FUNCTIONAL ELECTRICAL STIMULATION RECUMBENT BICYCLE FOR STROKE REHABILITATION

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By

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In dedication to my loving wife

Rosanne Guy

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

FUNCTIONAL ELECTRICAL STIMULATION RECUMBENT BICYCLE FOR STROKE REHABILITATION

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Stroke is a severe condition that is one of the leading causes to both disabilities and death in the United States. A stroke occurs when blood stops flowing to the brain. It only takes minutes without blood before the brain cells begin to be damaged and even die. Up to 90 percent of people who survive a stroke suffer from some form of paralysis. It is common among stroke patients to experience hemiparesis which paralyses on one side of the body. Functional remodeling of the brain can improve sensation and motor control. However, muscles and nerves degrade (atrophy) over time with disuse. The more a muscle atrophies the longer it takes to rehabilitate that muscle and the degree of recovery is reduced. Functional Electrical Stimulation (FES) can artificially stimulate these muscles and nerves. FES has been proven to be a viable tool for the rehabilitation of atrophied muscles and nerves. The purpose of this thesis project was to design, build and test a Functional Electrical Stimulation (FES) recumbent bicycle that can be used for stroke rehabilitation.

An off the shelf FES device was researched and analyzed to determine its capabilities. A circuit was then designed using a recumbent bicycle as the test bed and a Labview program was written as the control mechanism for the FES device. The data collection

was done by an optical encoder mounted onto the recumbent bicycle. The system was programmed using Labview for both control and data collection. After the completion of the recumbent bicycle, the protocol and methods were created to provide guidelines for the testing and data analysis. With these guidelines in place, human subject testing could be conducted. The twelve subjects were tested. Electrodes were attached to their thighs and stimulated using the FES device which was controlled by the Labview program. Each participant performed six trials, three with the FES device operating and three with the FES device switched off.

The results showed that there were no statistical difference between the test groups, except for the females only group. The female test group pedalled slower with the FES device switched on then with the FES device off. This research showed that the quality of movement was sufficient to allow cycling assisted by FES on the recumbent bicycle. These results may be encouraging for stroke patients with partial hemiparesis and other forms of paralysis to assist them during rehabilitation.

The future for FES systems are continuing to progress in a positive direction. This research in conjunction with other research in the biomedical engineering field are enabling new therapy methods that have the potential to improve the quality of life for stroke patients. The FES research completed for the recumbent bicycle showed that the device was capable of properly controlling the leg and propelling it forward with enough power to push the pedal. The experimental study showed that the quality of movement was sufficient to allow cycling assisted by FES on a Recumbent Bicycle. In fact, no statistical differences were found between normal cycling and FES assisted cycling for most groups studied. Initial testing seems suitable for future studies that assist with stroke patients during rehabilitation.

CHAPTER 1: INTRODUCTION

1.1 Stroke

Stroke is a severe condition that is one of the leading causes to both disabilities and death in the United States. A stroke occurs when blood stops flowing to the brain. It only takes minutes without blood before the brain cells begin to be damaged and even die. Strokes have two major causes, a blood clot that blocks a blood vessel supplying oxygen to the brain, or when a blood vessel breaks and the blood supply cannot reach the brain for a short period of time and blood leaks into the brain [1]. Strokes that are caused by blood clots are known as an ischemic stroke. The strokes caused by busted blood vessels are known as hemorrhagic stroke. Ischemic strokes are the more common and better the better known of the two types of strokes.

1.2 Paralysis

Paralysis is when a person is unable to voluntarily control their muscle or a group of muscles. Muscles rely on an electrical impulse provided by the brain to move. When the brain is damaged and losses brain cells it can lose vital connections that control motor functions within the body. These loses in motor function are sometimes referred to as movement impairments since the person might not lose complete control of a certain bodily function, but it could be less effective or responsive as prior to the stroke. Up to 90 percent of the people that survive a stroke suffer from some sort of paralysis [1]. Thus, there is a large percentage of the population affected by post stroke paralysis of some sort. It is common amongst stroke patients to experience hemiparesis in which paralysis occurs on only one side of the body. The reason for this is that the brain is divided into two separate hemispheres, the right hemisphere and the left hemisphere. Each hemisphere controls the opposite side of the body. So the right hemisphere controls the functions on the left side of the body, while the left hemisphere controls the right side of the body. As stated previously in the stroke section, the most common form of stroke is an ischemic stroke. Since a clot in a blood vessel most commonly only prevents blood flow to one hemisphere of brain this means that only one side of the brain is usually damaged in a ischemic stroke. This is why one-sided paralysis occurs so frequently in stroke patients. Hemiparesis affects roughly 80 percent of the people who have suffered a stroke [1]. This means that only roughly 10 percent of the people who suffer from some sort of paralysis after a stroke do not show signs of hemiparesis. Hemiparesis is an important area for rehabilitation engineering to focus since it encompasses such a large population. There are many opportunities for rehabilitation of stroke patients since the brain is capable of rewiring itself to repair broken connections. This is not all ways the case in the most sever examples of paralysis such as locked-in syndrome, were the person is only able to move his or her eyes and has no function of any other muscles.

Fortunately, most stroke victims though tend to recover their bodily functions over time while the brain repairs itself. During this process it is important to keep the body from degrading from muscle and nerve atrophy. Atrophy is when a part of the body begins to deteriorate [2]. This deterioration can occur in multiple ways such as malnutrition, poor circulation or disuse of the muscle or nerves. Amongst stroke patients, people who suffer from paralysis atrophy are most commonly associated with the disuse of a muscle do the lack of voluntary control. This type of muscle atrophy is also a concern for astronauts since they do not have the earth's gravity to work their muscles. That is why it is important for them to continuously exercise in space to maintain muscle mass and prevent atrophy. The more a muscle deteriorates from atrophy the harder and longer it takes to rehabilitate that muscle. This is why it is important to address this issue early and, if possible, even prevent it from starting.

1.3 Functional Electrical Stimulation

Functional Electrical Stimulation (FES) is primarily used in therapy and rehabilitation treatments for people who have a lack of muscle control or the complete inability to control their muscles voluntarily. These symptoms are usually due to severe spinal cord injury or other injuries that would cause nervous system damage that affect the movement and control of body parts [3]. FES is applied to the uncontrollable or dormant muscles to reactivate them and attempt to improve muscle functionality. An FES device applies a small current to the dormant muscle causing the muscle to contract. This contraction is called a muscle twitch. This type of muscle twitch is artificially induced by the electrical current supplied by the FES device [4]. The muscle twitch can be controlled by increasing or decreasing amplitude of the FES current. As the amplitude is increased, the strength of the muscle twitch becomes greater, but the muscle will also fatigue faster if this is done [5].

FES has proven to be an effective form a rehabilitation amongst stroke victims [6]. FES treatment has also been used for spinal cord treatment by applying the stimulation directly to the peripheral nerves that innervate muscles. In multiple clinical studies both external and implanted FES devices have been successfully developed and implemented [7] [8]. These implanted devices can be used for neuromuscular electrical stimulation, which is a more accurate and refined approach towards electrical stimulation [9]. Electrical stimulation systems have even been developed that are safe for the elderly [10].

FES has experienced a recent growth in the field of biomedical engineering and has become more advanced in its capabilities. FES is used for quadriplegics who are unable to perform muscle movements and have a need for assistive devices [11]. This has become more common as the information and the knowledge about FES has grown, but with some of the more advanced devices there are issues with convenience and ease of use. Chiou et. al. [12] performed a study to restore hand function using FES. Studies were also done by Lemay et. al. [13] in testing wrist flexion/extension in quadriplegics. The basis for this study was not to completely use FES as a form of control, but to analyze and create a profile of the muscle groups [14]. This means that to trigger certain responses in the hand a specific set of muscle groups are triggered and that response causes a specific reaction [15]. In this study they also created templates of where the functional electrical stimulator needed to be activated for desired responses. This test and setup gave valuable information on how functional electrical stimulation could be used as a form of muscle control that would actually control hand functions. This is an important step toward functional electrical stimulation being used in a way that could improve people's quality of life [16]. This type of functionality is a more precise form of control that requires a rigorous set of parameters to perform them properly [17].

1.4 Recumbent Bicycle

Test on cyclic motion were done by Stites and Abbas [18] which lead to progressing the research to a real world application. There are many different types of bicycle styles that all offer their own purposes and reasoning for their design. One example is the mountain bike design. It has uses two large tires with large treads that are optimized for gripping to off-road environments. A mountain bike is also designed for a rider to be able to ride in an upright position or a leaned forward position, to get a lower center of gravity. They also have shock absorbers built into the bike frame to reduce the force felt by the rider while riding over rough terrain. These are all design options to create a bicycle that provides a certain set of parameters for specific applications. Recumbent bicycles are a style that place the rider in a leaning back position. The rider sits on a seat that is inclined backwards at varying degrees depending on the design, and offers back support for the rider. This style of seat also provides a comfortable riding position since the riders body weight is spread across both the buttocks and back of the body. This is a better health option that a traditional bike that primarily places the body weight on only a small seat putting pressure on the ischium (sitting bones of the pelvis).

1.5 Objective

The objective of this research project was to develop a recumbent exercise bicycle with functional electrical stimulation capability that is able to help patients with hemiparesis recover motor function in the paralyzed leg. The scope of the project includes the design and construction of the FES bike and testing of its performance utilizing normal healthy young adults.

CHAPTER 2: FES BICYLE DESIGN AND CONSTRUCTION

A study on existing FES technology will be performed in section 2.1. Section 2.2 will cover the design and development of a FES control circuit. It will also describe how to control a FES device using LabVIEW. Section 2.3 contains a brief overview of the equipment that will be used to run the test.

2.1 Existing FES Device

In any design project it is important to understand the components that will be used. Test were ran by Liu et. al. [19] to test their FES system. A key component used in this project was the EMS 5000 (FES device). The first step was to investigate the FES device and assess how the device was actually functioning. This included capturing the waveform to evaluate its rise time and shape. The purpose of this test was for safety concerns to make sure that there would not be any sudden spikes in voltage upon connection and disconnection. This test was conducted by analyzing steady-state and non-steady state voltage to determine if there were any differences in the device behavior if the connection was disconnected and reconnected at random intervals.

The FES device was attached directly to an oscilloscope to record the different responses the device had when placed into different states. The first test was to see how the device ramped up to its peak voltage. This was to done to obtain the shape of the waveform as the voltage built up to the steady state. The Oscilloscope was set to capture the waveform 10ns after the voltage exceeded a threshold of 20v. This test was run using amplitude settings of 3, 4, 5, 6, 7, and 8. It is important to note that the numbers on the knob do not directly indicate the amplitude setting.

After determining the normal ramp rate, the next step was to test the steady state of the device and observe the shape of the waveform. The waveforms can be seen in the steady state portion in Figure 2.1. The configuration for this test was slightly different from the non-steady state test. For this test the FES device was set to maintain a constant voltage and the waveform was captured. Finally the device was left in the steady state, but the oscilloscope was disconnected from one of the leads. The oscilloscope was then set to capture the waveform after the voltage had crossed a certain threshold. This part of the experiment was similar to how the results were recorded for the non-steady state test.

No differences were observed in the output of the FES device when operated in the steady-state and when it was connected and disconnected. There was no impulse when the device was connected to the oscilloscope while the cycles were in steady state. This result is due to the fact that once the FES device reaches a certain voltage state it stays at a constant voltage level. This result also shows that this device is using a constant voltage source instead of a constant current source. If the FES device was a constant current source, then you would see a massive spike in voltage after connecting to the device to an object with a higher resistance.

Testing for voltage spikes was crucial to ensure the safety of people connected to the device as it was turned on and off. The FES device has no change in states whether the connection is manually broken or if it continues to run and shut off by itself. Once the FES device reached steady state, there were no impulses that occurred when the device was connected and disconnected. Because these test results showed that no spikes occurred during connecting and disconnecting the control circuit for switching on and off the FES can simply be a relay without the need to ramp up or down the voltage. This will make the switching circuit much easier to design and build. Since this device is using a constant voltage, then there is no concern with using a simple switching mechanism to control the voltage to the pads.

This data can be seen in Figure 2.1, and it shows the columns of graphs collected from the FES analysis test. The first column shows the device output as it is ramping up to maximum voltage for the current setting on the FES device . The second and third columns are both when the device had reached a steady state. The second column shows the FES device while it is continuously connected to the oscilloscope. While the third column represents the FES device after it has already reached its steady state output and is manually disconnect and reconnected to the circuit.

It is an important part of any experiment to know the effects that the main device will have. The FES applies a voltage to two conductive pads which cause electricity to flow through the muscles causing it to contract. Since a current is being applied to the human body this test was designed to evaluate the effects of prolonged use on a high device setting. The high setting for this test was a value of seven which was able to force the muscle in the arm to have complete contractions and lift the arm. When this was achieved the test was ran for 10 minutes with 1 minute of active muscle stimulation and 3 seconds of relaxation. The picture below shows the effects of the FES being applied to the bicep.

The marks in Figure 2.2 above show small spots, located at the base of the bicep, where one of the pads was placed. The spots were dark red, but they were not raised. The spots did not cause any discomfort or lasting effects. The spots lasted for two days and got lighter with each passing day. This same test was run, but the probes were placed on the forearm and were made to lift up the hand. The device was put at the same settings and ran for the same amount of time. Spots did not appear when the test was ran on the forearm,

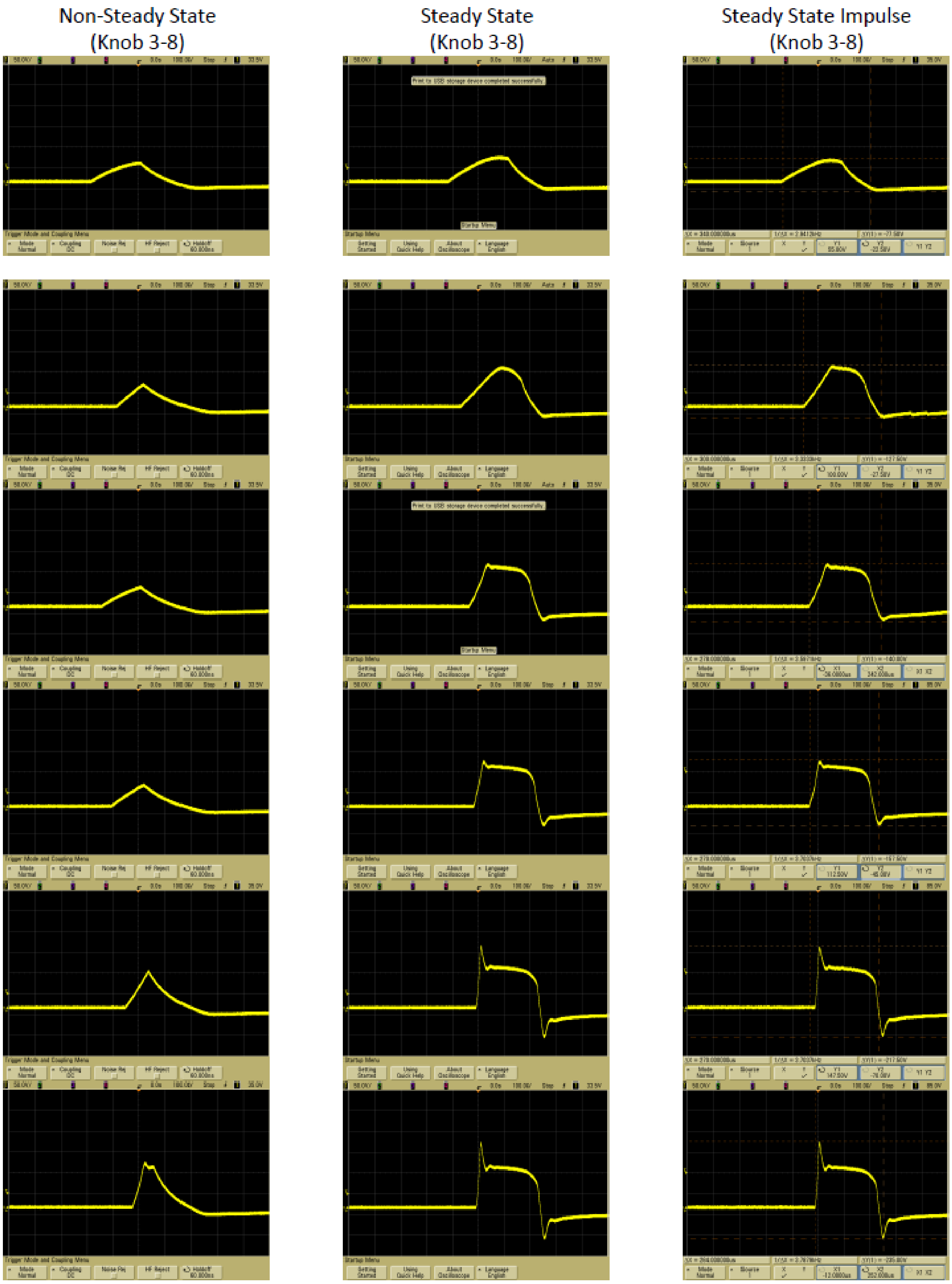

Figure 2.1: Waveform of EMS 5000 with a horizontal scale of $20\frac{ns}{div}$ and a vertical scale of $20\ \frac{v}{div}$

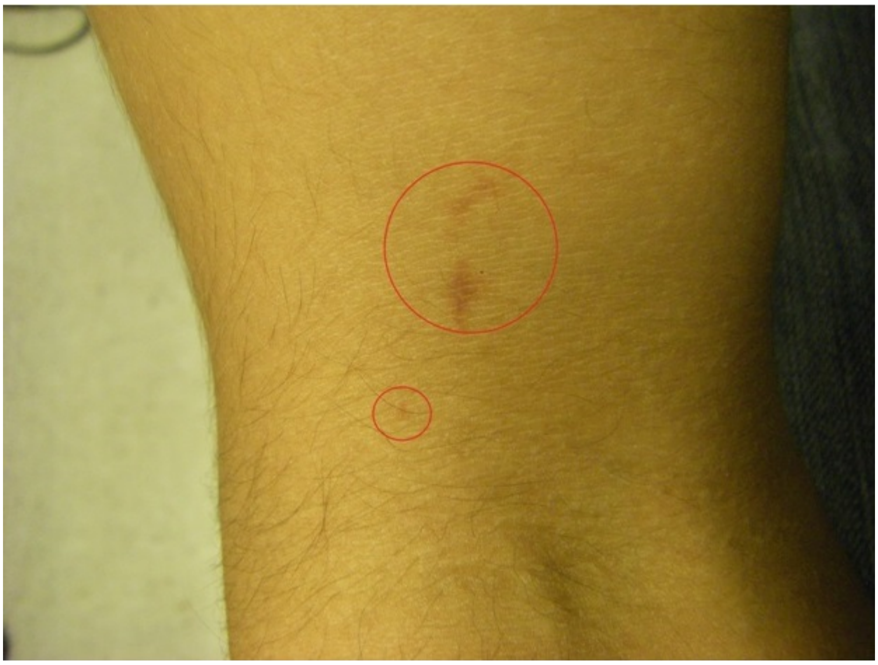

Figure 2.2: Bicep reaction

but there was red irritation that appeared. There was no pain associated with the reddened area and the affects lasted for less than 2 hours. The marks can be seen in Figure 2.3.

These were important test to perform so that possible side effects could be identified and study participants could be informed of the potential risk. It is important again to reiterate that there was no pain or change in physical ability was associated with these affects.

2.2 FES Circuit Design

The control circuit design in its basic form is a simple switching circuit. Its primary function is to take the information from the optical encoder and feed that into the NI Elvis. This information is then processed and depending on the angular positioning of the optical encoder the program determines which operation that the NI Elvis will take. The circuit

Figure 2.3: Forearm reaction

design is in Figure 2.4.

The optical encoder attached to the bicycle has three 10k pull-up resistors attached to channels: 1, A, and B. Theses pull-up resistors are used to insure that the optical encoder performs properly and has no wondering signals. The resistors were placed as close to the optical encoder as possible. Each line on the encoder is able to drive one ttl load. The primary outputs, channels A and B, are both attached to the inputs on the NI Elvis. These signals feed into the DAQ counters: CTR0Source and CTR1Source. Figure 2.5 shows the breadboarded circuit on the NI Elvis.

2.3 FES Exercise Bicycle

An exercise bicycle was chosen for this research because it constrains the movement and eliminates a many of extra variables. For example, an FES system could be used to help

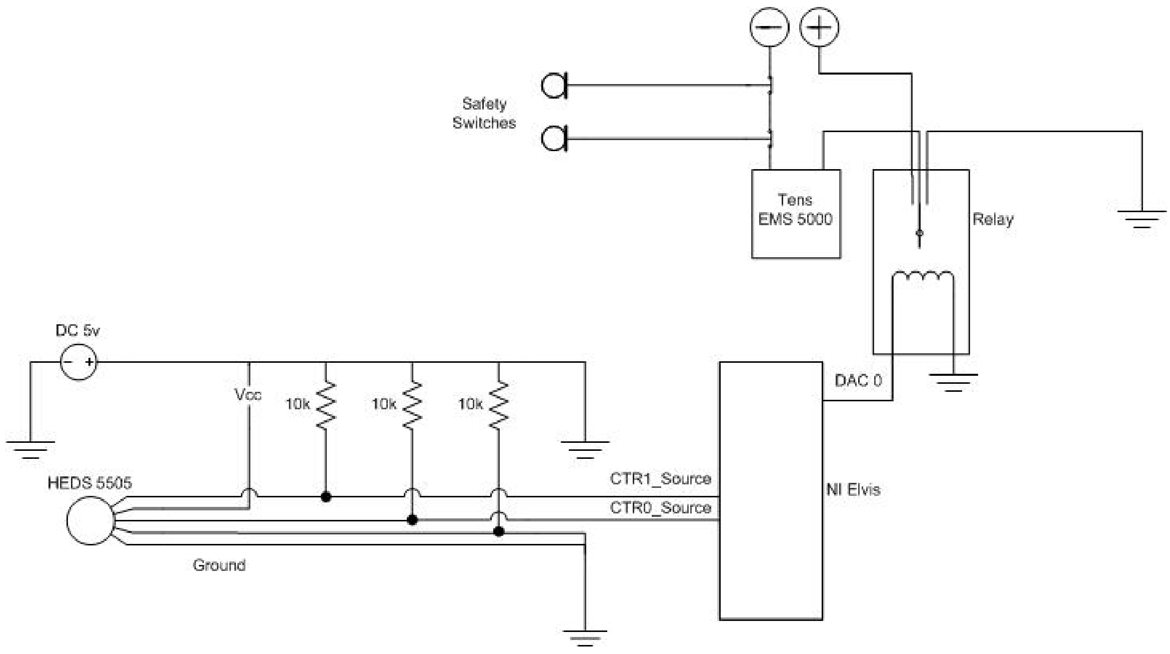

Figure 2.4: Circuit Diagram

a person walk, but this would require activation of multiple muscles, precise timing, and control of contraction strength in order to maintain walking stability [20]. Two types of exercise bicycles are common, upright bicycles and recumbent (Figure 2.5). In a recumbent bicycle a person sits on a large seat that cradles the bottom and supports the back the rider. With a recumbent exercise bicycle it is easy to understand the necessary activation angle since at all points in time the leg location is known due to the angle of the pedals. To measure the bicycle crank angle the exercise bike was equipped with an optical encoder (Figure 2.6). The optical encoder uses an infrared light and detects the pattern as the light crosses a filter. Each pattern corresponds to a specific angular position on the reference wheel. This data is used to determine the angular position of the crank.

The speed of the wheel and the position of the wheel will be measured using an optical encoder which can be seen in Figure 5.1.

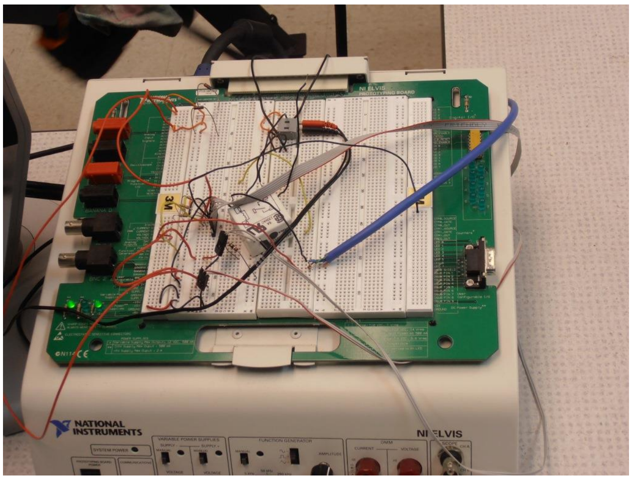

Figure 2.5: Physical Circuit

The optical encoder takes an infrared light and detects the pattern that is crossing the light. These patterns are used to determine the position of the wheel to obtain the angular position of the crank. The optical encoder analyzes a pattern that is placed upon a clear surface and by using optics it can determine the position of the wheel according to which pattern it is currently seeing. Each pattern gives an angle in reference to the wheel position.

The optical encoder had to be mounted onto the exercise bike so angular data could be received for both system control and data analysis. When the optical encoder revolves it a stream of raw data, but if there is extra wobble the data will spit out false pulses which will cause the data to continuously stray away from the actual value. By using the RPM meter it will constantly reconfigure itself every 180 degrees and check the value of the optical encoder and reconfigure it accordingly. This RPM meter is a very simple setup and the configuration was determined by running test on the bike to see how exactly it operated.

The first step was to determine what kind of voltage was being fed into the sensor.

Figure 2.6: Recumbent Exercise Bike

After hooking the bike up to a power source, 4 D batteries, the voltage was measured on the wires that lead up to this device. With the measurements taken it showed that it was being supplied 3.3v which is standard for some low power systems. After knowing the source voltage to the device it was time to determine how the device was functioning. The leads out of device run into a connector port. Two leads were plugged into these ports and then measured on an ohm meter. Whenever the magnet would pass over the sensor a small resistance would show up. This resistance was almost negligible, approximately

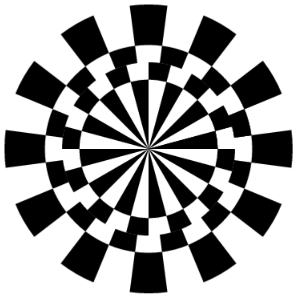

Figure 2.7: Optical Encoder

.167 ohms. So this device acts as a switch for the RPM meter. While the 3.3v are being fed into the switch it is left open until the magnet passes by and then the rising edge of the 3.3v spike can be seen as half a revolution on the RPM meter. In Figures 2.8- 2.11 shows the test connections for the Hall Effect sensor.

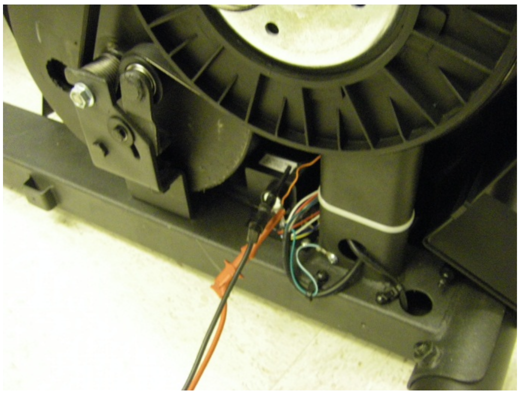

Figure 2.8: Hall Effect 1

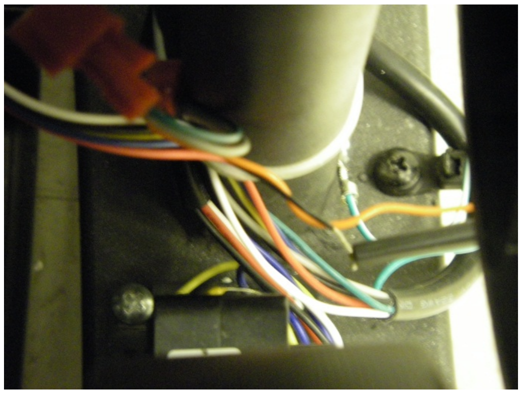

Figure 2.9: Hall Effect 2

2.4 System Program

This project required the develop of software components to control the FES device. Software implementations for FES systems have been created and implemented before, but for other applications [21] [22]. The programming language used was LabVIEW. The concept behind the LabVIEW code was to create a system code that would monitor the location of

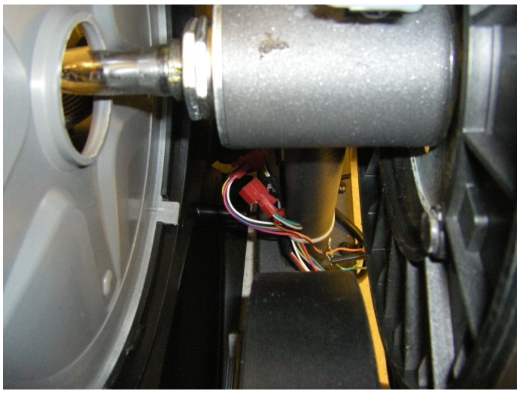

Figure 2.10: Hall Effect 3

Figure 2.11: Hall Effect 4

the bicycle crank and turn the FES device on and off at the appropriate angles. In addition, it also needed to collect angular data for the analysis of movement during pedaling.

The LabVIEW code can be seen in Figure 2.12. The program was constructed using two nested while loops that contain parameters for stopping the program. The outer while loop is a continuous while loop that does not stop without user input. The primary functions within the outer while loop are the create channel functions. The optical encoder and hall effect sensor input channels are initiated within this loop. The optical encoder channel counts the edges of the square wave from the EMS 5500 encoder. LabVIEW is configured to count the rising edges with an initial value of zero in a forward count direction. The second channel is an analog input for the hall eect sensor. This analog input channel reads a voltage from the sensor and assigns it a numerical value within LabVIEW.

The inner loop is where the calculations and data interpretation are per- formed. The main functions of the inner loop are to 1) obtain raw data from the optical encoder and converting it into a 360 degree measurement, 2) store the previous value of the loop to monitor the accumulated phase angle as well as the phase angle for the current revolution, and 3) trigger the analog switch to turn on and o the FES device at the appropriate angles.

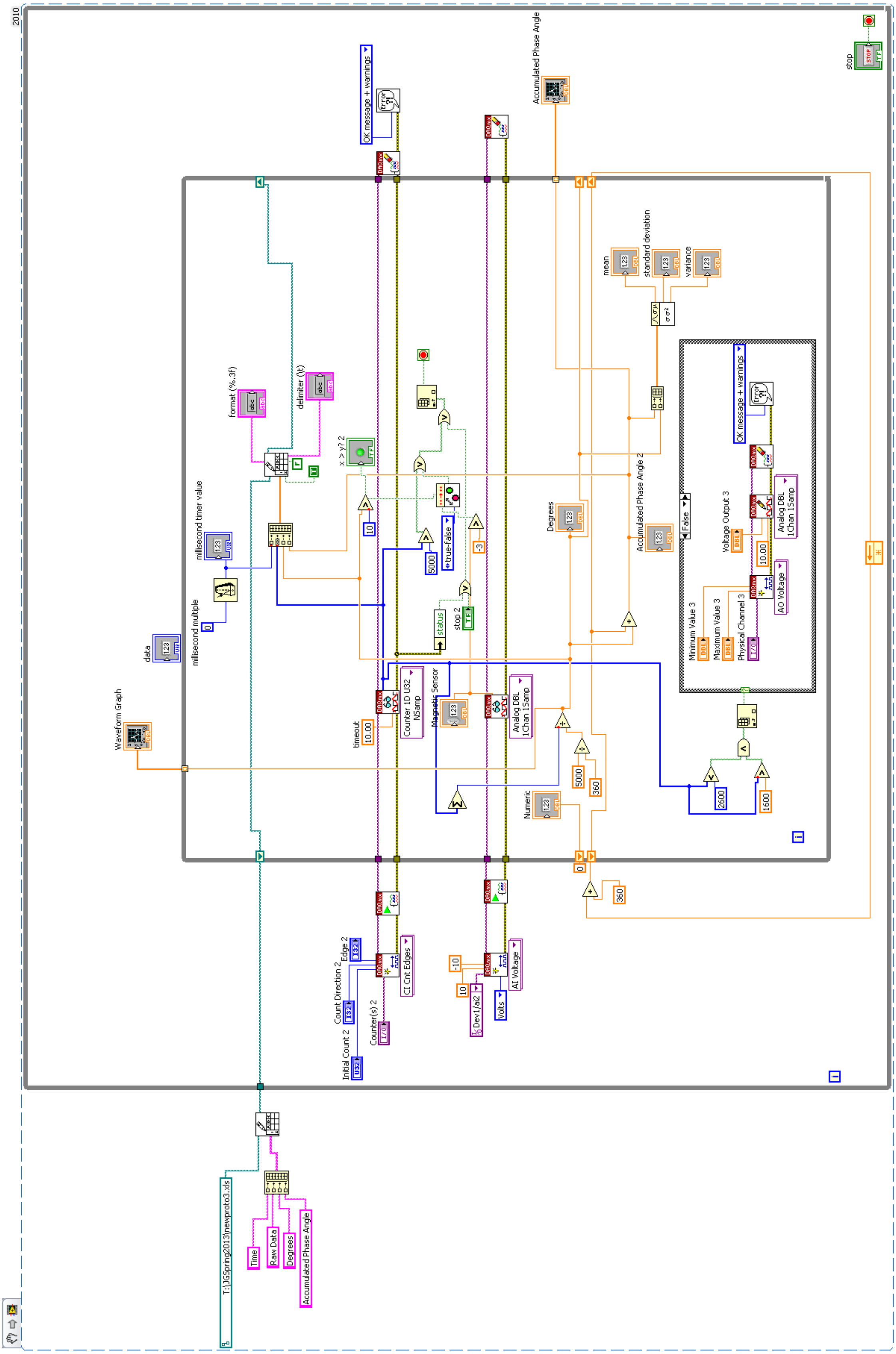

Figure 2.12: Final LabVIEW Code

Accumulated phase angle is calculated within the LabVIEW code using a shift register that is connected to a feedback loop. The shift register collects the data being fed by the phase angle until the inner while loop reaches the exit state, a value of 360 degrees. When this occurs, then previous value is added to the current value on the shift register. The code also has a correction feature to carry over any remainder from a previous loop to the next iteration. For example, if the last measurement was 360.56 degrees before it was reset to 0, the remainder of 0.56 degrees would be carried forward to begin the next iteration at 0.56 degrees instead of simply restarting at zero.

CHAPTER 3: EXPERIMENTAL METHODS

3.1 Protocol

3.1.1 Objective

Human testing was performed to evaluate the functionality and performance of the FES Recumbent Bicycle. Participants were asked to only pedal with their left leg while their other leg was controlled by the FES bicycle. This tested the accuracy of the FES control system. It also determined whether the muscle contractions were enough to propel a pedal forward. This research will create a control group for future studies by using young and healthy participants. The data obtained by the controls will provide the normalized data so a stroke patient can have their performance evaluated against the normalized data. Throughout the patients recovery process the goal is to have the patients data approach the normalized control data.

3.1.2 Inclusion and Exclusion Criteria

This project required a test population that meets certain criteria. Restrictions were placed on age, weight, physical condition, and the presence of implanted electrical devices. Participant age restrictions were determined by multiple factors. The legal age to be considered an adult by the federal government for research purposes is 21 years. This was set as the minimum age. The maximum age of 35 was chosen to avoid extraneous factors in the data analysis associated with old age. Age could be a confounding factor in a participant performance. The age range was kept small because the number of subject was low and there was a desire to used healthy young adults as a control group in later studies. A weight restriction of 30 BMI (body mass index) was established because the FES device operates better with less electrical resistance. Fat tissue covering the muscle creates resistance for the device which reduces its effectiveness. Participants with heart conditions were excluded from the study. This test could put people with heart conditions at increased risk, so as a safety precaution they were excluded from the study. Participants could not have any injuries to the legs or lower back that would have inhibited their performance on the recumbent bicycle. This study was designed to determine normal values for healthy young controls so a person with an injury is excluded from being part of this control group. People with implanted devices were also excluded from participating since their devices could be at risk of malfunctioning due to the electrical impulses being sent into the body.

3.1.3 Study Participants

Twelve participants were recruited for the study with an even distribution of males and females. Participants were young adults with an average age of 25 years. The average height was 68 inches and the average weight was 144 lbs. The participant demographics are shown in Table 3.1.

Table 3.1: Study Group

Gender	Age	Height(in)	Weight(lbs)
Female	26	67	137
Male	23	71	190
Female	24	63	122
Male	22	72	143
Male	22	73	165
Male	23	67	140
Male	23	66	155
Female	34	66	135
Female	25	67	137
Female	23	63	130
Male	26	70	146
Female	25	65	130
Mean	24.7	67.5	144.2

Subjects were block randomized into two groups. Half the males were tested with no FES first and FES second while the other half was tested FES first and no FES second. The same blocking method was done with the female group. This blocking method ensures that there will be an even number of members in each group. Blocking the subjects was important since the test was using a small test population was used.

Participant #____________________

FES Bike Test Participant Information and Qualification Form

This form is the check list that a participant must pass in order to participate in this experiment. It is a measure of the participants' current physical status as well as pertinent medical history that could exclude them from participating in the study. The qualifications that must be met are: Age 18-35, BMI < 40

Participant Information:

Name:____________________

Age:____________________

Gender:____________________

Height:____________________

Weight:____________________

BMI = __________

BMI = __________

BMI = __________

Each box must be checked in order to participate in this study:

- ☐ No previous or current heart conditions
- ☐ No musculoskeletal injuries in the legs or lower back that inhibit your ability to ride a bicycle
- ☐ No electrical device that is currently implanted within to your body (Pacemaker, Insulin Pump, ect.)

Figure 3.1: Test Qualification Form

3.1.4 Test Procedure

For this project it was important to establish a legitimate test procedure that covered every individual step, in enough detail, so that no steps would be missed. The test procedure is displayed in Figure 3.2 and 3.3. The test procedure was followed for every test subject. It includes each individual step needed to complete a successful recumbent bicycle FES test and was used to ensure that every test was executed in the precisely same order and every step performed consistently. Reducing variation between test participants can help to improve the accuracy and validity of the tests.

3.1.5 Testing

Participants were recruited from the university and surrounding areas. They were instructed to wear shorts on the day of testing. Upon arrival participants signed the informed consent form approved by the Institutional Review Board of Western Carolina University prior to being tested. This form described the nature of the study, risks that are involved and insures that the participants are aware of any possible problems and who to contact if they occur. Participants were also verbally informed, in full detail, about the testing process and what was going to be done during the trials. It was also made clear to them that they could stop the study and were free to leave at any point in time.

The subjects were instructed to sit on the FES bicycle and the electrodes were attached to their right leg (Figure 3.4). Subjects were shown how to adjust the recumbent bicycle seat and were instructed to adjust the seat to a comfortable distance from the pedals.

Next, the participants FES threshold was found. The FES threshold was defined as the maximum intensity level that each individual subject could tolerate from the FES device without experiencing pain or excessive discomfort. To nd the FES threshold, participants were asked to pedal with both legs manually at a moderate self-selected speed. While the subject was pedaling, the intensity of the FES device was slowly increased from an initially low value to higher values. After each incremental increase the subject was asked how they felt and if they were willing to go to the next higher level. In addition to verbal feedback from the participant, the researcher observed the quadriceps muscle for visible contractions.

Once the participants threshold was found, testing began. The first participant began her first trial by pedaling with both legs while the FES bicycle recorded the foot

Test Procedure

Overview: This procedure will go over the steps that will be required to complete the testing for the FES bike.

Pretest Setup

1. Get participants for the testing.
2. The participants will be 6 males and 6 females.
3. The participants will be blocked by gender.
4. Participants will randomly be placed into 2 groups.
5. Group one participants will run the FES test first and the no FES test second.
6. Group two participants will run the no FES test first and the FES test second.
7. Have participant sign up for an experimentation date.
8. Request that the volunteer wears shorts so that the electrode pads can be placed in direct contact with the skin.

Primary Test

9. Ask participants to sign the informed consent form.
10. Ask participant to fill out FES Bike Test Participant Information and Qualification Form.
11. Explain how a visual analog scale works and how to fill one out.
12. Ask participant to mark question 1 of the visual analog scale form.
13. Setup LabVIEW so it's ready to record the runs from the test.
14. Ask volunteer sit down on bike and pedal for until the FES device is calibrated to their personal stimulation level.
15. The volunteer will then rest for at least 2 minutes before beginning the first test.
16. Setup for test run 1(No FES)
    a. Have participant sit on the bike.

Figure 3.2: Test Procedure 1

b. Adjust bike seat to a comfortable pedaling placement.

17. Setup for test run 2(FES) the electrodes will be placed on the quadriceps of the volunteer. The volunteer will flex their muscle, to the best of their ability, to find the desired placement on the muscle.
    a. The volunteer will flex their quadriceps to help the tester find their rectus femoris.
    b. After the placement of the muscle has been determined a skin prep dopper, which will improve the electrode pad contact and allow for better electric flow.
    c. The 2 electrode pads will be placed close to the top and bottom of the rectus femoris and will be smoothed against the skin to ensure complete skin contact.
    d. Ask participant sit on the bike.
    e. Adjust bike seat to a comfortable pedaling placement.
    f. The volunteer will be asked to relax their non-dominant leg and not us it. The non-dominant leg will have the FES device controlling it. The volunteer will attempt to pedal at the same pace that they would in the no FES device test with their dominant leg.
18. Hit run button when the participant is ready to pedal.
19. The volunteer will be asked to pedal at a steady pace that is comfortable for 3 minutes for both runs.
20. After each run the volunteer will be given another sliding scale chart to evaluate their experience on the bike and the effectiveness and comfort level of it.
21. The volunteers will then be done with their part of the experiment.
22. Recorded data file for each participant will be labeled accordingly
23. Subject data will then be compiled into a comprehensive spreadsheet for further analysis.

Figure 3.3: Test Procedure 2

Figure 3.4: Electrode Application

crank angle. During the second trial the participant was instructed only to pedal with the left leg and to let the FES device control the right leg. The order of trials alternated between no FES and the right leg being FES controlled. All trials lasted 60 seconds. Whether a participants first trial was with FES or without FES was determine by block randomization as described above. Each participant performed six trials, three with FES and three without FES.

3.1.6 Survey

After finishing the experiment each subject was asked to complete a short survey describing their experience during and after the experiment. The purpose of these questions is to understand how the subject felt during and after the experiment. All of these questions were answered using a visual analog scale (Figure 3.5). A visual analog scale is a technique that can be used to collect continuous quantitative data about subjective parameter such as mood, feelings, and levels of pain. The visual analog scale used in the experiment can be seen in Figure 3.5. Question 1 was answered prior to testing and instruction describing how to properly complete the form were provided. Question 2 was answered at the end of the testing to collect data on the participants individual perception of the test.

FES Bicycle Test Sheet

This sheet is to gauge the participants comfort level before, during, and after the test, as well as assess their current physical condition.

Question 1:

How do you feel physically today?	Poor ——— Great

Question 2:

Conditions	Without FES Device	With FES Device
How did you feel your performance was during the test?	Poor ——— Great	Poor ——— Great
What was your comfort level during the test?	Poor ——— Great	Poor ——— Great
What was your comfort level after the test?	Poor ——— Great	Poor ——— Great
Was there any pain associated with the test?	No Pain ——— Great	No Pain ——— Great

Figure 3.5: Visual Analog Scale

3.2 Data Analysis

3.2.1 Analysis Methods

Properties of the angular velocity will be used to compare the tests performed with FES and without FES. The three main values that were evaluated are the mean, standard deviation, and coefficient of variation. The mean, $\bar{x}$, is the average value for a group of numbers,

$$\bar{x} = \frac{\sum_{i-1}^{n} x_i}{n} \tag{3.1}$$

where x is each individual the parameter value, i is the index counter, and n is the number of members in the group. The standard deviation of a sample, s, is a measure of how far the values deviate from the mean value,

$$s = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \tag{3.2}$$

Lastly, the coefficient of variation, CoV, is a normalized measure of the standard deviation given by,

$$CoV = \frac{s}{\bar{x}} \tag{3.3}$$

3.2.2 Statistical Methods

Subjects performed tests with and without FES so a paired t-test was used to improve results by accounting for variability between subjects. A paired t-test is used when the there is subject data that needs to be compared to itself. The mathematical equation to preform a t-test is,

$$t = \frac{\sum d}{\sqrt{\frac{n(\sum d^2)-((\sum d))^2}{n-1}}} \tag{3.4}$$

where d is the difference between test conditions for each individual subject, and n is the number of pairs within the data sets. Using the entire population, n = 12, but when a specific gender is evaluated, n = 6. The values from these test are then averaged to obtain a value for the entire population. These data is also broken down by gender blocks for further analysis.

One of the objectives of the FES bicycle study was to determine if FES could be used to induce muscular contractions necessary to push a bicycle pedal. The quality of pedaling may be quantied by the variability in angular velocity. Higher variability in angular velocity indicates more erratic motion and lower quality pedaling. It was hypothesized that variability in angular velocity would be higher when FES was used than the value obtained for normal cycling.

3.3 Pilot Test and Preliminary Results

Before conducting the full scale experiment it was important to evaluate the system performance and determine if the data was yielding promising results. A volunteer was found for the pilot test. The test subject qualification form was completed to ensure that the subject met the inclusion criteria and a test was conducted following the established test procedure. In the first trial, the subject rode the FES bicycle out without stimulation for three minutes. This was followed by three minutes of riding with FES. Matlab was used to calculate the mean values and generation plots. The phase angle, accumulated phase angle, angular velocity (deg/s), and filtered angular velocity (deg/s) were calculated for the subject with and without FES. Filtering was performed with a 7th order Butterworth low pass filter with a cut off frequency of -3dB . The phase angle without FES (Figure 3.6) is similar to the phase angle with FES (Figure 3.7). Figures 3.8 and 3.9 represent the accumulated phase angle for both test. These two figures visually have similar slopes. The velocity in Figures 3.10 and 3.11. The scale of each graph is thrown off due to the anomalies in the data. These anomalies cause the velocity to record a much higher value then the actual value. This is why the 7th order Butterworth low pass filter was added to Figures 3.12 and 3.13 suppress the spikes in velocity.

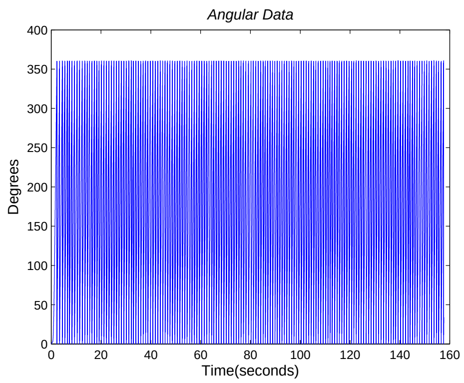

Figure 3.6: Phase Angle

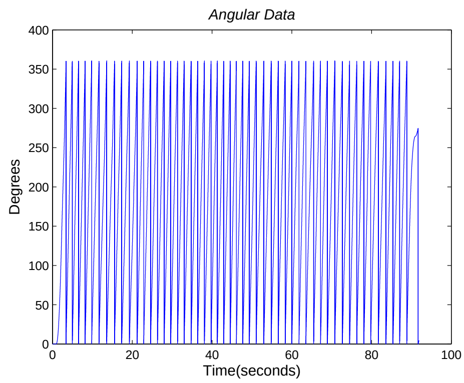

Figure 3.7: Phase Angle with FES

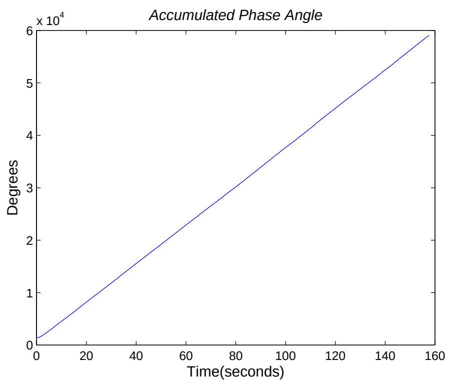

Figure 3.8: Accumulated Phase Angle

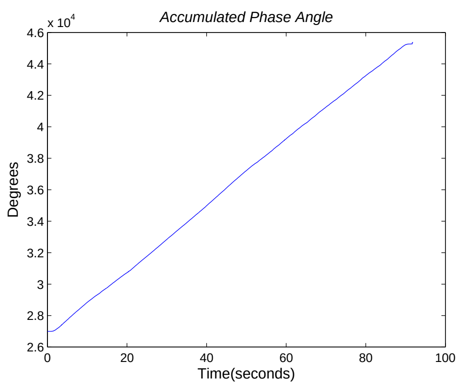

Figure 3.9: Accumulated Phase Angle with FES

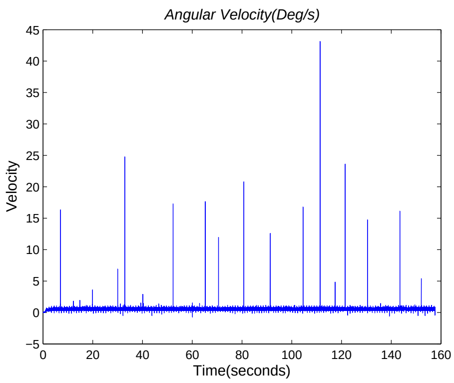

Figure 3.10: Velocity($\frac{Degree}{Sec}$)

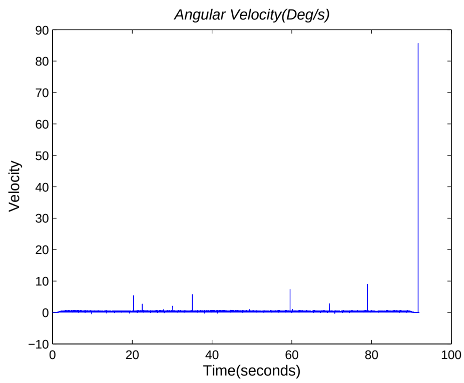

Figure 3.11: Velocity($\frac{Degree}{Sec}$) With FES

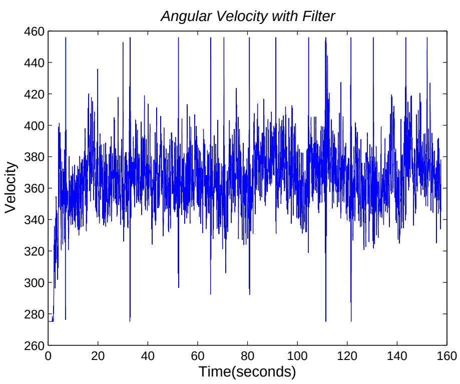

Figure 3.12: Velocity($\frac{Degree}{Sec}$)wFilter

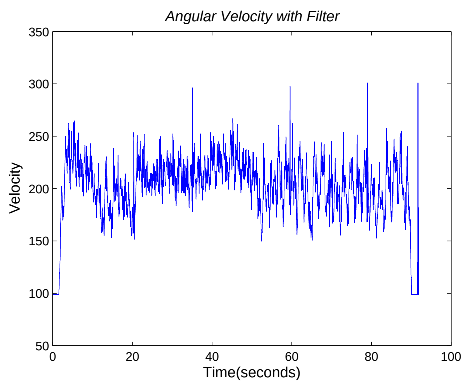

Figure 3.13: Velocity($\frac{Degree}{Sec}$) wFilter With FES

CHAPTER 4: RESULTS

Angular data for a typical subject (5) was exported from LabVIEW and plotted using Matlab (Figures 4.1 and 4.2). The results show the motion of the wheel on each revolution starting from a value of 0 and resetting at 360 degrees. Visually the FES and no FES graphs look similar. The accumulated phase angle was created from the phase angle by continuously adding the angular displacement and not resetting at 360 degrees. Instead it continues on indefinitely. The plots of accumulated phase angle were also visually similar (Figure 4.3 and 4.4). The angular velocity it calculated by taking the change in over the change in time and expressed in degrees/second (Figure 4.5 and 4.6). High amplitude spikes were observed in the velocity data. Because the phase angular is measuring the movement of a large steel wheel, the change in angular velocity will be gradual due to the angular momentum of the system. Thus, these spikes were determined to be anomalies and a filter was applied to remove them (see Butterworth filter in Section 3.3). Like the other parameters, the filtered angular velocity for the FES and the no FES appeared visually similar (Figures 4.7 and 4.8). After the completion of all the trials the subjects test data were compiled into Table 4.1. The table combines the average between each subjects three trials for the the FES trials and the none FES trials. This table shows the data points that were used in the data analysis to create the statistical results.

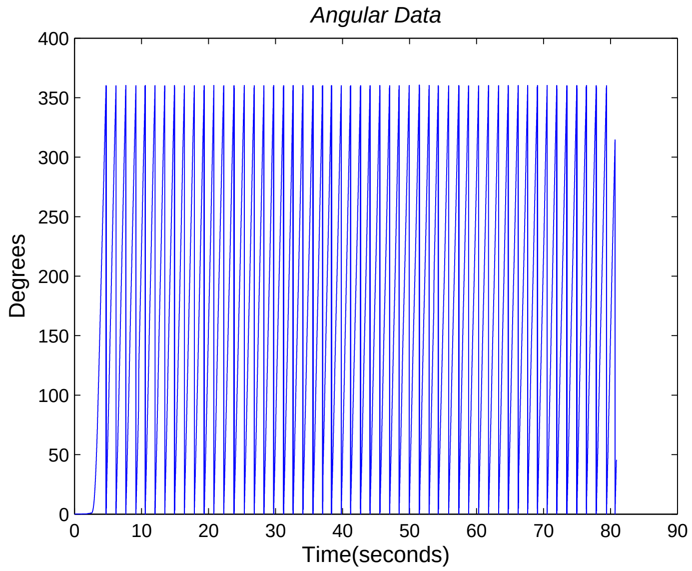

Figure 4.1: FES Phase Angle

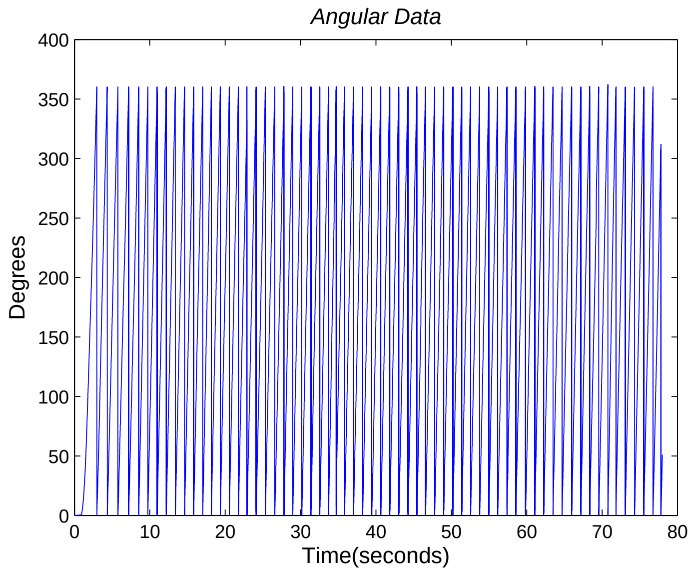

Figure 4.2: No FES Phase Angle

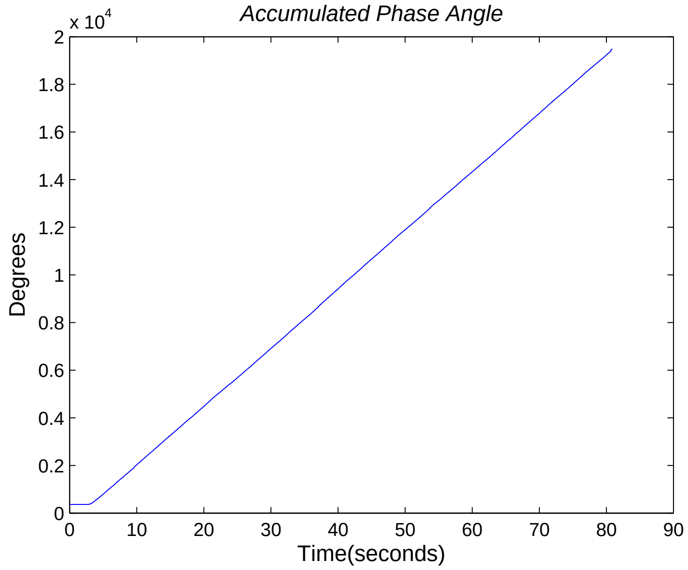

Figure 4.3: FES Accumulated Phase Angle

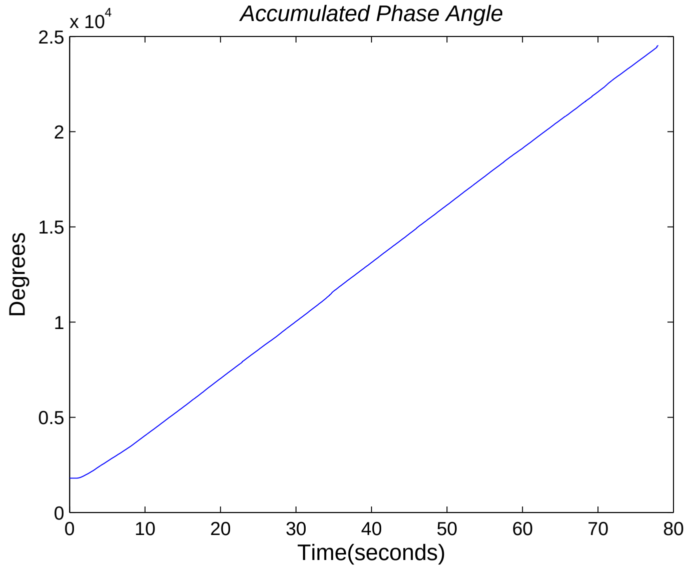

Figure 4.4: No FES Accumulated Phase Angle

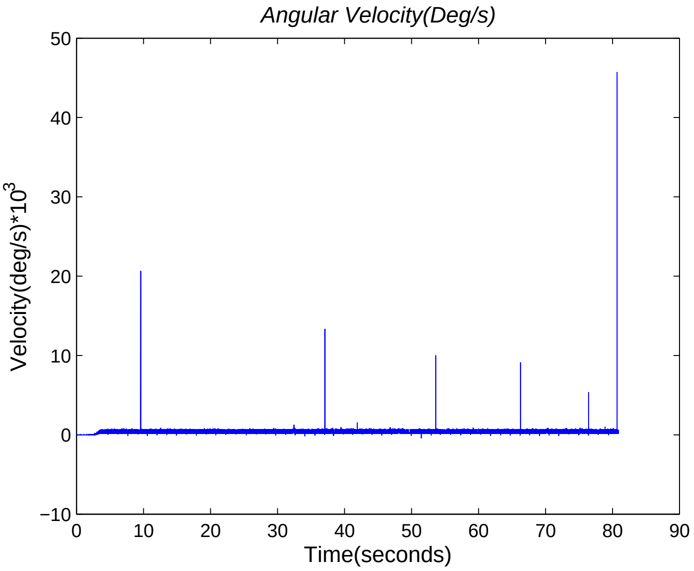

Figure 4.5: FES Angular Velocity

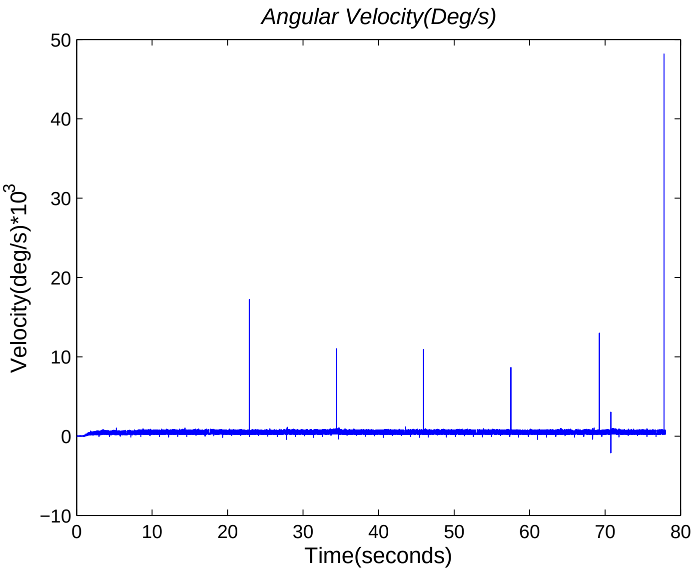

Figure 4.6: No FES Angular Velocity

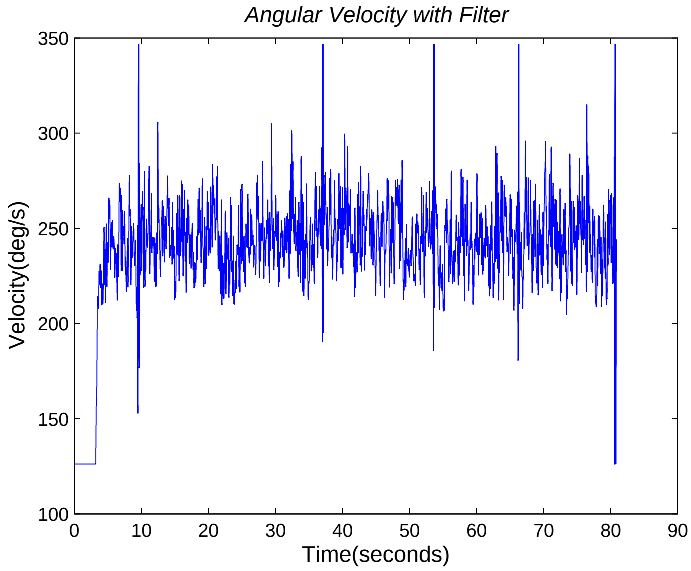

Figure 4.7: FES Filtered Angular Velocity

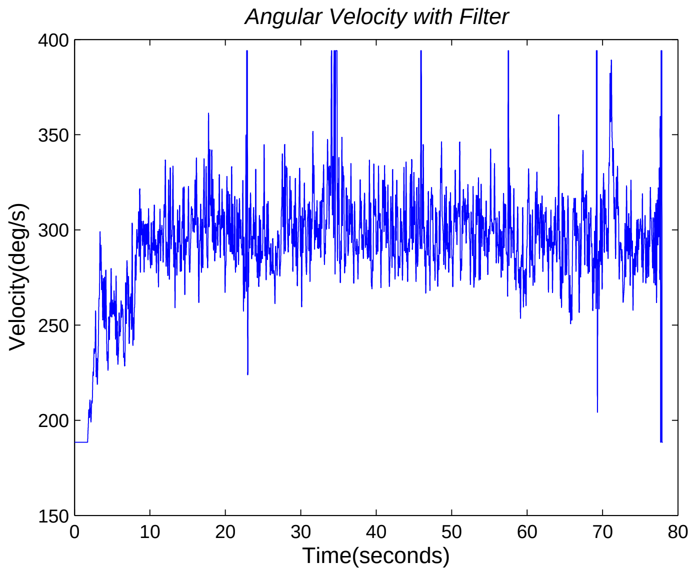

Figure 4.8: No FES Filtered Angular Velocity

Table 4.1: Subject Test Data

	Meanω_f FES	Meanω_f No FES	SDω_f FES	SDω_f No FES	CoVω_f FES	CoVω_f No FES
1	268	279	74	63	0.274	0.227
2	146	96	51	50	0.348	0.519
3	96	132	42	40	0.436	0.304
4	214	231	42	55	0.198	0.236
5	244	248	31	26	0.126	0.105
6	167	168	26	21	0.156	0.123
7	358	293	186	116	0.519	0.394
8	288	352	67	86	0.234	0.245
9	116	215	68	50	0.586	0.231
10	186	205	74	88	0.398	0.426
11	375	412	95	116	0.254	0.283
12	279	296	78	68	0.279	0.231
Mean	228	244	70	65	0.317	0.277
SD	90	90	42	31	0.143	0.12

4.1 FES vs. No FES: Both Genders

Even though visually there was no difference between the two curves, statistical analysis was used to determine if a visually undetectable difference was actually there. The mean value of ω_f for FES was 228 deg/s and for No FES it was 224 deg/s. There was no significant difference between these two values (p=0.242). The standard deviation of ω_f with FES was 42 deg/s and with No FES it was 31 deg/s. There was no significant difference was observed between for the standard deviation of ω_f (p=0.525). The coefficient of variance of ω_f was 0.317 and 0.277 for FES and No FES, respectively. No significant difference were observed covariance of ω_f (p=0.298). These results differed from those from the pilot test which showed dramatic differences standard deviation of ω_f and the covariance of ω_f .

Table 4.2: Both Genders Statistics

Paired Samples Statistics				
		Mean	N	Std. Deviation
Pair 1	Meanω_f FES	228	12	90
	Meanω_f No FES	244	12	90
Pair 2	SDω_f FES	70	12	42
	SDω_f No FES	65	12	31
Pair 3	CoVω_f FES	0.317	12	0.143
	CoVω_f No FES	0.277	12	0.12

Table 4.3: Both Genders Paired Sample T-Test

Paired Samples Test				
		Paired Differences		Sig. (2-tailed)
		Mean	Std. Deviation	
Pair 1	Meanω_f FES - Meanω_f No FES	-16	44	0.242
Pair 2	SDω_f FES - SDω_f No FES	4.58	24	0.525
Pair 3	CoVω_f FES - CoVω_f No FES	0.040	0.127	0.298

4.2 FES vs. No FES: Males Only

The mean value of ω_f for FES was 251 deg/s and for No FES it was 242 deg/s. There was no significant difference between these two values (p=0.586). The standard deviation of ω_f with FES was 72 deg/s and with No FES it was 64 deg/s. There was no significant difference was observed between for the standard deviation of ω_f (p=0.573). The covariance of ω_f was 0.267 and 0.277 for FES and No FES, respectively. No significant difference were observed covariance of ω_f (p=0.81).

Table 4.4: Male Statistics

Paired Samples Statistics				
		Mean	N	Std. Deviation
Pair 1	Mean FESω_f	251	6	96
	Meanω_f No FES	242	6	108
Pair 2	SDω_f FES	72	6	61
	SDω_f No FES	64	6	42
Pair 3	CoVω_f FES	0.267	6	0.146
	CoVω_f No FES	0.277	6	0.159

Table 4.5: Male Paired T-Test

Paired Samples Test				
		Paired Differences		
		Mean	Std. Deviation	Sig. (2-tailed)
Pair 1	Mean FES - Mean No FES	9.4	40	0.586
Pair 2	SD FES - SD No FES	8	32	0.573
Pair 3	CoV FES - CoV No FES	-0.01	0.1	0.81

4.3 FES vs. No FES Females Only

The standard deviation of ω_f with FES was 67 deg/s and with No FES it was 66 deg/s. There was no significant difference was observed between for the standard deviation of ω_f (p=0.846). The covariance of ω_f was 0.368 and 0.277 for FES and No FES, respectively. No significant difference were observed covariance of ω_f (p=0.178). The mean value of ω_f for FES was 206 deg/s and for No FES it was 247 deg/s. There was a significant difference between these two values (p=0.033). The female subjects statistically pedaled slower when the FES device on. The difference in mean value was greater than one standard deviation. Since there is a significant difference between mean values then the null hypothesis is rejected and the alternate is accepted.

Table 4.6: Female Statistics

Paired Samples Statistics				
		Mean	N	Std. Deviation
Pair 1	Meanω_f FES	206	6	85
	Meanω_f No FES	247	6	78
Pair 2	SDω_f FES	67	6	13
	SDω_f No FES	66	6	19
Pair 3	CoVω_f FES	0.368	6	0.133
	CoVω_f No FES	0.277	6	0.078

Table 4.7: Female Paired T-Test

Paired Samples Test				
		Paired Differences		
		Mean	Std. Deviation	Sig. (2-tailed)
Pair 1	Meanω_f FES - Meanω_f No FES	-41	35	0.033
Pair 2	SDω_f FES - SDω_f No FES	1.2	15	0.846
Pair 3	CoVω_f FES - CoVω_f No FES	0.09	0.142	0.178

CHAPTER 5: DISCUSSION

5.1 FES Bicycle Development

Throughout this testing process the background on FES devices and systems were studied. Obtaining the EMS 5000 functional electrical stimulator early helped to dictate the direction in which the project evolved. Initially the limitations of a handheld FES device were unknown. A plan was created to analyze the FES device to establish a comprehensive understanding of the EMS 5000. The testing of the device revealed that not only was it safe to manually disconnect it from a circuit and reconnect it, but that it had enough power to move body parts. This discovery helped to define the thesis project and ultimately the design and construction of the FES recumbent bicycle. The initial idea was to perform this test on a street bike instead of on a stationary exercise bike. This direction was shifted when the limitations of using a street bike were considered. Although common two wheeled bicycles are inexpensive the cost of a recumbent street bicycle exceeded the resources we were willing to spend at the time. In addition, a stationary recumbent bicycle would provide a simpler system to being research in this area.

There were some problems with the first iteration of the LabVIEW code used as the control the FES bicycle. The DAQ assistant had timing problems due to its memory heavy processing. The primary problem with the code was that the response time was too slow to function properly. The program needed to have a response rate of around 10 milliseconds. However, the actual response time was approximately 3 seconds, far greater than the desired value. The source of this delay time was found to be a problem with the

LabVIEW code. 2000 samples were being taken and 2000 constants were being fed into the DAQ assistant which resulted in a signal length of one second.(Figure 5.1).

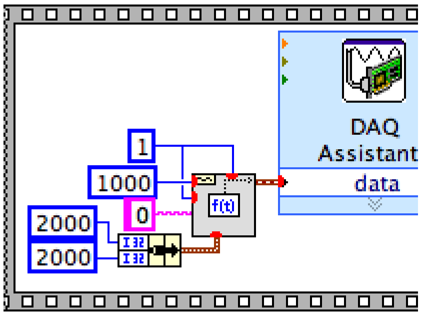

Figure 5.1: Optical Encoder

A second problem with the LabVIEW code was that there were case statements inside the program that were redundant that slowed down the program. The case structure setup was a problematic because there were multiple setups for the DAQ assistant within the case structure which caused the program to constantly reconfigure and setup of the DAQ. The DAQ assistant was moved outside the case statement so that it was only configured once.

Even after configuring the DAQ assistant to improve performance there were still issues with this programming approach. For this program to function properly it needed to record data every millisecond and be able to respond it that same amount of time. This performance level was not possible using the DAQ assistant to communicate with the NI Elvis. This problem was solved by using the DAQmx function in LabVIEW to communicate with the NI Elvis. There several differences between the DAQ assistant and the DAQmx. The primary difference is that the DAQ assistant is a larger subVI that contains the individual parts including the DAQmx functions. It has multiple functions running in parallel in the background, many of which are not being used. This inefficiency can lead to time delays.

5.2 Participant Testing

Initially we were concerned that participants would experience discomfort and even mild pain during the testing. However, the majority of the subjects indicated that they felt comfortable during the testing and that after three to five revolutions of the FES device activating the muscle that they quickly grew accustomed to the sensation. There were two subjects out of the twelve that did not grow accustomed to the sensation of the device within the one minute trials. The other ten subjects indicated that after the initial cycles the power seemed to drop off and stabilize at a lesser level, even though the device was operating at a constant power level. This sensation was attributed to muscle fatigue and desensitization of nerves, which is common during the use of FES. The desensitization of nerves is a common bodily function. As an example, the smell sensation is less after you have been in the presence of the scent for a period of time. Most people do not notice the pressure applied to the body by the load of clothing.

There were no significant differences in standard deviation of the angular velocity were observed in any of the test groups. Furthermore, no significant difference were found for coefficient of variance of the angular velocity either. The standard deviation of the angular velocity is a measure of the quality of cycling. The lower standard deviation, the smoother the bicycle is being pedaled. While a greater standard deviation indicates a more erratic the pedaling motion. Because no differences were found between the FES and No FES conditions these results indicate that the FES Bicycle is capable of generating smooth cyclic pedaling during stimulation equivalent to that of pedaling without stimulation. However, care should be taken when interpreting these results because they may have been affected by the small test population. Future studies with sufficient statistical power are required to verify these results. The one significant difference parameter was that female pedaled slower with using FES stimulation that without it. This reduction in speed was likely caused by some of the females who were hesitant towards the device activation. This hesitancy to receive the electrical impulse may have caused the overall velocity of the FES value to drop.

Another key point is that a patient population with paralysis could have quite different results. The threshold for the FES device would be less of an issue with paralyzed subjects since there would not be able to feel discomfort at high power. As a result the FES level could be increased until a strong visible contraction was observed. The ability to visually observe a muscle contraction is shown in the figures below. Prior to activation of the FES device the muscle show tone, but no visible contraction (Figure 5.2). Upon activation by the FES device, a clear and powerful muscle contraction occurs (Figure 5.3). These strong contractions were a good indicator during testing that the device was functioning properly.

Figure 5.2: Leg without FES device Active

Figure 5.3: Leg with FES Device Active

CHAPTER 6: CONCLUSIONS

6.1 Conclusion

The future for FES systems are continuing to progress in a positive direction. This research in conjunction with other research in the biomedical engineering field are enabling new therapies that have the potential to improve the quality of life for stroke patients. The FES research completed for the recumbent bicycle showed that the device was capable of properly controlling the leg propelling it forward with enough power to push the pedal. The experimental study showed that the quality of movement was sufficient to allow cycling assisted by FES on the Recumbent Bicycle. In fact, no statistical differences were found between normal cycling and FES assisted cycling for most groups studied. These results may be encouraging for stroke patients having partial hemiparesis. Initial testing seems suitable for future studies that assist with stroke patients during rehabilitation.

6.2 Future Work

Another feature that could be added to the recumbent bicycle is a strain gauge to measure pedal force (6.1). The strain gauge electrical resistance changes as it stretches. The strain gauge consists of a metal strip that is adhered to a flat surface. When the strain gauge is pulled it causes the metal to stretch and become thinner and longer. This causes the resistance to increase.

In order to quantify the pushing force on a strain gauge, it is necessary to design a

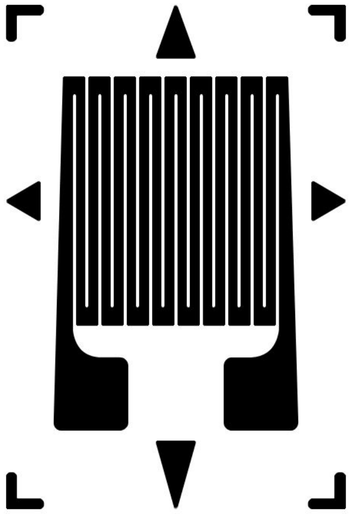

Figure 6.1: Strain Gauge

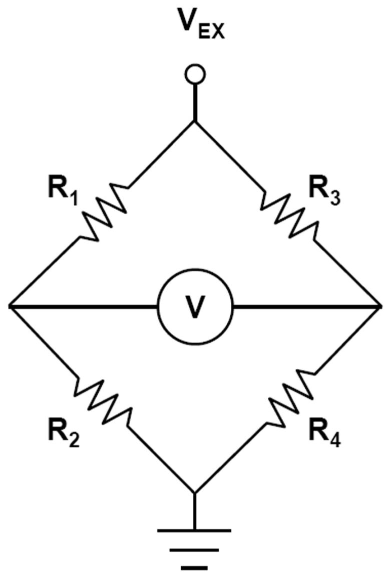

Figure 6.2: Wheatstone Bridge

hardware interface. One of the components of this hardware interface is the Wheatstone bridge. The Wheatstone bridge is a simple circuit that is used to analyze and measure an unknown resistance. In Figure 6.2 there are four resistors with a voltage measurement being taken from the voltage differential. The value of R4 can be found by solving equation

$$R_4 = \frac{R_2}{R_1} * R_3 \tag{6.1}$$

Another technique that could be used to advance this setup would be electromyography(EMG). EMG can tell the electrical impulses in muscles [23]. This is one of the few sensors that can be used in a FES system [24]. Another test that can be ran using a similar setup is a biceps and triceps control mechanism. The purpose of this control mechanism would be to control the arm flexion and extension upon receiving an electrical impulse from the FES device. This control system would give another perspective on the effectiveness of the FES system, especially the actuation speed of the muscles.

This circuit controlling the arm switches direction upon hitting a contact switch. This action repeatedly bounces the arm back and forth between the two sensors. This circuit it will help to test the ability to switch between two individual inputs to apply voltage to the subject (Figure 6.3). The circuit can be designed using LabVIEW VI and a basic switching circuit for the control. The two contact switches in the circuit are limit switches that have snap action triggering. The snap action limit switches open and close the circuits each time button is pressed. This type of test could support claims made by Crago and Abbas [25].

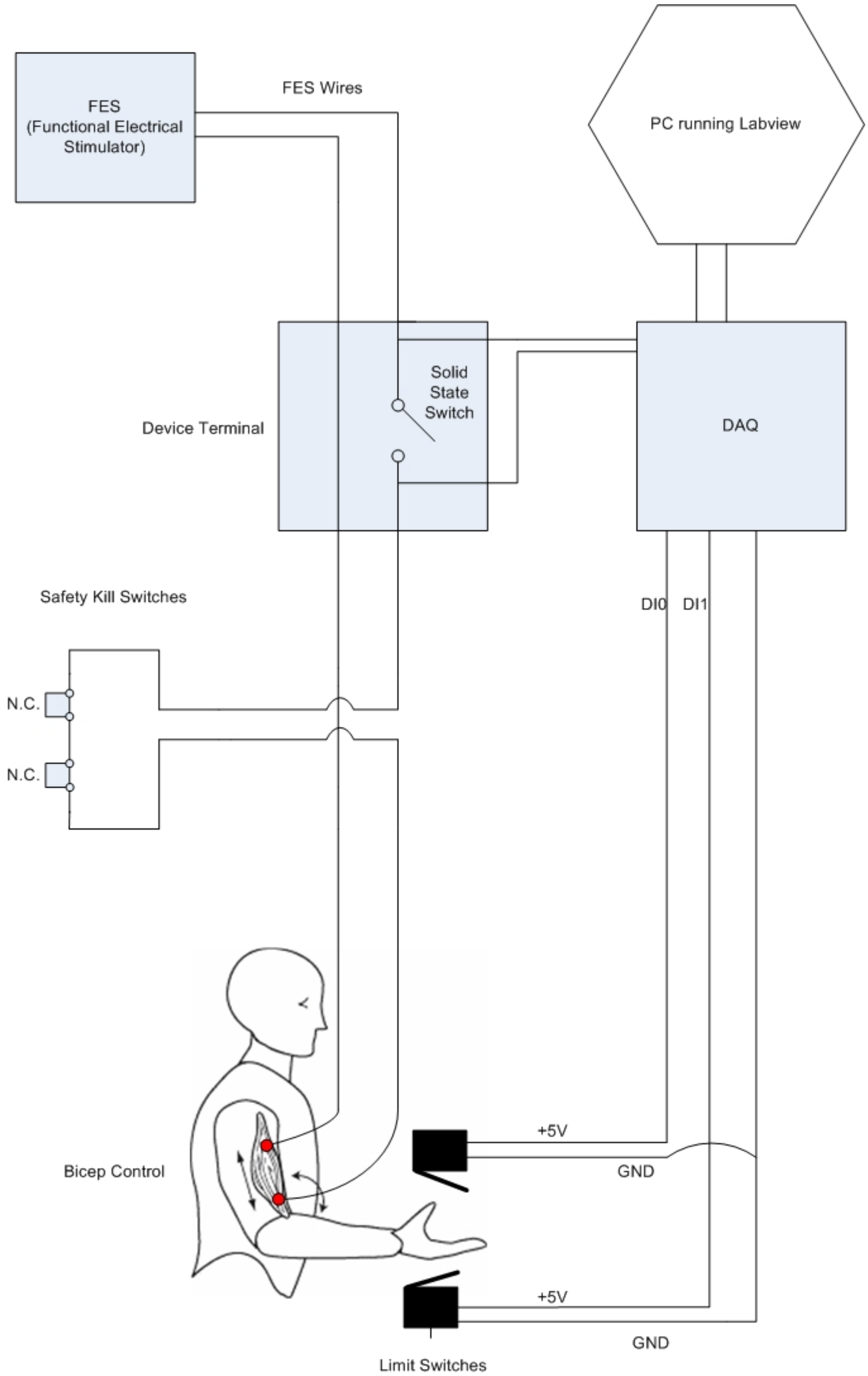

Figure 6.3: Circuit Layout for Biceps/Triceps Control Mechanism

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Appendices

APPENDIX A: MATLAB CODE

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FES Recumbant Bicycle Main Program
%%%
%%% Justin E. Guy
%%% Original: October 14, 2013
%%% Last update: October 14, 2013
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tic
clc
clear all
%%%%%%%%%%%%%%%%%%%%%%%% Input parameters
    %%%%%%%%%%%%%%%%%%%%%%%%
    dirname = ['C:\Users\Justin Guy\Desktop\JEG FES Bicycle
        \Input_files\'];


%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


disp('FES Recumbant Bicycle Main Program')
disp(' ')
disp(['Input file directory name = ',dirname])

disp(' ')

t_step = .001;              % time step in mili-seconds

samp_freq = 25;             % Downsampling frequency (25 Hz
    )
filt_freq = samp_freq/pi  % Calculated Filter frequency

```

```
%%%%%%%% Analysis of rifle stability during static hold %%%%%%%%%%
for s = 87:89              % Repeat for each subjects

%          name = ['Working on : ','KMS_s',int2str(s), '_t',int2str(k)];
%          disp(name)
         filename = ['Justintest',int2str(s),'.txt'];
         dat = dlmread([dirname,filename],'\t',5,0);

         t = dat(:,1)*t_step;      % time in seconds
         theta = dat(:,3);         % angle (deg)
         atheta = dat(:,4);        % accumulated angle (deg)
         omega = dat(:,5);         % angular velocity (deg/s)

         omega2 = diff(atheta)/t_step;  % calculates the angular velocity
         omega2 = [0;omega2];           % adds an extra zero at the start to make the vectors the same lenght

          mean_omega2 = mean(omega2);
          SD_omega2 =  std(omega2);

          disp(['Original mean =',int2str(mean_omega2),' deg/s   Standard Deviation =',int2str(SD_omega2),' deg/s']);

         % Anti-aliasing filter before sub-sampling
         [b,a]  = butter(7,filt_freq*t_step/.5,'low'); % lowpass filter coefficients
         omega2 = filtfilt(b,a,omega2);                         % lowpass filter

         mean_omega2 = mean(omega2);
         SD_omega2 =  std(omega2);

         disp(['filtered: mean =',int2str(mean_omega2),' deg/s   Standard Deviation =',int2str(SD_omega2
```

```
        ),' deg/s']);

        upper_limit = mean_omega2+2*SD_omega2;
        lower_limit = mean_omega2-2*SD_omega2;
        for i=1:length(omega2)
            if(omega2(i)>upper_limit)
                omega2(i) = upper_limit;
            end
            if(omega2(i)<lower_limit)
                omega2(i) = lower_limit;
            end
        end

        mean_omega2 = mean(omega2);
        SD_omega2 =  std(omega2);

        disp(['Data cropped: mean =',int2str(mean_omega2),' deg/s   Standard Deviation =',int2str(SD_omega2),' deg/s']);

end   % s

figure(1)
plot(t,theta)
ylabel('Degrees','FontSize',12)
xlabel('Time(seconds)','FontSize',12)
title('\it{Angular Data}','FontSize',12)

figure(2)
plot(t,atheta)
ylabel('Degrees','FontSize',12)
xlabel('Time(seconds)','FontSize',12)
title('\it{Accumulated Phase Angle}','FontSize',12)

figure(3)
plot(t,omega)
ylabel('Velocity','FontSize',12)
xlabel('Time(seconds)','FontSize',12)
title('\it{Angular Velocity(Deg/s)}','FontSize',12)
```

```
figure(4)
plot(t,omega2)
ylabel('Velocity','FontSize',12)
xlabel('Time(seconds)','FontSize',12)
title('\it{Angular Velocity with Filter}','FontSize',12)





time = toc;
hours = floor(time/60/60);
mins = floor( (time-(hours*60*60))/60);
seconds = time-(hours*60*60)-(mins*60);

disp(['Time expired = ',int2str(hours),' Hours, ',int2str(
    mins),' Mins, ',int2str(seconds),' Seconds']);
```