	1.51805E-19
19	F	Reject	2.81063E-62
20	M	Reject	8.79097E-89

Table 27: Two-tailed t-test for vibration comparing the last 6 seconds of scenario 1b (prolonged vibration) vs scenario 2 (Control)

Subject	Gender	Acute Vibration vs Control	p value
1	M	Reject	0
2	M	Fail to Reject	0.119063317
3	M	Fail to Reject	1
4	F	Reject	6.13779E-28
5	M	Reject	4.82219E-73
6	F	Fail to Reject	1
7	M	Reject	0
8	F	Reject	1.83648E-27
9	F	Reject	5.68056E-39
10	M	Reject	0.00014132
11	F	Reject	3.0019E-106
12	M	Reject	0
13	F	Reject	0
14	F	Fail to Reject	1
15	M	Fail to Reject	1
16	M	Reject	0
17	F	Reject	9.77206E-17
18	F	Reject	7.59023E-20
19	F	Fail to Reject	1
20	M	Reject	4.39548E-89

Table 28: One-tailed t-test results for acute vibration vs control

Subject	Gender	Prolonged Vibration vs Control	p value
1	M	Reject	0
2	M	Reject	1
3	M	Reject	2.245E-174
4	F	Fail to Reject	0.999583491
5	M	Reject	0.010192933
6	F	Reject	5.52789E-58
7	M	Reject	4.7173E-159
8	F	Fail to Reject	1.02528E-08
9	F	Reject	0.602980522
10	M	Fail to Reject	1
11	F	Reject	5.67867E-08
12	M	Reject	0.002530985
13	F	Reject	6.545E-59
14	F	Fail to Reject	6.68454E-64
15	M	Reject	6.90043E-19
16	M	Fail to Reject	1
17	F	Reject	1
18	F	Reject	4.5807E-172
19	F	Reject	0.999999998
20	M	Reject	6.37164E-09

Table 29: One-tailed t-test results for prolonged vibration vs control

Subject	Gender	ON/OFF	p value
1	M	Reject	2.27217E-16
2	M	Reject	2.46036E-38
3	M	Reject	0.008779181
4	F	Reject	3.0084E-201
5	M	Reject	1.11312E-13
6	F	Reject	4.40926E-18
7	M	Reject	1.24233E-10
8	F	Reject	1.1012E-117
9	F	Reject	1.77872E-61
10	M	Reject	2.9074E-133
11	F	Reject	2.4363E-29
12	M	Reject	2.38977E-39
13	F	Fail to Reject	0.978416957
14	F	Reject	2.33599E-82
15	M	Reject	1.06195E-26
16	M	Reject	1.69873E-08
17	F	Reject	2.35439E-06
18	F	Reject	1.7123E-172
19	F	Reject	8.0858E-37
20	M	Reject	2.325E-51

Table 30: Two-tailed t-test results for vibration for scenario 3 comparing 3s of vibration vs 3s with no vibration

Subject	Gender	OFF/ON	p value
1	M	Reject	2.91031E-18
2	M	Reject	4.49464E-11
3	M	Reject	1.1592E-111
4	F	Reject	2.76859E-43
5	M	Reject	2.57576E-59
6	F	Reject	1.2445E-159
7	M	Reject	4.74311E-27
8	F	Reject	9.77001E-23
9	F	Reject	1.7156E-252
10	M	Reject	2.13963E-51
11	F	Reject	4.3651E-160
12	M	Reject	3.78527E-06
13	F	Reject	4.48098E-23
14	F	Reject	2.72087E-53
15	M	Fail to Reject	0.745895883
16	M	Reject	3.84237E-08
17	F	Reject	3.32058E-45
18	F	Fail to Reject	0.209481441
19	F	Reject	1.00563E-88
20	M	Reject	1.07989E-38

Table 31: Two-tailed t-test results for vibration for scenario 4 comparing 3s of no vibration vs 3s with vibration

Subject	Gender	ON/OFF	p value
1	M	Reject	1.13608E-16
2	M	Reject	1.23018E-38
3	M	Reject	0.004389591
4	F	Fail to Reject	1
5	M	Reject	5.56562E-14
6	F	Fail to Reject	1
7	M	Fail to Reject	1
8	F	Fail to Reject	1
9	F	Fail to Reject	1
10	M	Fail to Reject	1
11	F	Fail to Reject	1
12	M	Fail to Reject	1
13	F	Fail to Reject	0.510791522
14	F	Fail to Reject	1
15	M	Fail to Reject	1
16	M	Reject	8.49364E-09
17	F	Fail to Reject	0.999998823
18	F	Fail to Reject	1
19	F	Fail to Reject	1
20	M	Fail to Reject	1

Table 32: One-tailed t-test results for vibration for scenario 3 comparing 3s of vibration vs 3s with no vibration

Subject	Gender	OFF/ON	p value
1	M	Reject	1.45515E-18
2	M	Reject	2.24732E-11
3	M	Reject	5.7962E-112
4	F	Reject	1.38429E-43
5	M	Reject	1.28788E-59
6	F	Reject	6.2224E-160
7	M	Fail to Reject	1
8	F	Reject	4.88501E-23
9	F	Reject	8.5779E-253
10	M	Reject	1.06982E-51
11	F	Reject	2.1825E-160
12	M	Reject	1.89264E-06
13	F	Reject	2.24049E-23
14	F	Reject	1.36044E-53
15	M	Fail to Reject	0.627052058
16	M	Reject	1.92119E-08
17	F	Reject	1.66029E-45
18	F	Fail to Reject	0.104740721
19	F	Reject	5.02815E-89
20	M	Reject	5.39944E-39

Table 33: One-tailed t-test results for vibration for scenario 4 comparing 3s of no vibration vs 3s with vibration

Subject	Gender	OFF vs OFF	p value
1	M	Reject	2.58959E-39
2	M	Reject	4.90e-324
3	M	Fail to Reject	1
4	F	Reject	1.3689E-222
5	M	Fail to Reject	1
6	F	Reject	1.5703E-122
7	M	Reject	9.1427E-186
8	F	Reject	4.17364E-71
9	F	Reject	7.4722E-215
10	M	Reject	1.61284E-36
11	F	Reject	4.5517E-156
12	M	Reject	4.685E-137
13	F	Reject	4.9432E-268
14	F	Reject	0.037822212
15	M	Fail to Reject	0.944264926
16	M	Reject	9.33638E-45
17	F	Reject	7.0334E-101
18	F	Reject	4.68459E-35
19	F	Reject	2.08587E-92
20	M	Reject	5.5227E-51

Table 34: One-tailed t-test results for vibration trial 1 comparing the OFF data from the ON/OFF scenario to the OFF data from the OFF/ON scenario.

Subject	Gender	ON vs ON	p value
1	M	Fail to Reject	1
2	M	Fail to Reject	1
3	M	Reject	4.8839E-227
4	F	Reject	1.04633E-18
5	M	Reject	4.92569E-59
6	F	Reject	3.07418E-05
7	M	Fail to Reject	1
8	F	Reject	3.53956E-51
9	F	Reject	2.78687E-58
10	M	Reject	7.3573E-154
11	F	Reject	3.25376E-34
12	M	Fail to Reject	1
13	F	Fail to Reject	1
14	F	Reject	5.9018E-237
15	M	Reject	1.3997E-123
16	M	Fail to Reject	1
17	F	Fail to Reject	0.75556159
18	F	Reject	1.38833E-66
19	F	Reject	8.5501E-35
20	M	Reject	5.79477E-41

Table 35: One-tailed t-test results for vibration trial 1 comparing the ON data from the ON/OFF scenario to the ON data from the OFF/ON scenario.

Subject	Gender	OFF vs OFF	p value
1	M	Fail to Reject	6.3416E-176
2	M	Reject	1
3	M	Fail to Reject	6.32667E-11
4	F	Reject	1
5	M	Reject	1
6	F	Fail to Reject	1.51128E-38
7	M	Reject	1
8	F	Reject	1
9	F	Reject	1
10	M	Reject	1
11	F	Fail to Reject	3.5745E-16
12	M	Reject	1
13	F	Reject	1
14	F	Reject	1
15	M	Reject	1
16	M	Fail to Reject	0.011393369
17	F	Reject	1
18	F	Reject	1
19	F	Fail to Reject	6.7393E-08
20	M	Fail to Reject	1.1338E-139

Table 36: One-tailed t-test results for vibration trial 2 comparing the OFF data from the ON/OFF scenario to the OFF data from the OFF/ON scenario.

Subject	Gender	ON vs ON	p value
1	M	Reject	9.55944E-31
2	M	Reject	5.20534E-24
3	M	Reject	2.0374E-278
4	F	Fail to Reject	0.999443741
5	M	Reject	2.3697E-114
6	F	Reject	1.7434E-191
7	M	Fail to Reject	1
8	F	Reject	2.2308E-139
9	F	Fail to Reject	1
10	M	Reject	2.32632E-46
11	F	Reject	2.0757E-303
12	M	Reject	2.6968E-223
13	F	Reject	5.5898E-204
14	F	Reject	1.46894E-30
15	M	Reject	5.56659E-47
16	M	Reject	1.9644E-188
17	F	Reject	6.39209E-29
18	F	Fail to Reject	0.37976837
19	F	Fail to Reject	0.9999992
20	M	Reject	2.5661E-216

Table 37: One-tailed t-test results for vibration trial 2 comparing the ON data from the ON/OFF scenario to the ON data from the OFF/ON scenario.

Subject	Gender	Prolonged Stimulation vs Acute Stimulation	p value
1	M	Reject	0
2	M	Reject	3.29506E-18
3	M	Reject	1.29905E-43
4	F	Reject	1.29523E-76
5	M	Reject	0
6	F	Reject	4.53241300000000e-317
7	M	Reject	0
8	F	Reject	6.7996E-185
9	F	Reject	2.6609E-139
10	M	Reject	0
11	F	Reject	2.3494E-237
12	M	Reject	0
13	F	Reject	1.696E-223
14	F	Reject	0
15	M	Reject	0
16	M	Reject	7.456E-200
17	F	Reject	0
18	F	Reject	0
19	F	Reject	1.19063E-87
20	M	Reject	0

Table 38: Two-tailed t-test for SR stimulation comparing the last 6 seconds of scenario 1a (prolonged stimulation) vs scenario 1b (acute stimulation)

Statistics Tables from Chapter 4

Subject	Gender	Prolonged Stimulation vs Control	p value
1	M	Reject	3.3968E-236
2	M	Reject	4.35425E-31
3	M	Reject	1.58967E-48
4	F	Reject	0
5	M	Reject	0
6	F	Reject	2.5805E-290
7	M	Reject	0
8	F	Reject	7.05376E-35
9	F	Reject	2.22171E-68
10	M	Reject	3.6987E-240
11	F	Reject	0
12	M	Reject	0
13	F	Reject	2.57000000000000e-322
14	F	Reject	0
15	M	Reject	0
16	M	Reject	5.107E-158
17	F	Reject	0
18	F	Reject	2.0454E-101
19	F	Reject	1.07443E-80
20	M	Reject	0

Table 39: Two-tailed t-test for SR stimulation comparing the last 6 seconds of scenario 1a (prolonged stimulation) vs scenario 2 (Control)

Subject	Gender	Acute Stimulation vs Control	p value
1	M	Reject	0
2	M	Reject	8.0758E-152
3	M	Fail to Reject	0.145030027
4	F	Reject	0
5	M	Reject	9.52881E-77
6	F	Reject	0
7	M	Reject	0
8	F	Reject	0
9	F	Reject	0
10	M	Reject	9.3685E-101
11	F	Reject	6.15151E-97
12	M	Reject	1.12785E-60
13	F	Reject	1.45451E-85
14	F	Reject	9.539E-109
15	M	Reject	8.87371E-14
16	M	Reject	5.0191E-132
17	F	Reject	1.9E-20
18	F	Reject	0
19	F	Fail to Reject	0.130217419
20	M	Reject	2.3157E-223

Table 40: Two-tailed t-test for SR stimulation comparing the last 6 seconds of scenario 1b (prolonged stimulation) vs scenario 2 (Control)

Subject	Gender	Acute vs Control	p value
1	M	Fail to Reject	1
2	M	Fail to Reject	1
3	M	Fail to Reject	0.072515013
4	F	Reject	0
5	M	Fail to Reject	1
6	F	Reject	0
7	M	Fail to Reject	1
8	F	Fail to Reject	1
9	F	Fail to Reject	1
10	M	Reject	4.6843E-101
11	F	Reject	3.07576E-97
12	M	Reject	5.63924E-61
13	F	Reject	7.27255E-86
14	F	Fail to Reject	1
15	M	Fail to Reject	1
16	M	Fail to Reject	1
17	F	Fail to Reject	1
18	F	Reject	0
19	F	Fail to Reject	0.06510871
20	M	Reject	1.1579E-223

Table 41: One-tailed t-test results for acute SR stimulation vs control

Subject	Gender	Prolonged vs Control	p value
1	M	Fail to reject	1
2	M	Fail to reject	1
3	M	Reject	7.94837E-49
4	F	Reject	0
5	M	Reject	0
6	F	Reject	1.2903E-290
7	M	Reject	0
8	F	Reject	3.52688E-35
9	F	Fail to reject	1
10	M	Fail to reject	1
11	F	Reject	0
12	M	Reject	0
13	F	Reject	1.30000000000000e-322
14	F	Reject	0
15	M	Reject	0
16	M	Reject	2.5535E-158
17	F	Reject	0
18	F	Fail to reject	1
19	F	Reject	5.37215E-81
20	M	Reject	0

Table 42: One-tailed t-test results for prolonged SR stimulation vs control

Subject	Gender	ON/OFF	p value
1	M	Reject	0
2	M	Reject	1.3244E-201
3	M	Reject	9.9612E-142
4	F	Reject	0
5	M	Reject	8.8892E-161
6	F	Reject	3.1696E-242
7	M	Reject	0
8	F	Reject	2.3063E-199
9	F	Reject	0
10	M	Reject	0
11	F	Reject	0
12	M	Reject	0
13	F	Reject	0
14	F	Reject	3.04708E-98
15	M	Reject	8.11962E-18
16	M	Reject	3.4392E-279
17	F	Reject	0
18	F	Reject	2.08404E-24
19	F	Reject	0
20	M	Reject	0

Table 43: Two-tailed t-test results for SR stimulation for scenario 3 comparing 3s of no stimulation vs 3s with stimulation

Subject	Gender	OFF/ON	p value
1	M	Reject	0
2	M	Reject	6.1875E-301
3	M	Reject	0
4	F	Reject	0
5	M	Reject	0
6	F	Reject	0
7	M	Reject	0
8	F	Reject	0
9	F	Reject	0
10	M	Reject	0
11	F	Reject	0
12	M	Reject	0
13	F	Reject	0
14	F	Reject	0
15	M	Reject	0
16	M	Reject	0
17	F	Reject	0
18	F	Reject	0
19	F	Reject	0
20	M	Reject	2.15692E-15

Table 44: Two-tailed t-test results for SR stimulation for scenario 3 comparing 3s of stimulation vs 3s with no stimulation

Subject	Gender	ON/OFF	p value
1	M	Fail to Reject	1
2	M	Reject	6.6222E-202
3	M	Reject	4.9806E-142
4	F	Fail to Reject	1
5	M	Fail to Reject	1
6	F	Fail to Reject	1
7	M	Fail to Reject	1
8	F	Fail to Reject	1
9	F	Fail to Reject	1
10	M	Fail to Reject	1
11	F	Fail to Reject	1
12	M	Fail to Reject	1
13	F	Fail to Reject	1
14	F	Fail to Reject	1
15	M	Reject	4.05981E-18
16	M	Fail to Reject	1
17	F	Fail to Reject	1
18	F	Fail to Reject	1
19	F	Fail to Reject	1
20	M	Fail to Reject	1

Table 45: One-tailed t-test results for SR stimulation for scenario 3 comparing 3s of stimulation vs 3s with no stimulation

Subject	Gender	OFF/ON	p value
1	M	Reject	0
2	M	Fail to Reject	1
3	M	Reject	0
4	F	Reject	0
5	M	Reject	0
6	F	Reject	0
7	M	Fail to Reject	1
8	F	Reject	0
9	F	Reject	0
10	M	Reject	0
11	F	Reject	0
12	M	Reject	0
13	F	Reject	0
14	F	Reject	0
15	M	Reject	0
16	M	Reject	0
17	F	Reject	0
18	F	Reject	0
19	F	Reject	0
20	M	Fail to Reject	1

Table 46: One-tailed t-test results for SR stimulation for scenario 4 comparing 3s of no stimulation vs 3s with stimulation

Subject	Gender	OFF vs OFF	p value
1	M	Reject	7.2115E-13
2	M	Fail to Reject	1
3	M	Reject	0.001571403
4	F	Reject	0
5	M	Fail to Reject	1
6	F	Reject	0
7	M	Reject	9.7099E-198
8	F	Reject	0
9	F	Reject	0
10	M	Fail to Reject	1
11	F	Fail to Reject	1
12	M	Reject	2.54171E-31
13	F	Reject	0
14	F	Reject	4.29846E-23
15	M	Reject	0
16	M	Reject	3.94208E-39
17	F	Reject	0
18	F	Reject	0
19	F	Reject	0
20	M	Reject	0

Table 47: One-tailed t-test results for SR stimulation trial 1 comparing the OFF data from the ON/OFF scenario to the OFF data from the OFF/ON scenario.

Subject	Gender	ON vs ON	p value
1	M	Reject	0
2	M	Fail to Reject	1
3	M	Reject	0
4	F	Fail to Reject	1
5	M	Reject	0
6	F	Reject	0
7	M	Fail to Reject	1
8	F	Reject	6.94805E-65
9	F	Fail to Reject	1
10	M	Reject	0
11	F	Reject	0
12	M	Reject	0
13	F	Reject	0
14	F	Reject	0
15	M	Fail to Reject	1
16	M	Reject	0
17	F	Reject	0
18	F	Reject	0
19	F	Fail to Reject	1
20	M	Fail to Reject	0.999998932

Table 48: One-tailed t-test results for SR stimulation trial 1 comparing the ON data from the ON/OFF scenario to the ON data from the OFF/ON scenario.

Subject	Gender	OFF vs OFF	p value
1	M	Reject	2.18063E-87
2	M	Reject	0
3	M	Reject	0
4	F	Fail to Reject	1
5	M	Reject	0
6	F	Reject	0
7	M	Fail to Reject	1
8	F	Reject	1.3159E-228
9	F	Reject	0
10	M	Reject	3.0721E-216
11	F	Reject	7.59e-311
12	M	Reject	0
13	F	Reject	0
14	F	Reject	0
15	M	Reject	0
16	M	Reject	0
17	F	Fail to Reject	1
18	F	Fail to Reject	1
19	F	Reject	7.7253E-107
20	M	Reject	0

Table 49: One-tailed t-test results for SR stimulation trial 2 comparing the OFF data from the ON/OFF scenario to the OFF data from the OFF/ON scenario.

Subject	Gender	ON vs ON	p value
1	M	Reject	1.79429E-10
2	M	Reject	1.8201E-115
3	M	Reject	7.372E-161
4	F	Reject	0
5	M	Fail to Reject	1
6	F	Reject	2.7137E-285
7	M	Reject	0
8	F	Reject	0
9	F	Fail to Reject	1
10	M	Reject	3.49581730000000e-317
11	F	Reject	3.5944E-111
12	M	Reject	0
13	F	Reject	1.5411E-106
14	F	Reject	0
15	M	Reject	1.0088E-146
16	M	Reject	0
17	F	Fail to Reject	1
18	F	Reject	0
19	F	Reject	0
20	M	Fail to Reject	1

Table 50: One-tailed t-test results for SR stimulation trial 2 comparing the ON data from the ON/OFF scenario to the ON data from the OFF/ON scenario.

Oklahoma State University Institutional Review Board

Date:	10/07/2020
Application Number:	IRB-20-394
Proposal Title:	Quantification of the effects of low intensity electrical stimulation on muscle contraction
Principal Investigator:	Rushi Kamalapurkar
Co-Investigator(s):	Jerome Hausselle
Faculty Adviser:	
Project Coordinator:	
Research Assistant(s):	Katrine Hareland
Processed as:	Expedited
Expedited Category:	

Status Recommended by Reviewer(s): Approved

Approval Date: 10/06/2020

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

This study meets criteria in the Revised Common Rule, as well as, one or more of the circumstances for which continuing review is not required. As Principal Investigator of this research, you will be required to submit a status report to the IRB triennially.

The final versions of any recruitment, consent, and assent documents bearing the IRB approval stamp are available for download from IRBManager. These are the versions that must be used during the study.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be approved by the IRB. Protocol modifications requiring approval may include changes to the title, PI, adviser, other research personnel, funding status or sponsor, subject population composition or size, recruitment, inclusion/exclusion criteria, research site, research procedures and consent/assent process or forms.
2. Submit a status report to the IRB when requested
3. Promptly report to the IRB any harm experienced by a participant that is both unanticipated and related per IRB policy.
4. Maintain accurate and complete study records for evaluation by the OSU IRB and, if applicable, inspection by regulatory agencies and/or the study sponsor.
5. Notify the IRB office when your research project is complete or when you are no longer affiliated with Oklahoma State University.

If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB Office at 405-744-3377 or irb@okstate.edu.

Sincerely,
Oklahoma State University IRB

Oklahoma State University Institutional Review Board

Date:	01/29/2020
Application Number:	EN-19-24
Proposal Title:	Quantification of the effects of vibration on muscle contraction
Principal Investigator:	Rushi Kamalapurkar
Co-Investigator(s):	Jerome Hausselle
Faculty Adviser:	
Project Coordinator:	
Research Assistant(s):	Katrine Hareland
Processed as:	Expedited
Expedited Category:	

Status Recommended by Reviewer(s): Approved
Approval Date: 01/29/2020

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

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2. Submit a status report to the IRB when requested
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Sincerely,
Oklahoma State University IRB

VITA

Katrine Jacqueline Marie Hareland

Candidate for the Degree of

Master of Science

Thesis: IMPACT OF VIBRATION AND STOCHASTIC RESONANCE ELECTRICAL STIMULATION ON MUSCLE CONTRACTION

Major Field: Mechanical Engineering

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