Novel EMG-IMU Sensor Array for a 5-DOF Wearable Robotic Upper-Limb Exoskeleton

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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***Abstract*—A wearable upper-limb exoskeleton is a device that has applications in upper-body traumatic injury rehabilitation. The Fourth Year Mechanical Engineering Capstone group will design a robotic exoskeleton for five degrees of freedom. Both electrical and mechanical solutions are required to compose the prototype. The aim of this paper is to design a sensor array for a wearable robotic exoskeleton. Using eight electromyography (EMG) sensors to detect muscle activity and three inertial measurement unit (IMU) sensors to give angle feedback, a unified input device can be constructed to use muscle activity to control external actuators. A prototype wearable sensor array of this description was built and tested. The results demonstrated the efficacy of the design and warrant further iteration.**

Keywords—EMG, IMU, Exoskeleton, Upper-limb, Wearable

I. INTRODUCTION

A. Overview and Motivation

Wearable devices provide medical assistance for patients who need to be monitored and recorded through the transmission of biological signals. The wearable robotic upper-limb exoskeleton has the potential to drastically improve rehabilitation. These devices can operate as motion exoskeleton devices for active use like power and motion assistance or rehabilitation exoskeleton for passive uses like treatment of patients with neuromuscular disorders [1].

The upper-limb robotic exoskeleton requires mechanical, electrical, and software components to provide the wearer with a functioning device for continuous arm motion. This study will use five degrees of freedom (DOF) to develop the design. To achieve this, the design will use three DOFs in the shoulder and two DOFs in the elbow. The objective of this project and focus of this paper will be to determine the sensor types, design a sensor array in a textile exoskeleton, and develop a code to monitor the sensors.

B. Background and Literature Review

A literature review was conducted to examine the current state of wearable sensors in an upper-limb wearable device. The first paper was a review of EMG-based motor intention prediction of continuous human upper-limb motion [2]. This text included an overview of the different models widely used in the field accompanied by general information on various aspects of development. Areas of study included upper-limb motion mechanics, EMG signal processing and acquisition, types of EMG sensors, and models/algorithms for continuous motion. The paper also highlighted the current issues that the field currently faces such as interference from other electronic devices and sensors shifting while using the various assistive devices. Additional solutions proposed included the recommendation of using decomposed EMG signals to maintain data integrity and a transition to higher-density EMG sensors to mitigate the degradation of signals if the sensors move from their original position.

The second paper was a review of current upper-limb exoskeletons and prototypes [3]. The authors describe classifications, comparative solutions, and an overview of the designs. The review acknowledges the lack of studies examining the complex interaction between the human and robotic exoskeleton of the arm and wrist. Sixteen available systems and fifty-three prototypes were examined based on the degree of freedoms, control input, actuator type, control strategies, and possible strategies. Each of the aforementioned factors influenced the sensor choice. Additionally, sensor choice is controlled by the goal of the exoskeleton and the weight of the device parts.

The third paper focused on a study looking at an exoskeleton that targeted both the shoulder and elbow joints [4]. The performance of the exoskeleton was evaluated in a study with eight healthy individuals, and the results demonstrated that shoulder muscle activity decreased with increasing magnitude of assistance. This paper focused on the gap in multi-joint exoskeletons, and in the exoskeleton developed they only used 3 IMUs. Limitations, in this case, were the lack of evaluation for any individuals with a need for the exoskeleton.

II. SUMMARY OF GOALS AND CONTRIBUTION

The goal of our team was to create a unified input technology for human-robotics interaction. To achieve this, we created a wearable, textile sensor array that monitored and read out muscle activity from the EMG sensors and determined the upper-limb joint angles from the IMU sensors. The design and testing process allowed a deeper understanding of effective sensor placements for the EMGs on the muscles and the IMUs near the joints. The developed code interpreted the signal data so that it could be used to communicate with the actuators involved in creating the motion of the arms. The muscle activation and joint angles would work in conjunction with the actuators to apply an appropriate amount of force to achieve the user's intended motion. The findings of this report should contribute to the process of ultimately building an exoskeleton capable of assisting those with neuromuscular disorders to perform simple motor functions.

III. Technical Details

A. EMG Sensor Design

The EMG sensor array will interpret muscle signals by directly reading the nerve signals from the brain. When movement is desired, the brain will sense an electrical signal via the nervous system to the muscle groups responsible for motion. These signals will be detected by the electrodes of the EMG sensor, amplified, filtered through a band-pass filter, and then send it to an Arduino microcontroller for analysis.

The signals that are collected through the EMG sensor will be amplified and then filtered with a bandpass filter. The resultant signal will have frequencies in the range of 30-150 Hz and be used for further processing. The parameters for the bandpass filter circuit were calculated with the components that were readily available for sale and are: R1 = 10 kΩ, R2/R3 =4.7 kΩ, C1/C2 = 0.47 µF. These figures will allow the signals in the range of 33-144 Hz. The processed signal will then be transferred to the microcontroller for further actions. The bandpass filter circuit and EMG sensor design shown in Fig 1 and Fig 2, respectively, are proposed but will ultimately be used in future iterations of the design. For the prototypes constructed in this research, the commercially available "MyoWare Muscle Sensor" was purchased, soldered, and used for the experiment.

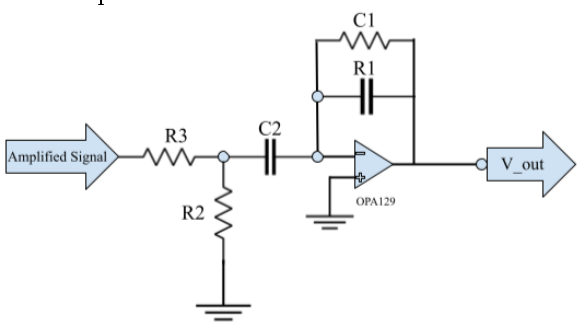

Fig. 1. Schematic of the band-pass filter circuit, with components labeled to match design parameters stated above.

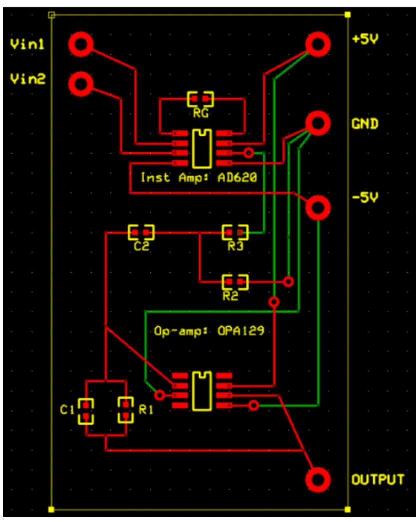

Fig. 2. PCB Drawing of a simple EMG Sensor

For shoulder flexion and extension, the posterior deltoid, the anterior deltoid, the pectoral muscle, and the biceps are important contributing muscles. The muscles of the deltoid and the pectoral muscle are also associated with shoulder abduction and adduction. For shoulder rotation, the main muscles used are the anterior deltoid and the pectoral muscle. At the elbow joint, the intended arm motions were flexion, extension, and rotation of the forearm. The triceps and biceps help to extend and flex the forearm, respectively. To rotate the forearm so that the palm faces downwards, the pronator teres is the activating muscle while the supinator allows the forearm to rotate so that the palm faces upwards [5]. By placing the EMG sensors on these eight muscles, the electrical activity can be measured and distinguished for each type of arm movement from the signals.

As for sensor location on a particular muscle group, it is known that for two- or three-electrode EMG sensors that one electrode should be placed on the "belly" of the muscle. This is the location along the muscle that maximizes the action potential of the nerve signals. For certain muscles, like the supinator teres, a portion of the muscle is located under another muscle and further from the skin; therefore, the site of the greatest action potential may not be in the belly of the muscle. The area of the highest action potential, in this case, is the area closest to the center and closest to the skin.

B. IMU Sensor Specifications

The function of the IMU sensor is to give feedback information on the location of the exoskeleton. This is a very significant component of the design because it will allow the exoskeleton to adjust the amount of force produced by the actuators in the case of overshooting or undershooting the desired movement and destination.

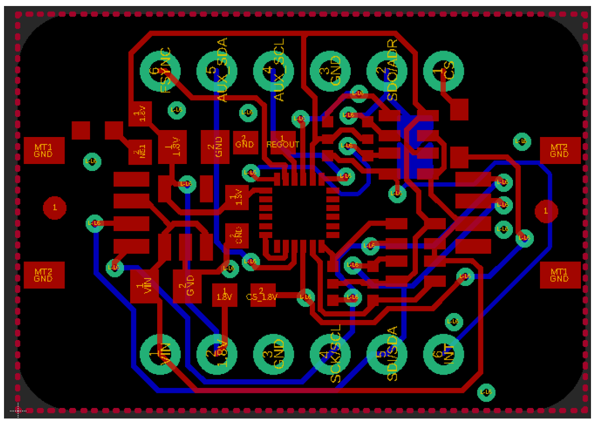

Fig. 3. PCB Drawing of the EMG Sensor

The IMU sensor that will be used in this research project is the commercially available Adafruit LSM6DSOX + LIS3MDL - Precision 9 DoF IMU. This sensor has a 3-Axis Gyroscope and 3-Axis Accelerometer, which allows for the collection of absolute rotation data. The PCB drawing of the IMU is available in Figure 4. There are 6 degrees of freedom accounted for with the use of the gyroscope and accelerometer, which will allow for accurate documentation of each joint. The shoulder joint has 3 degrees of freedom, the elbow joint has 2 degrees of freedom (Figure 4).

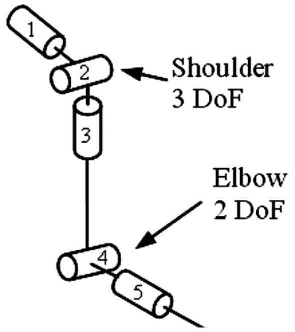

Fig. 4. Degrees of Freedom in the Shoulder and Elbow Joints

Closed-loop kinematic feedback will be provided by IMU sensors placed on the deltoid, the end of the upper arm above the elbow, and at the end of the wrist. The reason each IMU sensor is placed at the center of the joint is that while acceleration data can be measured anywhere along the arm structure, rotation occurs within the joint. It is necessary to have a separate IMU sensor for each joint because each joint has different degrees of freedom that are separate and must be accounted. Due to the fact that the exoskeleton only has two joints (shoulder and elbow), the IMU placed at the wrist is used as a reference point. Based on this understanding, the theoretical optimal placement was the center of the three joints as indicated in Figure 4. In Figure 5, the IMU sensors are represented by blue circles.

The IMU sensors will recognize the muscular motion and enable the actuators through unique programming. The specific measures of a working IMU sensor array in the exoskeleton would monitor the muscular change in orientation and acceleration at which the muscle is moved. The accelerometer measures the change in acceleration, and the gyroscope measures the change in angular motion. To accurately use the IMU, the exoskeleton will need both accelerometer and gyroscope parts.

The data collected from the closed-loop kinematic feedback system will be used in two different ways. First, using the gyroscope, the force/torque versus angle will be plotted for each joint. Then, using the accelerometer, the acceleration will be used to calculate position, and then plot force versus position for each joint. By plotting both position and angle versus force, the appropriate force necessary for the angle and position orientation will be determined for each joint. This data will be used to help program the actuators.

The success depends on the physical limitations of the user. Generally, the elbow muscular motion range would be 0-180 degrees. The shoulder rotation range is typically 70-90 degrees [6]. The gyroscope measurements would need to be within the respective muscular ranges. The acceleration depends on the user's body and intended motion. The expectation would be accelerations up to one meter per second squared, and this is based on physics analysis of arm motions.

C. Sensor Array Design

The sensor array was carefully designed to read primary, distinct muscle signals to be able to mimic the user's motion intention. Accurate muscle activation information for the largest muscle groups involved in the most important arm movements can be detected by carefully determining the proper muscle groups and locations, allowing an external actuator system to mimic the patient's intent with the actuators. The data collected from the EMG sensors on the muscles will allow the exoskeleton to accurately reproduce desired motions and movements seamlessly to improve the patient experience. To accurately read both upper and lower arm movements, eight EMG sensors were placed on the following muscles: anterior deltoid, lateral deltoid, posterior deltoid, pectoral muscle, bicep, triceps, pronator teres, and the supinator. These placements were chosen because they are core muscle groups involved in many important arm motions and are detailed in Figure 5.

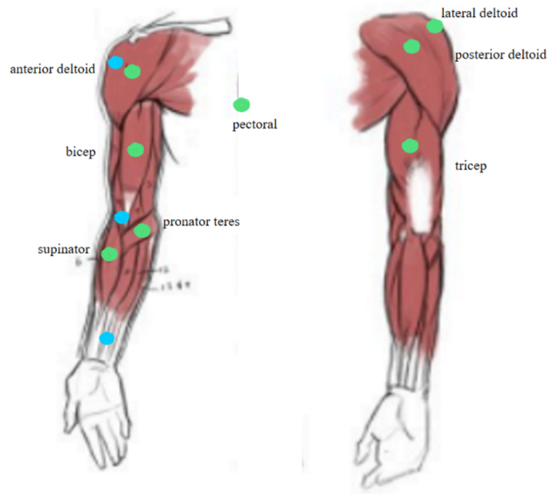

Fig. 5. Diagram with indicated locations of EMG and IMU sensor placement. (EMG sensors are represented by green dots, and IMU sensors are represented by blue dots)

Modeling the arm as a kinematic actuator with two joints (Fig. 4), each IMU must be placed on a different linkage to give real-time angular positions for each linkage and be able to understand the kinematic model of the arm.

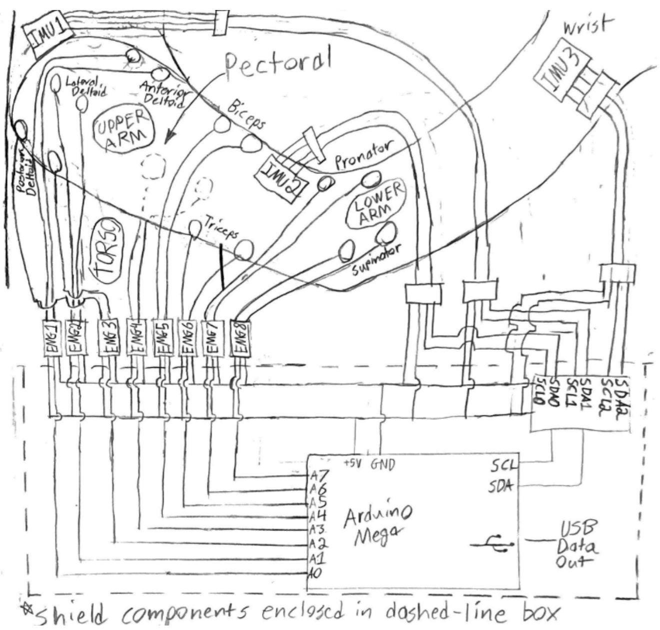

Fig. 6. Sensor array illustration detailing the full sensor array system design, including microcontroller and read-out circuitry

The IMU sensor array is used to give rotation and acceleration information which is used to generate feedback signals for actuator movement. This enables the system to understand its location and adjust the actuators according to new inputs. Determining the placements of each sensor represented a sizable focus of the experimental design. A simplified and labeled circuit illustration is provided above (Fig. 6). The Arduino Mega was used as a commercial solution with enough output pins to control all eleven sensors. The IMUs were attached via an I^2C multiplexer in order to connect all three IMU sensors to the Arduino.

The shield pictured below in Figure 7 was designed to simplify the wire connections to the Arduino Mega. Screw terminals were used in lieu of soldered connections or breadboard connections as a convenient way to create permanent connections without difficulty. It also allows for more organized wiring relative to the alternative of using soldered copper wires, jumper wires, and forced to manually hold wires in place during experiments. More work should be conducted to further simplify this interface.

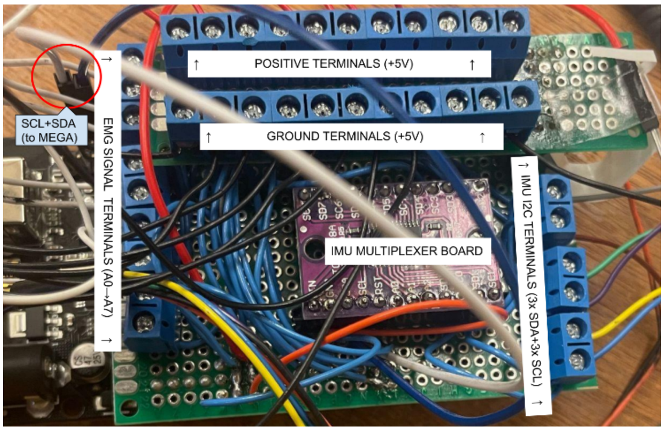

Fig. 7. Arduino Mega and Shield, labeled

D. Textile Version

A textile version of the sensor array was created for easier wearability. A long sleeve, compressive T-shirt design was selected as the base component. The shirt incorporated the wiring and 16 total EMG locations with each location composed of a snap connector for the belly of the muscle and a reference. Fig. 8 below depicts the intended EMG locations for the belly and end of the muscle.

Fig. 8. Planned design for the textile version of the EMG gel electrodes and wiring connections

Snap connectors were placed on each green ‘x’ on the shirt. Two, wire cables containing eight core wires connected the EMG gel electrodes snap connectors, and EMG sensor arrays. These wire cables were secured using fabric tape and fabric glue. Fig. 9 below shows the wire connections, fabric securing method, and snap connectors.

IV. *Methods*

The sensor array, comprising both EMG and IMU sensors, is designed to provide information regarding the patient's intended muscle action to the actuator system and to generate feedback for the actuators. The patient's intended motion is to be interpreted by eight EMG sensors that directly measure the electrical impulses of the local nervous system.

Each experiment involved connecting the EMG and IMU sensor array to a microcontroller to read the data. Then, a human test subject (a 22-year-old female) was fitted with the sensor array. The placements of the IMU sensors were consistent across every test. Each EMG sensor is attached to two gel electrodes, one of which is placed on the belly of the muscle and the other is placed at another point such that the sensor is parallel to the muscle fibers.

During testing, in all three experiments, the subject was instructed to perform certain motions while being video recorded. At the same time, the data from the sensors was being read out to the Arduino serial terminal. Aligning the video to the Arduino’s clock allowed the experimenters to determine when the motions took place without having to rely on either the EMG or IMU sensor data.

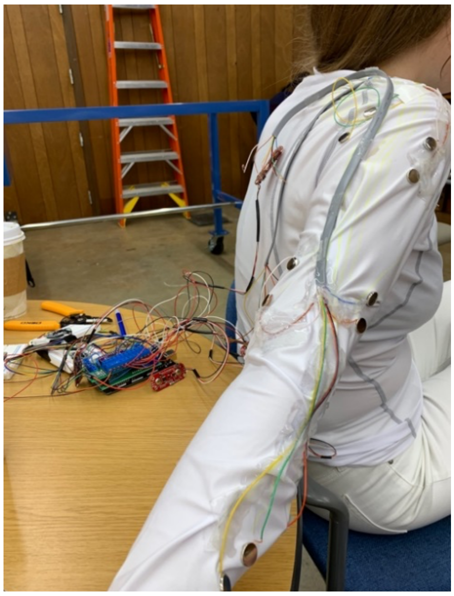

Fig. 9. The textile version of the sensor array depicts the snap connectors to gel electrodes, rainbow wire cables, sensor array, and wire-to-fabric stabilizing glue and tape

V. 1st Experiment Results

The purpose of the experiment was to determine the best sensors to use and verify the efficacy of their placements on the muscles. Due to material constraints, the arm motion experiments were separated into upper and lower arm testing, which were used to verify the efficacy of the EMG and IMU sensor array and to understand the signal output.

A. Upper Arm Motion Experiments

The upper arm test used an Arduino on the shoulder, an IMU sensor on the elbow joint, and an EMG sensor on each of the following muscles: anterior deltoid (A0), lateral deltoid (A1), posterior deltoid (A2), and pectoral (A3). Three to four trials were performed for each upper arm movement experiment were performed to verify the placement of EMG sensors and the efficacy of the coding used. The sensor array used for the upper arm experiments is depicted below in Figure 6. Each individual motion experiment is described in the body of this section.

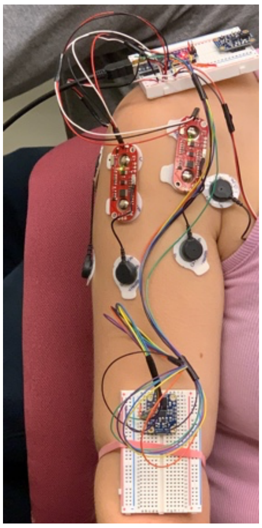

Fig. 10. EMG & IMU sensor array used for upper arm experiments

1. Motion 1: Upper Arm/Shoulder Flexion

The shoulder flexion motion was tested by starting the arm from the neutral position by the sides and moving it straight out in front. Physiologically, it is expected that the anterior deltoid and the pectoral muscles are mainly responsible for this motion. As shown in the graph, the anterior deltoid sensor (the blue line) displayed a strong signal, meaning that the muscle was activated during the motion. However, the pectoral sensor (the green line) did not register any muscle activity, which can be attributed to the poor placement of the sensor. The IMU data made sense as the motion caused a noticeable change in the z-direction and a smaller change in the y-direction with little change in the x-direction considering that the IMU was near the elbow joint.

2. Motion 2: Abduction & Adduction

This motion involves starting with the arms at the side of the body in a neutral position. With straightened elbows, the arms are then raised out to the side of the body until they are parallel to the ground (Abduction). The arms are then lowered in a control motion back to the side of the torso (Adduction). The main muscles that are involved in these movements are the deltoids. Due to this expectation, the deltoid signals in the EMG graph peak when the arm is parallel to the ground. What can be observed is the signal from the posterior deltoids after the simultaneous peaks from both the anterior and lateral deltoids. The signal from the pectoral muscles is basically nonexistent during these trials.

3. Motion 3: Upper Arm/Shoulder Extension

This motion involves rotating the upper and lower arm backward parallel to the motion of one's legs. An average person has a range of about 40º. The main muscle activations that were detected by the sensor array were the anterior and posterior deltoid muscles. The activations appear to max out the sensor reading, so it is difficult to know exactly where the peak activation occurs; however, the anterior deltoid activates slightly before the motion occurs and the posterior deltoid follows shortly after. After the arm is fully extended and brought back toward rest, the posterior deltoid is moderately activated and decreases slowly over time. The experiment detected no activation for either the pectoral muscle or the lateral deltoid, indicating improper gel electrode for both placements.

4. Motion 4: Horizontal Adduction with right-angle upwards arm bend

Motion 4 is horizontal adduction with the arm held at shoulder level and bent at a right angle. It demonstrated the most activation in the anterior deltoid (A0). The other muscle sensors were not activated as much as the anterior deltoid, which is surprising. It was expected that the posterior deltoid (A2) would have a reaction to the opposite motion of 5 because the anterior and posterior deltoids are antagonistic pairs of muscles. The IMU sensor data fits the prediction because there should be no activation in the Euler y and z directions. There is a spike in the Euler x-direction, which is explained by the raising of the hand to prepare the trails. Once raised, the upper arm remained in the same position, which is why the Euler x maintains position after the initial spike.

5. Motion 5: Upper Arm Internal/Medial Rotation with Arm Held Anterior to the Body (Goal Post)

The trial times are 260, 264, 269, 274, and 278 seconds.

This motion involved the upper arm held upright perpendicular to the torso and triceps, and the upper arm perpendicular to the lower arm. The arm motion was performed with the arm rotating internally towards the medial plane. As the upper arm trials were performed, the position of the IMU did not vary with time in Euler x or Euler y. The Euler z-direction of the IMU varies somewhat sinusoidally in each trial. The anterior, lateral, and posterior deltoid muscle actuation was present on the EMG Sensors Signals plot, with anterior deltoid having consistent moderate presence and posterior deltoid 'spiking' during arm motion. This indicates that the placement of the EMG sensor was correct. Additionally, the Arduino code was able to accurately measure muscular activity using EMG sensors and the positions of the IMU. The EMG Sensor Signals plot depicts very little pectoral muscle activity. This suggests that either the pectoral placement is not correct, or the pectoral muscle actuation is much lower than the deltoid muscle.

B. Lower arm motion experiments

The lower arm was evaluated using an Arduino on the wrist, an IMU sensor on the wrist, and EMG sensors on the following muscles: triceps, bicep, pronator teres, and supinator. The setup is depicted below in Figure 7. The lower arm movements performed in the experiment were bicep curl, pronation, and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table, and pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table.

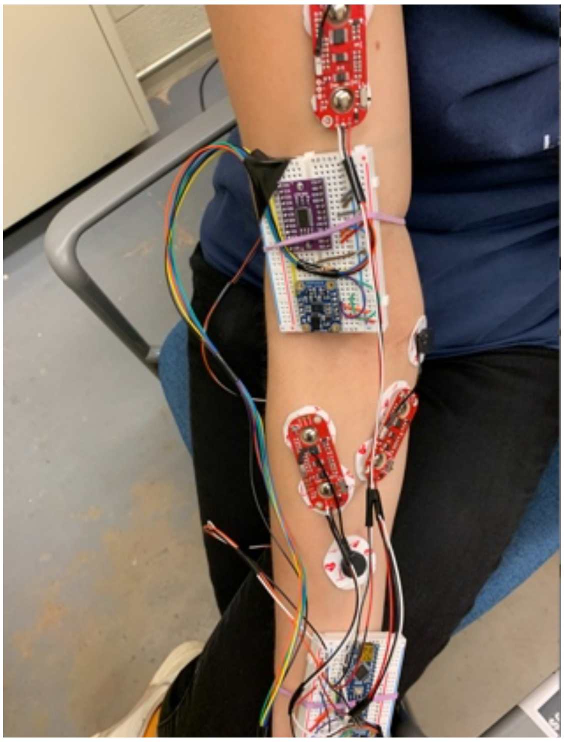

Fig. 11. EMG & IMU sensor array used for lower arm experiments

1. Motion 6: Bicep Curl

The first motion was a bicep curl. The EMG data demonstrates that the bicep was activated (A1) while the triceps was activated a few seconds after (A0). This makes sense because the muscles are antagonistic pairs. There was little activation from the pronator teres (A2) and a lot of activation from the supinator (A3). This does not make much sense. There should have been activation from the pronator teres, which demonstrates that the placement of the EMG signals on the lower arm was not effective. In terms of the IMU, no calibration was done, which is why the Euler x is at a higher degree from the start. However, the positions of Euler y and z correspond to the trial motions.

2. Motion 7: Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table

During this experiment, the elbow rested on the table and the arm was held at about a 45º angle while the forearm underwent pronation (rotated so that the palm was facing down) and then supination (rotated so that the palm was facing up). It was hypothesized that a noticeable activation of the pronator EMG sensor and the supinator sensor, but the graph showed almost no activity. The elbow was flexed while this experiment was run, so could that explain why the bicep was slightly active the entire time and it is also involved in supination. The elbow was extended as well as rotated during each trial, so that could explain the triceps activation, and the arm also moved down slightly (z-position dips on the IMU graph) during each trial. The slight movements in the x and y directions have to do with the small lower arm motions associated with the elbow rotation.

3. Motion 8: Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table

This motion experiment placed the lower arm at near level with a horizontal surface. The subject proceeded to pronate her wrist joint and then supinate the same joint for a total of seven trials. The EMG activation data was nearly identical to the data for the same motion at 45º but in lower intensity. This trial was useful in providing insight as to whether muscle activation was position-dependent, and the results are inconclusive. Since the only difference is in amplitude, the difference may instead result from a different level of exertion. It is unclear whether the subject felt that the necessary exertion was lesser, so further experiments must be done to decide whether the lower arm movement depends on the upper arm's position in space.

VI. 2ND EXPERIMENT RESULTS

This experiment included all eight EMG sensors and all three IMU sensors connected to the sensor array collecting data simultaneously. The goal was to demonstrate the sensor array's full capability as an input device to ensure that all the sensors worked at the same time and to make sure the code could measure the outputs from all eleven sensors. The five shoulder motions and three elbow motions were performed and collected with the Arduino code. Each motion consisted of five trials showing the three IMU and eight EMG signals. The data was processed and presented on the graphs in the Appendix under Experiment 2 similarly to Experiment 1.

A. Upper Arm Motion Experiments

1. Motion 1: Upper Arm/Shoulder Flexion

When comparing the IMU 1 graph to the IMU graph from Experiment 1, it is likely that the orientation of the IMU sensor was not the same in both experiments, which caused some of the discrepancies between the angle outputs. The other two IMU graphs show consistent results with distinct peaks that align with the EMG peaks from the motion. There were large angle changes in the elbow and wrist IMUs, which makes sense considering that shoulder flexion causes drastic changes in the position of those two joints relative to the shoulder.

The main issue with the Experiment 1 shoulder flexion graphs was the lack of a pectoral muscle signal that was supposed to contribute to the motion. Therefore, the placement of that EMG sensor for this experiment was changed and higher levels of activation were observed. However, the activation seems to be consistent throughout the duration rather than showing peaks when the motion occurred, which suggested that the placement was still not ideal to show pectoral muscle activity. The lateral and anterior deltoid EMGs displayed similar signals to the previous experiment, which was encouraging. The posterior deltoid signal was lower. Placing the EMG sensors on the skin was an educated guess as to where the belly of the muscle was located, so it was understandable that the data was not always consistent between experiments. The upper arm and lower arm EMG graphs were mostly to show the other sensors working, but shoulder flexion does not involve those muscles as much as the shoulder muscles.

2. *Motion 2: Abduction & Adduction*

The data from the EMG graphs for this motion strongly correlated with the expected muscle activity for adduction/abduction. The anterior and the lateral muscles displayed the most activity as they are responsible for lifting the arms and lowering them as well. The rest of the muscle groups, such as the biceps and pronator teres, did not have as much muscle activation since they are not utilized in these motions. The activation for these other groups was more consistent throughout the trials, rather than having peaks and troughs similar to the signals from the deltoids.

The data from the IMU sensors also correlated with the hypothesized results due to only one axis showing significant motion. The results deviated since the x-axis had the most motion and not the z-axis which is typically thought of as the axis for upward motion. This minor error is possibly due to improper mounting of the IMU sensor.

3. *Motion 3: Upper Arm Extension*

This motion was expected to activate the posterior and anterior deltoid muscles. The arm is raised from a resting position at the person's side and then raised until the extended arm is parallel to the ground. The data showed that the posterior and anterior muscle groups had the most activity as they are responsible for raising and lowering the arm. Surprisingly, the bicep and pronator teres muscles had significant activations.

The data from the IMU sensors showed the sensor array working as intended with regular peaks and troughs in the resultant activation signal. The only deviation in the data was toward the end of the trial where the x-axis for IMU 3 had drastic changes in the angle data that were possibly due to the wearer moving in that direction.

4. *Horizontal Adduction with right-angle upwards arm bend*

The internal/medial rotation with the arm held lateral to the body experiment was conducted to understand the bicep, triceps, pectoral, and shoulder muscles. All three IMUs measured changes in the Euler X, meaning that all three detected the change in angular position caused by the arm motion. However, what was expected was for IMU 1 to not detect any such change in position given that the aim is for the rotation in the upper body to be captured in the relative difference between IMU 1 and IMU 2. In line with expectation, all three IMUs showed no significant changes in Euler Y and Euler Z.

The EMG sensor positions aimed to detect muscular electrical activity in the anterior deltoid, lateral deltoid, and pectoral muscle. The desired activations were achieved in the anterior deltoid and the lateral deltoid, but the activity in the pectoral sensor does not correlate with any of the IMU-detected angle changes or the other EMG signal changes, reflecting the broader issues with the pectoral sensor. In conclusion, the deltoid activation was successful, the pec activation was less so, and IMU 1 should be moved so as not to detect motion in the shoulder.

5. *Motion 5: Upper Arm Internal/Medial Rotation with Arm Held Anterior to the Body (Goal Post)*

The trial times for this motion are 197, 201, 207, 210, and 215 seconds.

The IMU data from Experiment 1 demonstrates activation from the Euler X and Z but no signification activation from Euler y for IMU 1. In Experiment 2, all three IMUs correspond to the motion trials at all times (197, 201, 207, 210, and 215 seconds). This is a great improvement compared to Experiment 1.

In Experiment 1, the most significant sensor signal was demonstrated by the anterior deltoid. When comparing the EMG sensor graphs from Experiments 1 and 2, the anterior deltoid and lateral deltoid had the most activations that correlated to the motion trials (4 motions out of 5). The posterior deltoid in Experiment 2 only activated for two out of five upper arm motions. For the tricep and bicep, the sensor was only activated for one motion trial. During Experiment 2, there was signal activation from the pectoral muscle which is an improvement from Experiment 1, however, the activation did not correspond to any of the motions. The supinator sensor signal correlated to 3 out of 5 trials at times 197, 201, and 210 seconds. The pronator sensor signal only correlated to the motion at 207 seconds. It seems that the supinator muscle has significance in this motion, while the pronator does not.

B. *Lower Arm Motion Experiments*

6. *Motion 6: Bicep Curl*

This motion trial was designed to isolate and test the activation of the biceps EMG sensor. The results for the biceps did indicate the desired activation; however, the peaks were somewhat lower than expected, at around 400 -500 mV. Additional significant activations include the posterior deltoid EMG sensor and both the pronator and supinator sensors. Like the other trials, the pectoral sensor activation does not correlate with any motion and is thus dismissed as noise.

7. *Motion 7: Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table*

The IMU graphs for the pronation and supination at a 45-degree angle showed promising results. The shoulder and elbow sensors displayed small angle changes, which makes sense because both of those joints were relatively fixed during the test. The wrist IMU, as expected, showed five distinct peaks for each of the trials where the lower arm was rotated.

The main issue when observed performing this motion in Experiment 1 was the lack of pronator and supinator muscle activity that was supposed to contribute to the rotation of the forearm. Therefore, the EMG sensors at those locations were replaced and the observed activation signals saw a significant increase for the pronator and supinator muscles. The activity was still a bit inconsistent and did not achieve as high of a voltage reading as expected.

8. *Motion 8: Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table*

The pronation and supination at 5 degrees experiment were performed and indicated significant improvement in the gel electrode placement for the pronator teres and supinator. The supinator periodically ranged between 25 to 425 mV during actuation, and the pronator teres ranged between 0 and 70 mV during actuation. Other significant muscles contribution to this arm motion were the biceps and pectoral. The EMG results showed improvement for gel electrode placement on muscles. Additionally, through measuring and plotting the results for the three IMUs, the device connections and accuracy were successful. As expected, IMU-1 and IMU-2, placed on the shoulder and elbow respectively, were stagnant and showed little to no variation in the movement of angular position during the experiment. However, IMU-3 which was placed on the wrist showed increased movement somewhat periodically for Euler X, Y, and Z directions.

VII. 3RD EXPERIMENT RESULTS

The purpose of this experiment was to test the textile version by measuring the eight EMG sensors under different upper and lower arm motion experiments. The button connectors were successfully used to secure both the electrodes at the intended muscle sites and the wires at the EMG sensors. After grounding the EMG sensor array, the EMG data were collected, measured, and plotted. The following upper and lower arm motion experiments do not include IMU data, as the focus was to validate the EMG sensors worked.

A. Upper Arm Motion Experiments

6. *Motion 1: Upper Arm/Shoulder Flexion*

Although the IMU sensors worked for previous experiments, there were complications in integrating the sensors with the textile version of the sensor array. As a result, only EMG data was collected for the repeated motions tested in the prior two experiments. As shown in the Experiment 3 Shoulder Flexion EMG graphs, the anterior and lateral deltoids exhibited good muscle activity, but the posterior deltoid activity was minimal, and the pectoral sensor was not working properly. The sensors worked successfully with the shirt for this motion, but the improved placement of the electrodes is needed for more accurate data, and there was inconsistent pectoral data behavior.

7. *Motion 2: Abduction and Adduction*

In the previous experiments, the abduction and adduction motions produced accurate data signals. The lateral deltoid muscles showed the most muscle activity in this experiment with the "anterior and comparison to both the posterior and anterior deltoids. This corresponded with the data that was previously gathered in Experiments 1 and 2. The surprising observations in this data set were the max signals that came from the supinator, triceps, and pronator teres groups. These cyclic maximum signals possible resulted from the signal interferences at these locations and the shifting of the electrodes.

8. *Motion 3: Shoulder Extension*

Similar to the abduction and adduction muscle data, the lateral deltoid muscle groups were almost maxed out for the duration of the trials. The data, upon comparison, seems almost equal to that of the abduction and adduction muscle activation patterns with the lateral deltoids, pronator teres, supinator, bicep, and triceps muscle groups displaying the max muscle signal periodically. The only muscles that demonstrated moderate activation were the anterior and posterior deltoids. The pectoral muscles showed very little activation during these trials possibly due to improper placement. A possible reason for all these high values would be the lack of a reference electrode in these locations to quantify the signals that are being collected from the various muscle groups.

9. *Motion 4: Horizontal Adduction with right-angle bent arm*

The horizontal adduction trial was largely successful. The EMG sensors on the anterior deltoid and the lateral deltoid detect obvious peaks which align with the predicted activation times. However, other muscles were activated that do not seem to be involved. They may still be accurate readings, but they could provide evidence for interference. In this case, it is believed that they are truly activations given that the arm is flexed in a 90° bend.

10. *Motion 5: Upper Arm Internal/Medial Rotation with Arm Held Anterior to the body (Goal Post)*

The implementation of the sensor shirt greatly improved signal activation in all EMG sensor signals excluding the pectoral muscle sensor. In the shoulder, the posterior and lateral deltoid correlated in four out of five motion trials, while the anterior deltoid had signal activation for all trials. In the upper arm, the bicep and triceps also had activation that was significant and correlated to all five trials. The pectoral muscle sensor did not have any activation. In the lower arm, the pronator EMG sensor signal correlated to all five motion trials while the pronator sensor signal correlated to four out of five motion trials. For this motion, the use of a sensor shirt greatly improved EMG electrode placement and achieved the most instances of activation correlated to actual motion trials.

B. Lower Arm Motion Experiments

6. *Motion 6: Bicep Curl*

The bicep curl experiment was conducted to prove the accuracy of sensor location for the bicep, triceps, posterior deltoid, lateral deltoid, and posterior deltoid during arm motion. As expected, the plots in Appendix D.6 show high muscular activation in the lateral deltoid, biceps, and triceps. The pectoral muscle was not significantly used in the bicep curl arm motion; however, it was unexpected for such low muscular activity near zero for the entire experiment. This indicates improper gel electrode placement on the pectoral. Another finding of this experiment was the increased pronator teres and supinator activity from the prior bicep curl muscular activity. This motion proves the placement of both lower arm sensors near the elbow as more successful than in Experiment 1, but a better placement is necessary for accurate muscular activity measurement. This experiment additionally showed the volatility of EMG gel electrode placement and the muscular activity or success of the experiment.

7. *Motion 7: Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table*

The pronation and supination motions with the sensor shirt gave us much-improved pronator and supinator signals and signal strength compared to the previous two experiments. There were more distinct and aligned peaks for each of the five trials with voltage spikes as high as 800 mV. The graph suggests the correct placement of the lower arm electrodes with the shirt and outputs meaningful muscle activation results.

8. *Motion 8: Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table*

The pronation and supination at 5 degrees experiment was conducted to prove the effectiveness of the sensor array for the pronator teres and supinator muscles. As the plots in Appendix D.8 show, this experiment proved the increased effectiveness of gel electrode placement on the pronator teres and supinator muscles. The pronator teres showed periodic muscular actuation which ranged between 200 to 800 mV. The magnitude of this result cannot be verified, but the general range of voltages and periodic nature correlating to the actuation are indicative of more proper gel electrode placement for this sensor compared to Experiment 1. The supinator showed muscular activity for the entire experiment with some decreases during actuation. The supinator should expand and contract and appear in spikes on the plot, just as the pronator teres. This signifies that muscle placement was not properly detecting the supinator, but the placement was detecting muscular activity – a significant increase in observed activity over Experiment 1. As for other muscles in this experiment, the lateral deltoid and triceps showed increased activity in each trial, and as expected, the pectoral muscle was not a primary muscle used.

VIII. Future Work and Conclusion

There are numerous improvements and further considerations that should be addressed in the future. First, the sensor on the pectoral muscle needs to be placed in a more optimal position. It was clear from all five motions that the pectoral EMG sensor was not activating properly. To correct the position of the pectoral EMG sensor, a few isolated trials could be performed. Alternatively, other muscles could be explored, or the pectoral muscle could be deemed nonessential for differentiating muscle movements. The sensor placements on all three deltoid muscles were effective. Additionally, in the lower arm tests, the second and third motions (pronation/supination of the lower arm) displayed relatively weak signals from both the pronator teres and supinator muscles (peak activations were much lower than other muscles). These results deviated significantly from the expectation since these muscles are largely responsible for the twisting motion of the lower arm. Further isolated trials for these muscles should be performed to find optimal placements or other muscles involved in those motions that can be read by the sensors.

The unified EMG-IMU sensor array has been demonstrated with all 11 sensors reading out simultaneously, and the textile sensor array has been demonstrated with the eight EMG sensors. The construction of a prototype array is complete, and code enabling read-out has been written.

The textile version of the sensor array integrated electrode snap connectors and wiring and introduced several other inherent issues. One challenge was the snap connectors were difficult to place and did not hold the wires in place. Next, the wiring schedule went through several iterations to achieve the final design. The group attempted to stitch wires, solder connections, and clamp wires to the textile version to secure wires from breaking and/or moving. Arguably the largest challenge of the shirt was the electrode placement as the compressive T-shirt material shifted with each use and when taking off and putting on the prototype. This made it difficult and laborious to trial. In the future, the shirt would have to be customized but easier to put on, adjust sensor placement, and be less bulky. One fix to achieve this is by adding a long zipper down the inner seam to allow for easier access to place EMG sensors.

Other future considerations for the textile version of the sensor array would include replacing the current wiring with fabric-sheathed copper wires, a backpack or other storage medium, and proper EMG grounding to the body. Fabric-sheathed wire tape would improve the aesthetics of the design, ease of construction, organize the wiring, and could potentially be easier to sew onto the shirt. A backpack would help manage the EMG boards, Arduino Mega. Last, Proper EMG grounding to the body is necessary for accurate sensor measurements. In the next iteration of the shirt, a more careful method of wiring and interfacing with snap connectors in the textile version of the sensor array should be devised.

To complete the unified human input device for the actuator system, two software components must be written. The first remaining component is an algorithm for predicting human motions given EMG input data. Given the complexity of the raw EMG inputs, a machine learning algorithm is a good candidate for this part. Second, a software implementation of a PID controller must be written. This would take in the angle data from the IMU array and actuate the artificial muscles to minimize the error.

Through this project, it was observed that it is difficult to correctly place the EMG electrodes to obtain consistent results. The pronator and supinator sensor positions were able to be corrected and thus produce reliable signals. The pectoral muscle sensor signals never produced meaningful data, which demonstrates that placement is an ongoing issue and worthy of further investigation. Overall, the EMG sensor data from the shirt was largely successful. In some instances, the use of the sensor shirt improved data collection for the EMG sensors and correlated better with the motion trials. While the sensor shirt is the first design iteration, the results demonstrated that the EMG sensors do not have to be local and there is little signal loss. The IMUs demonstrated meaningful results when tested in the second experiment. Another important consideration is to conduct tests on a diversity of patients, as all the above results were determined using a 22-year-old female human participant.

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[2] L. Bi, A.->Genetu Feleke, and C. Guan, "A review on EMG-based motor intention prediction of continuous human upper limb motion for human-robot collaboration," *Biomed. Signal Process. Control*, vol. 51, pp. 113–127, May 2019, doi: 10.1016/j.bspc.2019.02.011.

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Appendix A:

Arduino Mega Code to Measure Three IMU Sensors and Eight EMG Sensors

EMG_IMU_ARRAY_READOUT_MEGA.INO

```
#include
#include
#include
#include
#define BNO055_SAMPLERATE_DELAY_MS (100)

float posDelt;
float latDelt;
float antDelt;
float pectoral;
float biceps;
float triceps;
float pronator;
float supinator;
float time;
float timeReset;

/* select I2C channel using TCA9548A multiplexer
*/
void tcaselect(uint8_t channel)
{
// Serial.print("I2C Channel: ");
// Serial.println(channel);
Wire.beginTransmission(0x70);
Wire.write(1 << channel);
Wire.endTransmission();
}

Adafruit_BNO055 bno = Adafruit_BNO055(70);

void displaySensorDetails(void)
{
sensor_t sensor;
bno.getSensor(&sensor);
Serial.println("-----------------------------------
--");
Serial.print ("Sensor: ");
Serial.println(sensor.name);
Serial.print ("Driver Ver: ");
Serial.println(sensor.version);
Serial.print ("Unique ID: ");
Serial.println(sensor.sensor_id);
Serial.print ("Max Value: ");
Serial.print(sensor.max_value); Serial.println("
xxx");
Serial.print ("Min Value: ");
Serial.print(sensor.min_value); Serial.println("
xxx");
Serial.print ("Resolution: ");
Serial.print(sensor.resolution); Serial.println("
xxx");
Serial.println("-----------------------------------
--");
Serial.println("");
delay(500);
}

void setup(void)
{
Serial.begin(115200);
Serial.println(""); Serial.println("Orientation
Sensor Test"); Serial.println("");

Wire.begin();

uint8_t ch;
for (ch = 0; ch < 3; ch++) // multiple I2C devices
{
tcaselect(ch);

/* Initialise the sensor */
if (!bno.begin())
{
/* There was a problem detecting the BNO055 ...
check your connections */
Serial.print("Ooops, no BNO055 detected ... Check
your wiring or I2C ADDR!");
while (1);
}
}

delay(1000);

for (ch = 0; ch < 3; ch++) // multiple I2C devices
{
tcaselect(ch);

/* Display some basic information on this sensor
*/
displaySensorDetails();
}
timeReset = millis();
}

void loop(void)
{
time = millis() - timeReset;

Serial.print(time);
Serial.print(",");
uint8_t ch;
for (ch = 0; ch < 3; ch++) // multiple I2C devices
{
tcaselect(ch);

/* Get a new sensor event */
sensors_event_t event;
bno.getEvent(&event);
/* Calculates Euler Angles from Quaternion Readout
*/

imu::Quaternion q = bno.getQuat();
float temp = q.x(); q.x() = q.y(); q.y() = temp;
q.z() = -q.z(); // fly.c convention
q.normalize();
imu::Vector<3> euler;

/* Adafruit's confusing x,y,z names are actually
axis Z,Y,X rotations heading,roll,pitch */

euler.x() = 180 / M_PI * atan2(q.w() * q.z() +
q.x() * q.y(), 0.5 - q.y() * q.y() - q.z() *
q.z()); // yaw/heading
euler.y() = 180 / M_PI * atan2(q.w() * q.x() +
q.y() * q.z(), 0.5 - q.x() * q.x() - q.y() *
q.y()); // roll
euler.z() = 180 / M_PI * asin(2 * (q.w() * q.y() -
q.x() * q.z())); // pitch

/* Prints Euler Angle Readout */

Serial.print(euler.x()); // heading, nose-right is
positive, z-axis points up
Serial.print(F(","));
Serial.print(euler.y()); // roll, rightwing-up is
positive, y-axis points forward
Serial.print(F(","));
Serial.print(euler.z()); // pitch, nose-down is
positive, x-axis points right
Serial.print(F(","));
/* Also send calibration data for each sensor. */
// uint8_t sys, gyro, accel, mag = 0;
```

```
// bno.getCalibration(&sys, &gyro, &accel, &mag);
// // Serial.print(F("Calibration: "));
// Serial.print(sys, DEC);
// Serial.print(F(" "));
// Serial.print(gyro, DEC);
// Serial.print(F(" "));
// Serial.print(accel, DEC);
// Serial.print(F(" "));
// Serial.println(mag, DEC);
}
/* Arduino Nano Readout */
posDelt = analogRead(A0);
latDelt = analogRead(A1);
antDelt = analogRead(A2);
pectoral = analogRead(A3);
biceps = analogRead(A4);
triceps = analogRead(A5);
pronator = analogRead(A6);
supinator = analogRead(A7);
Serial.print(antDelt);
Serial.print(",");
Serial.print(latDelt);
Serial.print(",");
Serial.print(posDelt);
Serial.print(",");
Serial.print(pectoral);
Serial.print(",");
Serial.print(biceps);
Serial.print(",");
Serial.print(triceps);
Serial.print(",");
Serial.print(pronator);
Serial.print(",");
Serial.print(supinator);
Serial.println();

}
```

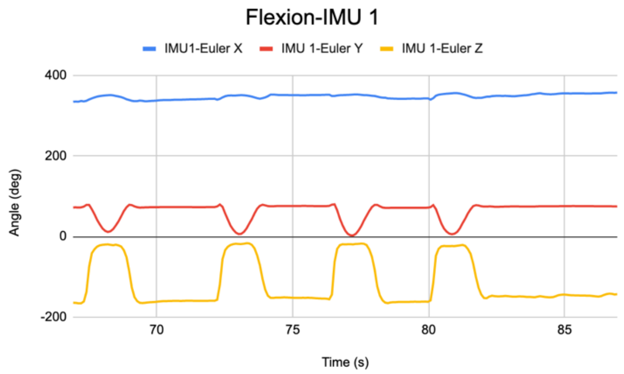
Appendix B

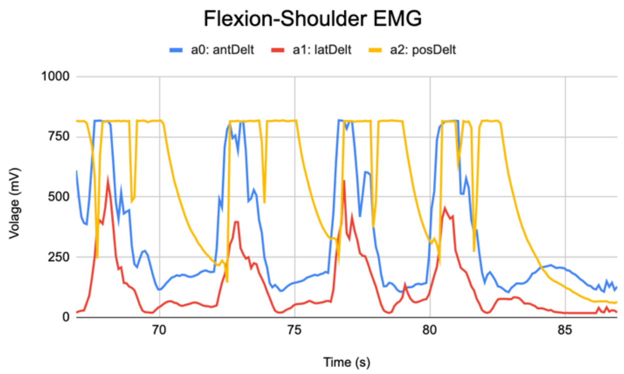
Experiment 1- Two individual experiments to analyze the interaction of IMU and EMGs

Experiment 1a - Upper arm experiments with an IMU placed on Elbow and Four Total EMGs (on the anterior deltoid, lateral deltoid, posterior deltoid, and pectoral muscles).

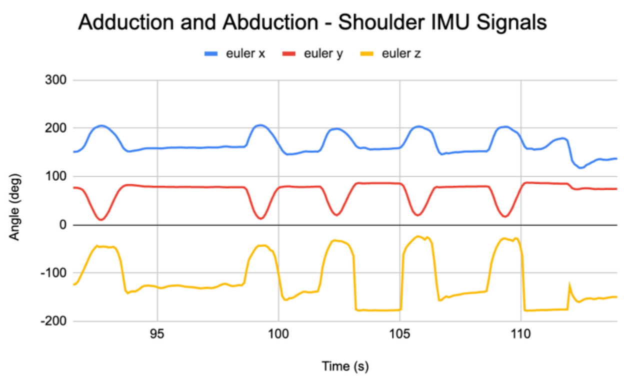
Experiment 1b – Lower arm experiments with an IMU placed on the Wrist and Four Total EMGs (on the bicep, triceps, pronator teres, and supinator muscles)

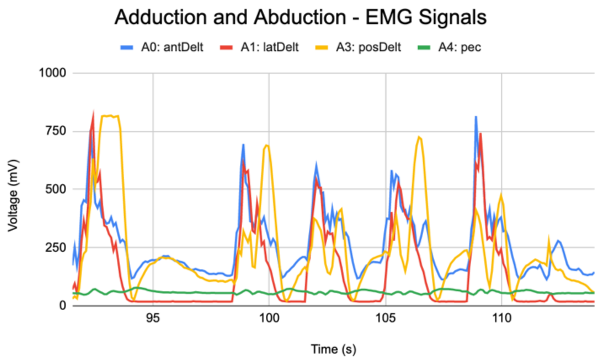
1. *Upper Arm/Shoulder Flexion*



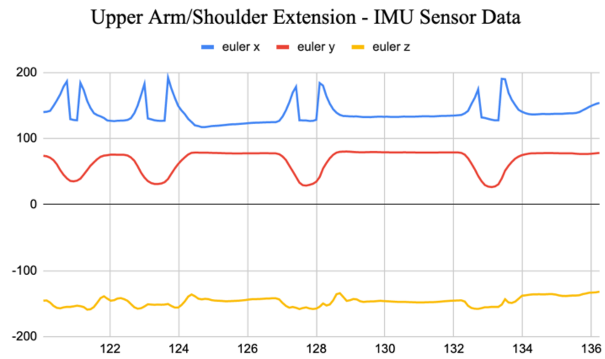


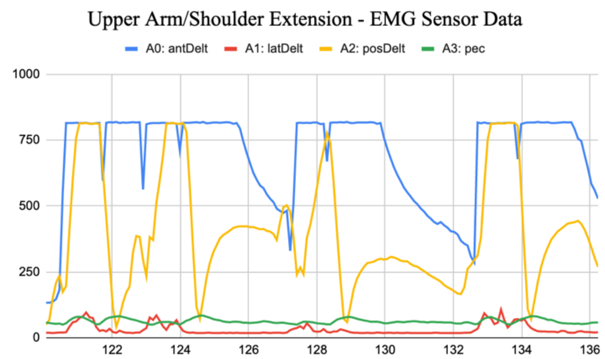
2. *Abduction & Adduction*



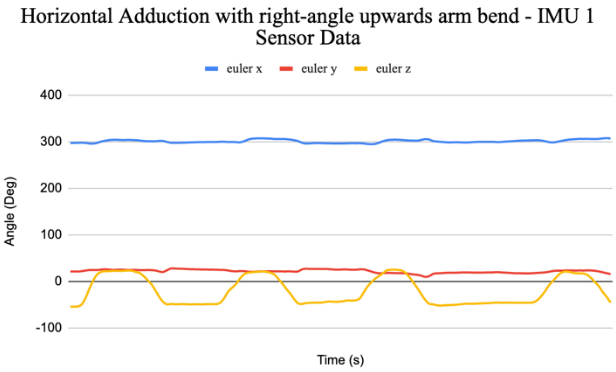


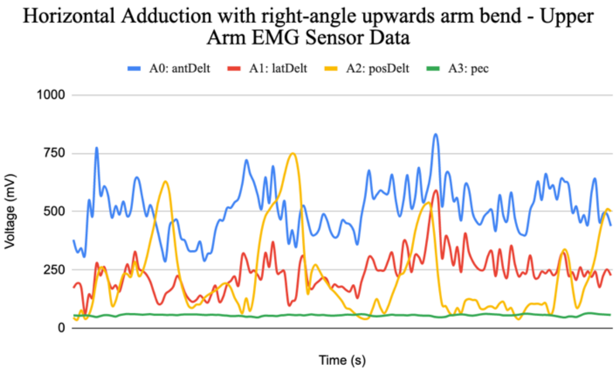
3. *Upper Arm/Shoulder Extension*



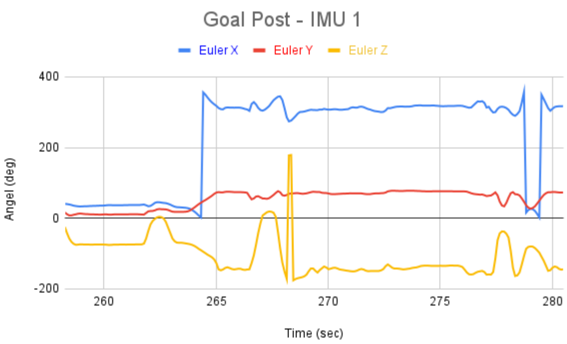


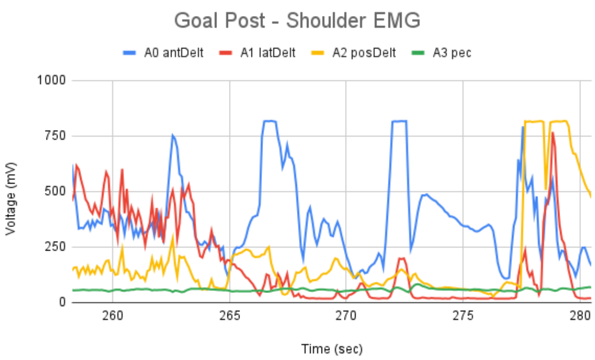
4. *Horizontal Adduction with right-angle upwards arm bend*



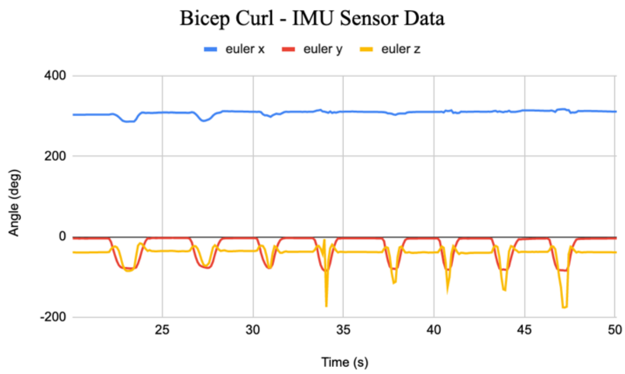


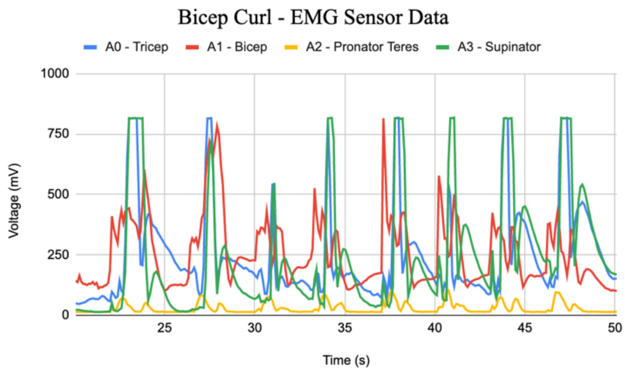
5. *Upper Arm Internal/Medial Rotation with Arm Held Anterior to the Body (Goal Post)*



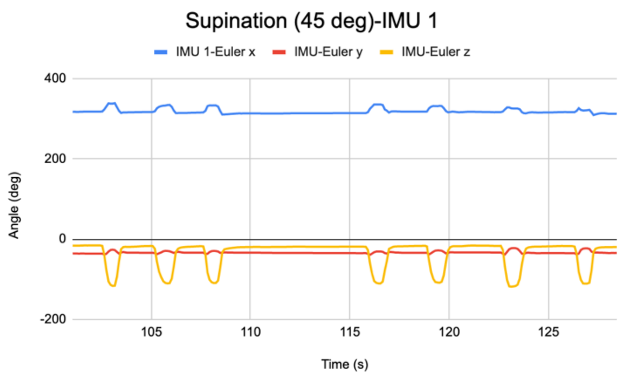


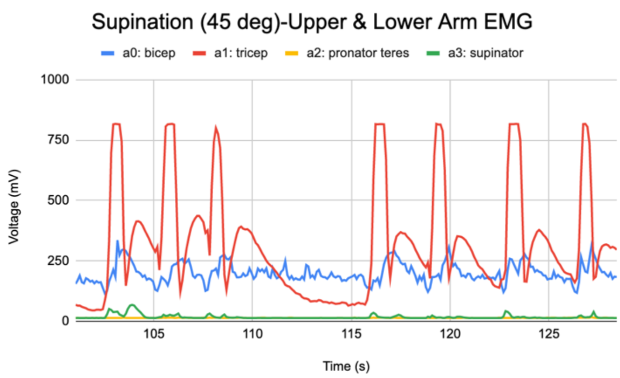
6. *Bicep Curl*



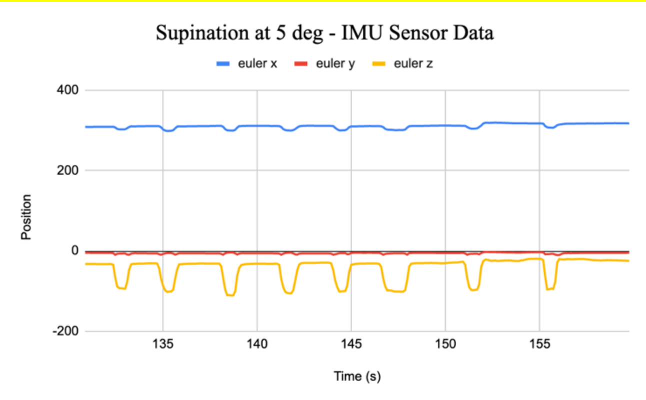


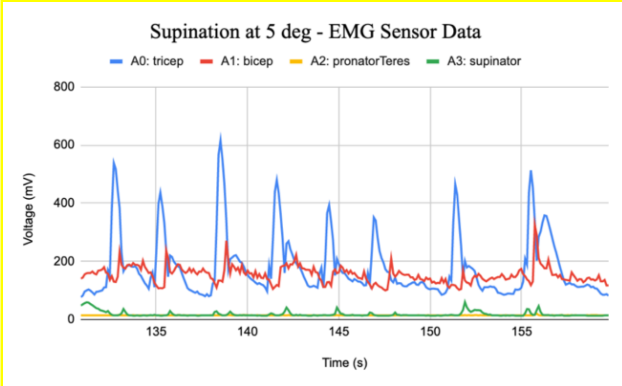
7. *Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table*





8. *Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table*

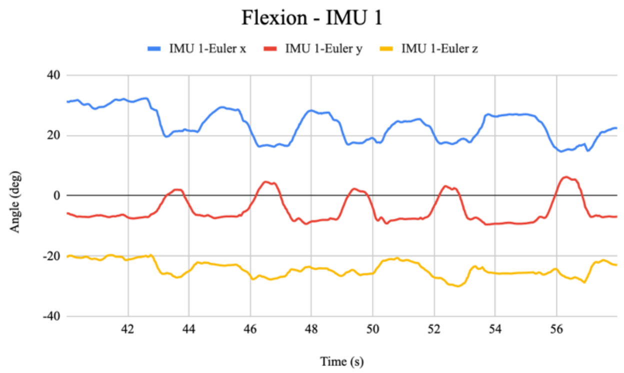

Supination at 5 deg - IMU Sensor Data
euler x
euler y
euler z
400
200
0
-200
Position
135
140
145
150
155
Time (s)

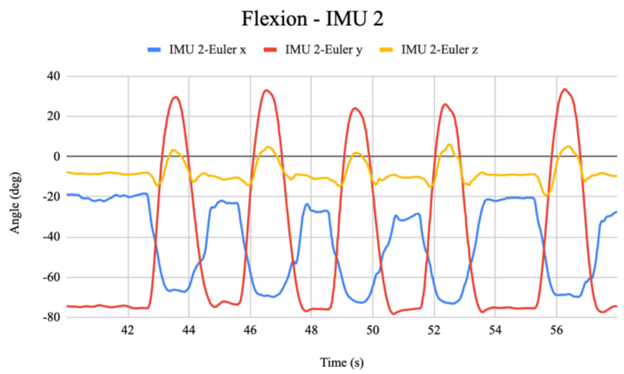

Supination at 5 deg - EMG Sensor Data
A0: tricep
A1: bicep
A2: pronatorTeres
A3: supinator
800
600
400
200
0
Voltage (mV)
135
140
145
150
155
Time (s)

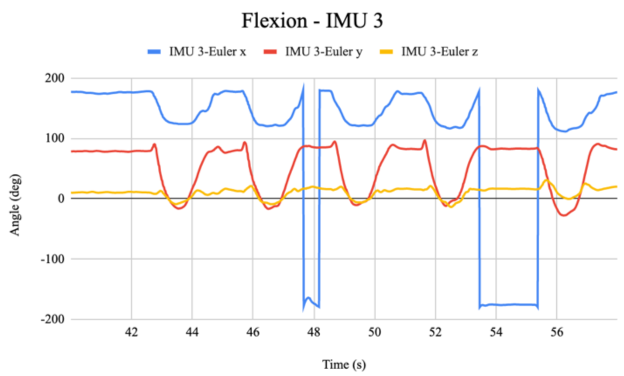
Appendix C:

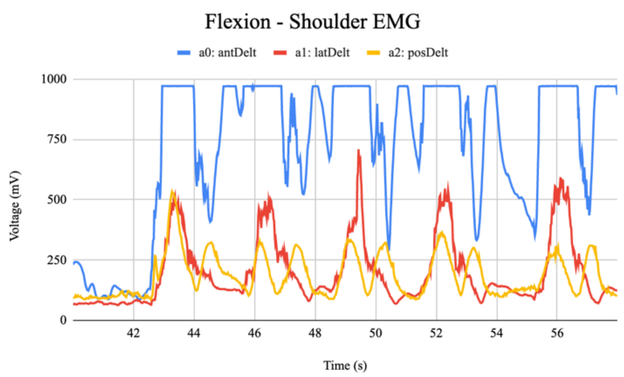
Experiment 2: Full Arm Experiments with Three IMUs and Eight EMGs

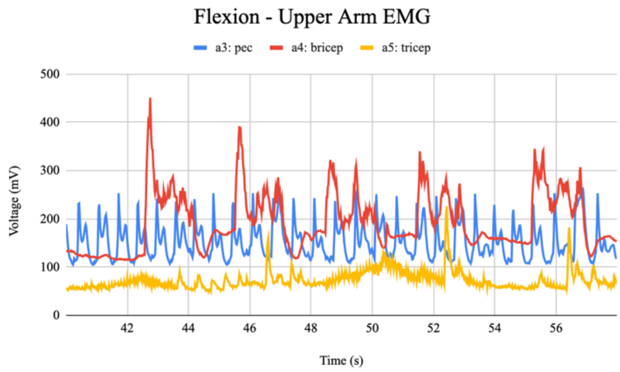
1. *Upper Arm/Shoulder Flexion*

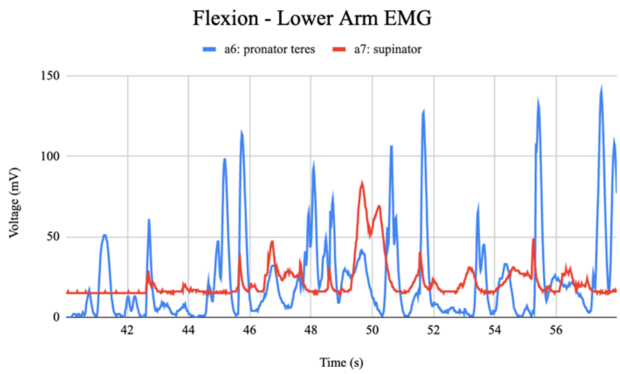




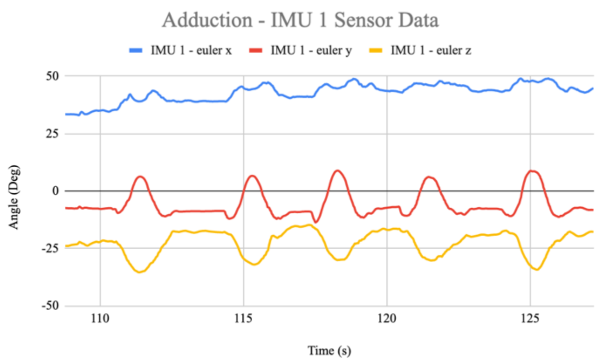


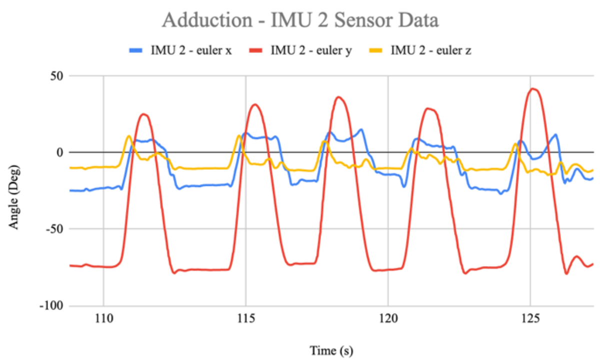


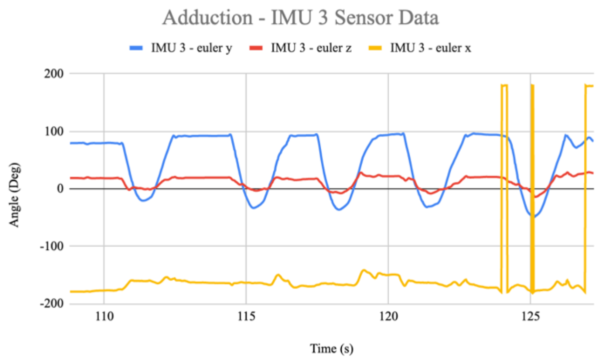


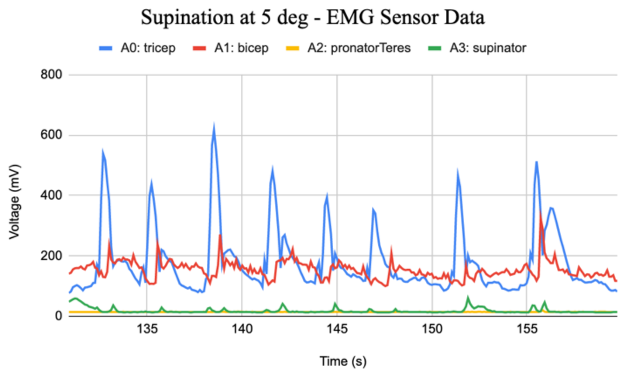


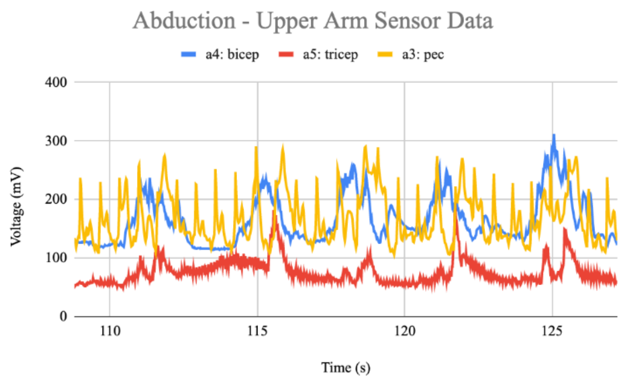
2. *Abduction & Adduction*

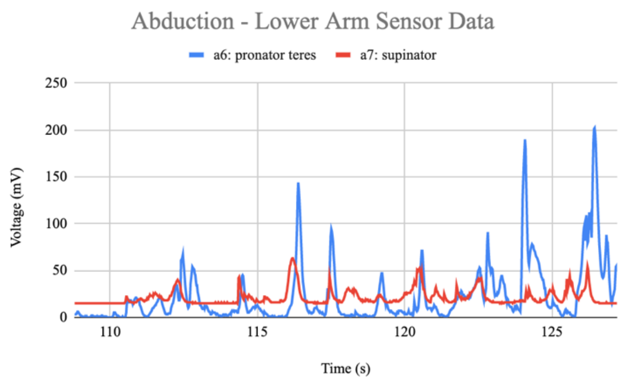




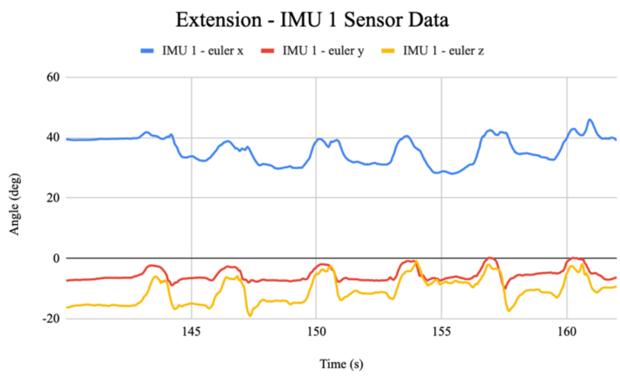


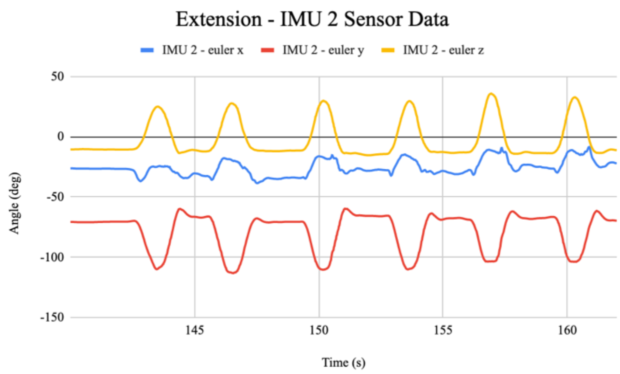


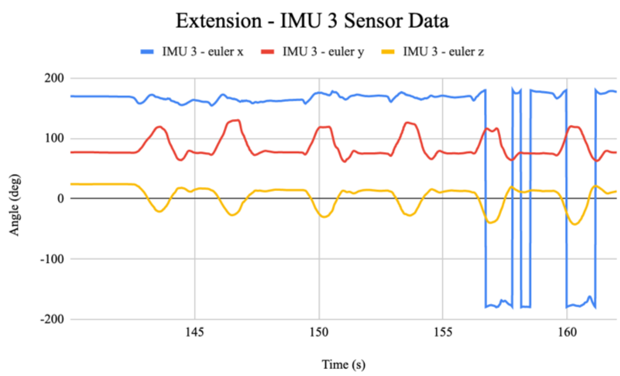


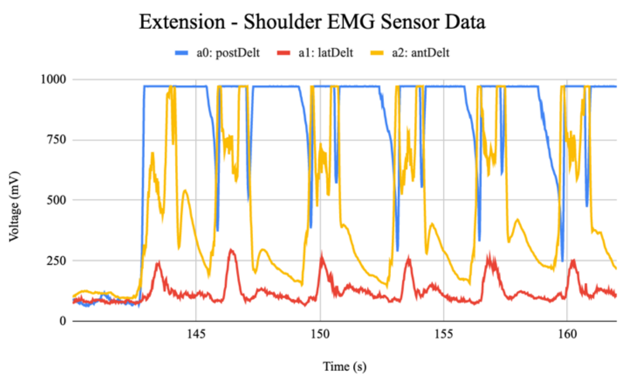


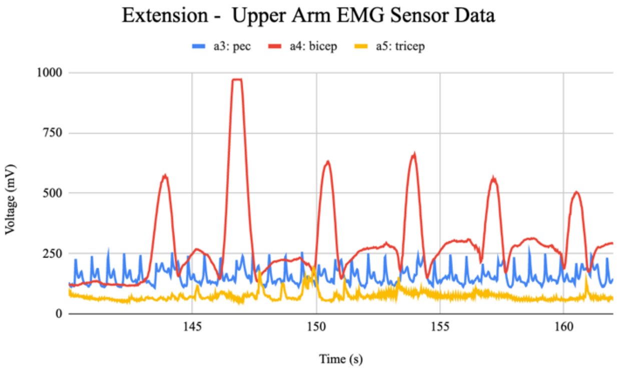
3. *Upper Arm/Shoulder Extension*

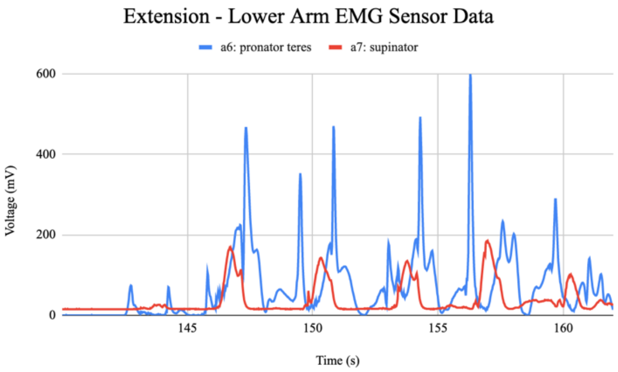




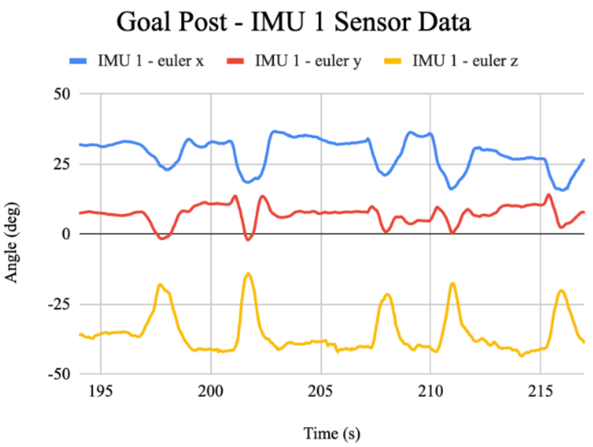


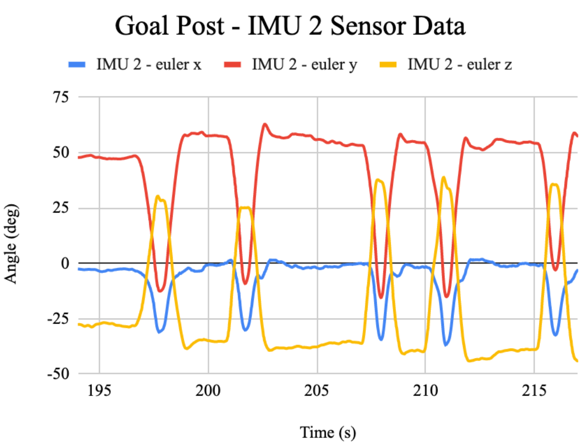


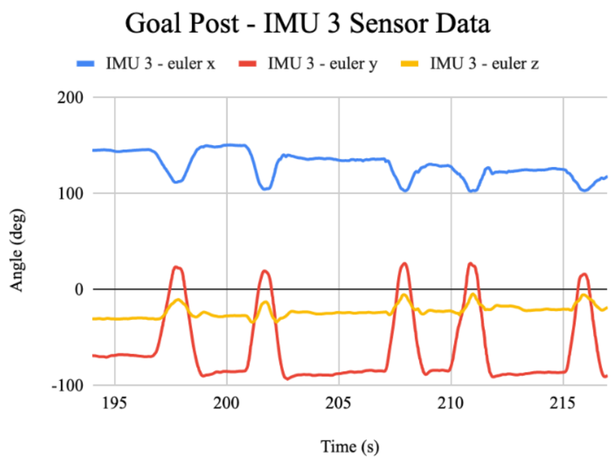


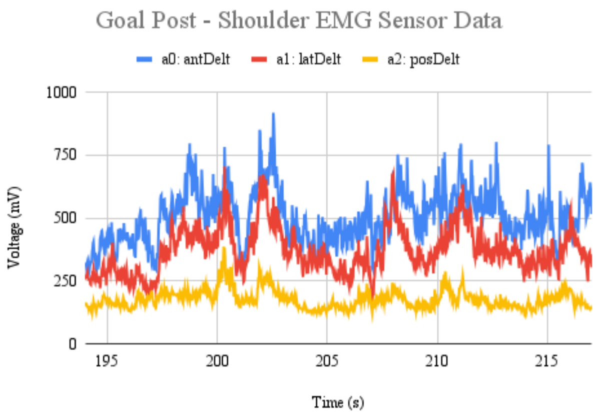


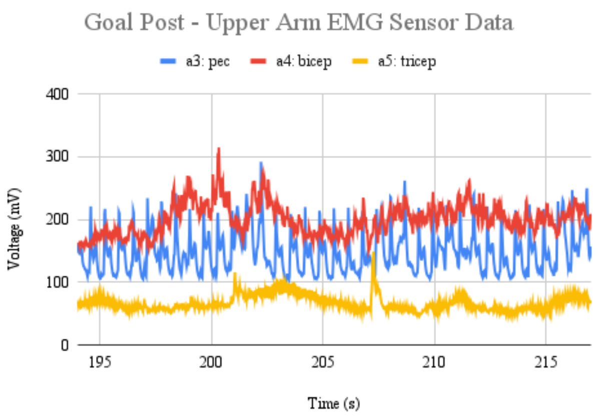
4. *Upper Arm Internal/Medial Rotation with Arm Held Anterior to the Body (Goal Post)*

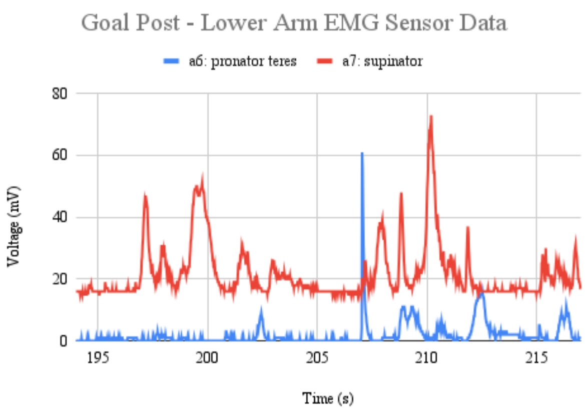




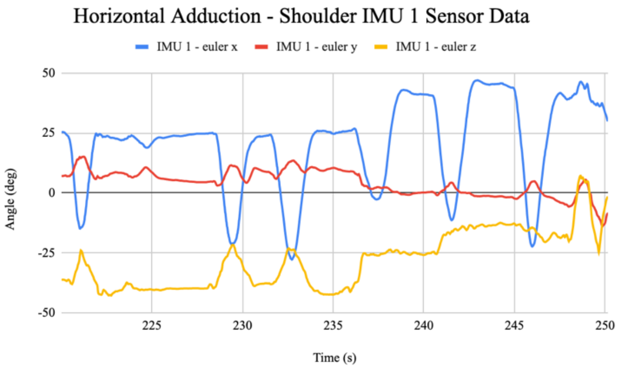


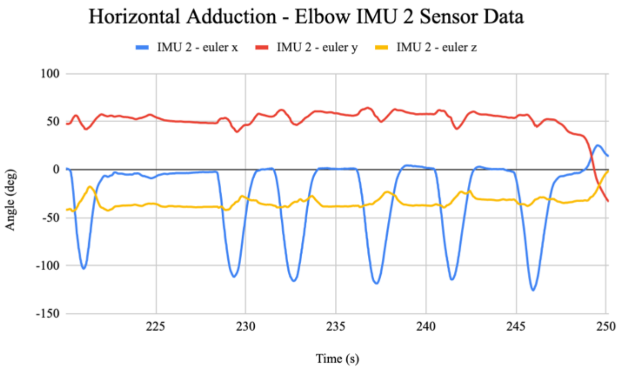


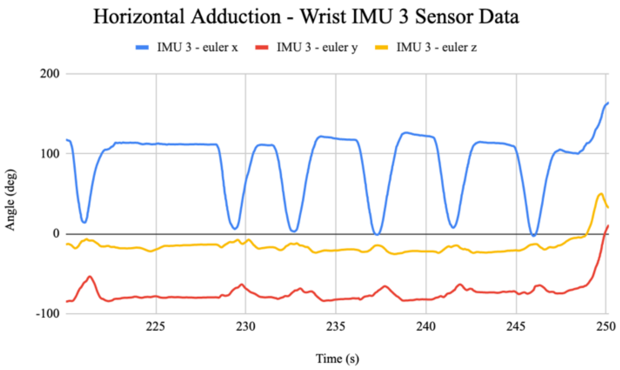


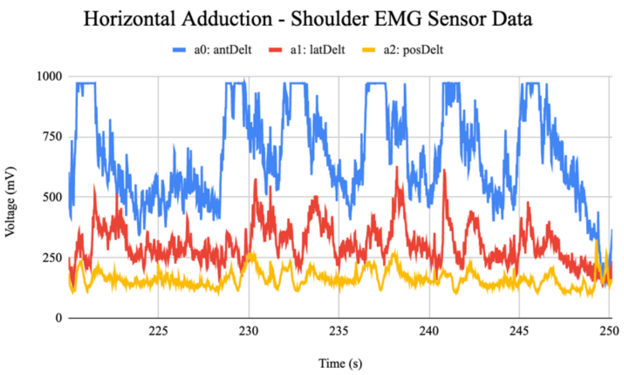


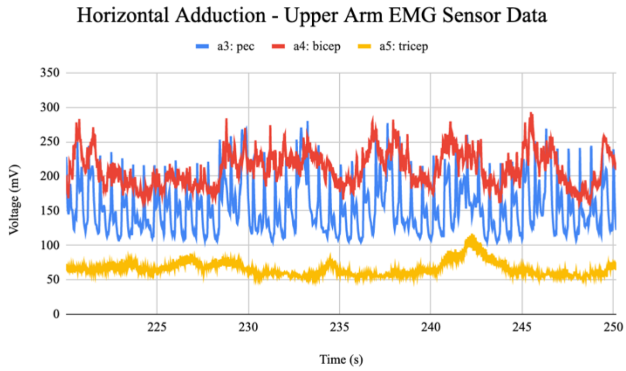
5. *Horizontal Adduction with right-angle upwards arm bend*

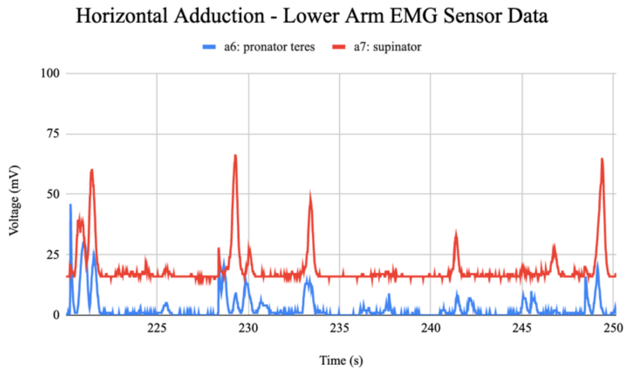




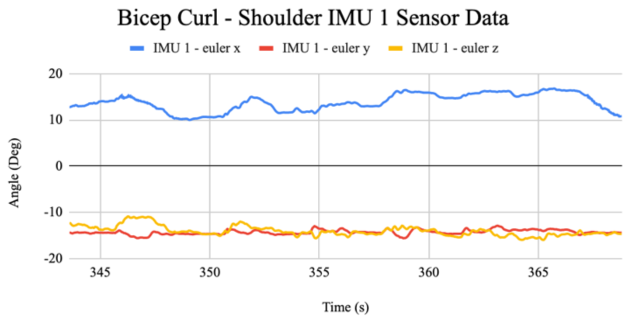


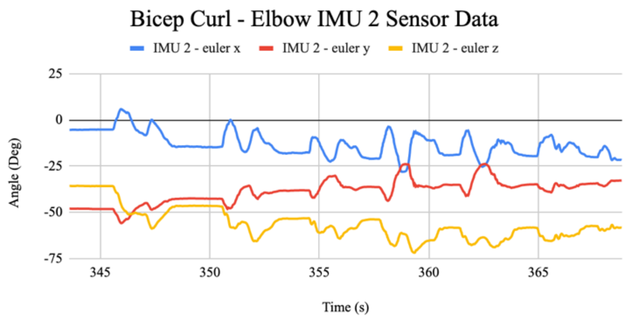


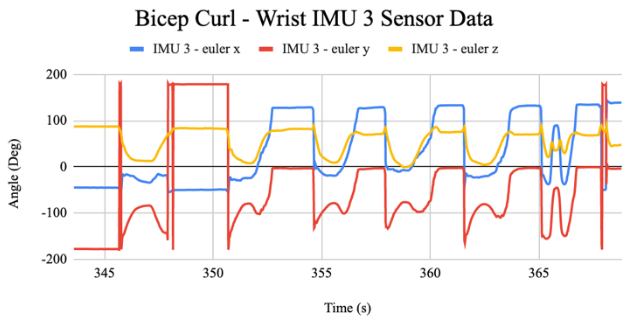


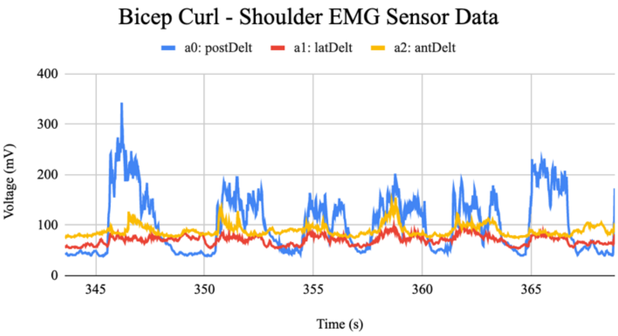


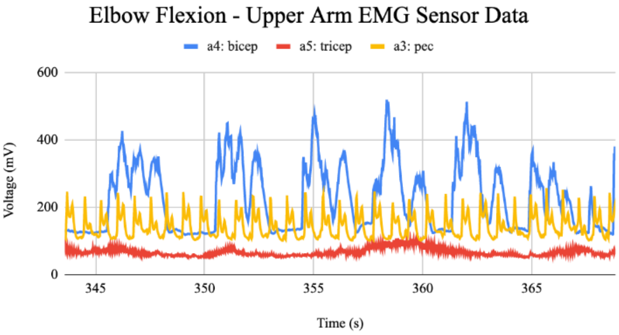
6. *Bicep Curl*

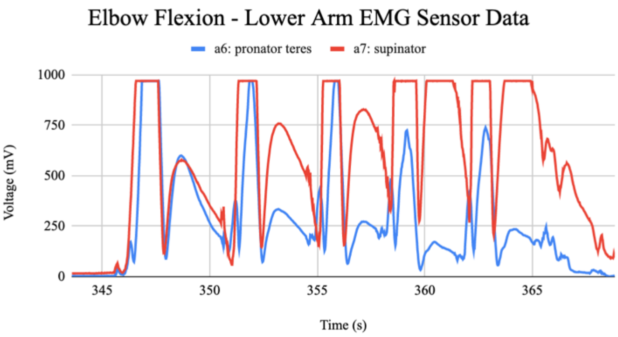




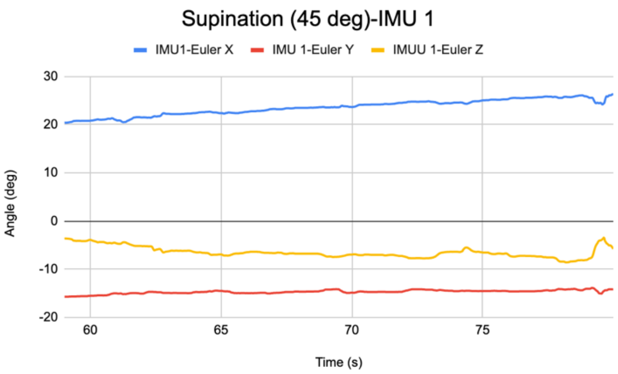


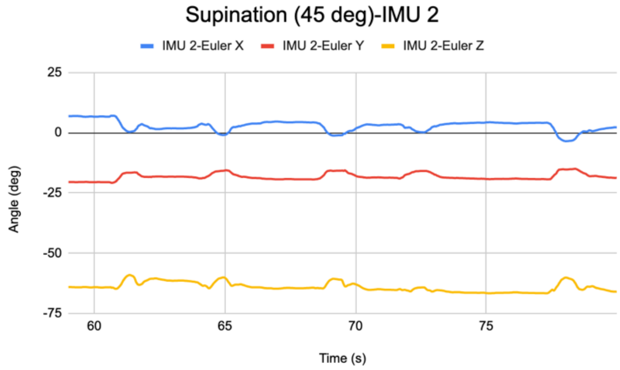


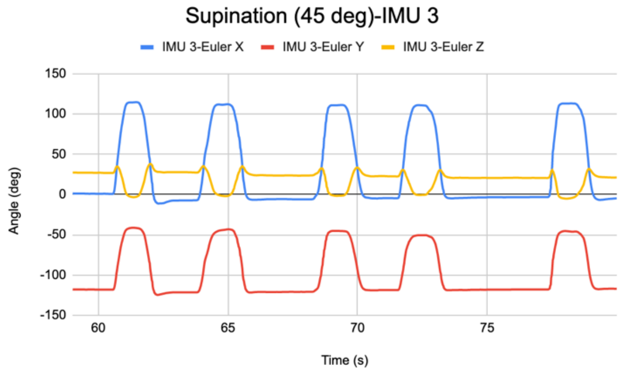


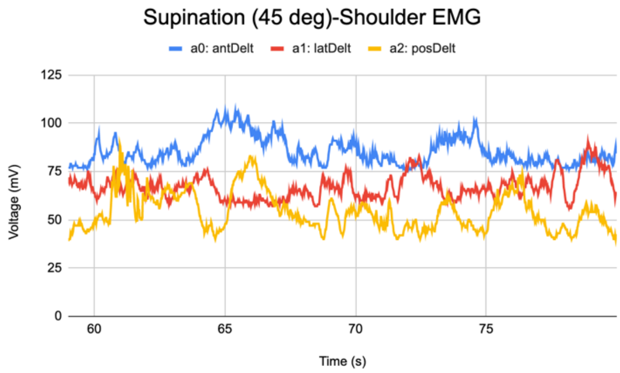


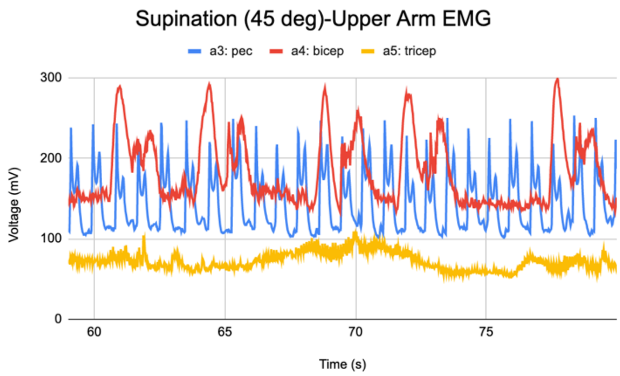
7. *Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table*

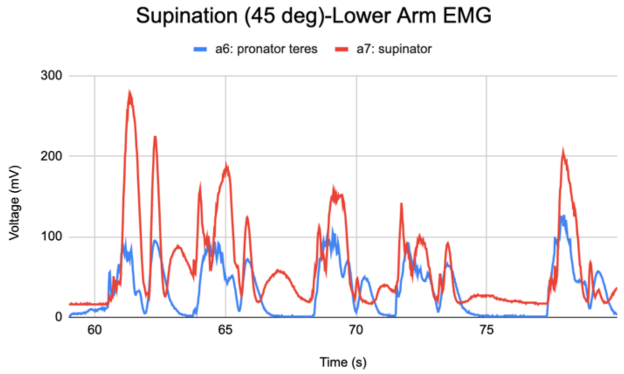




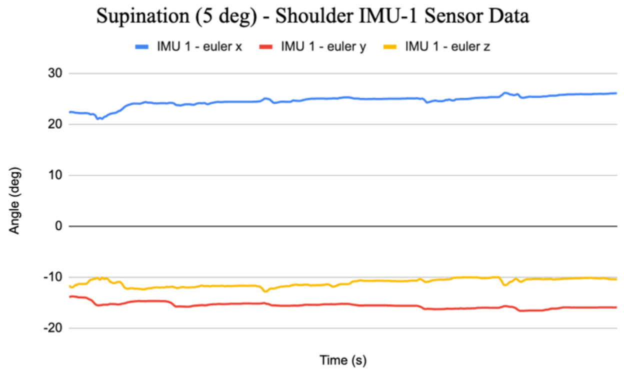


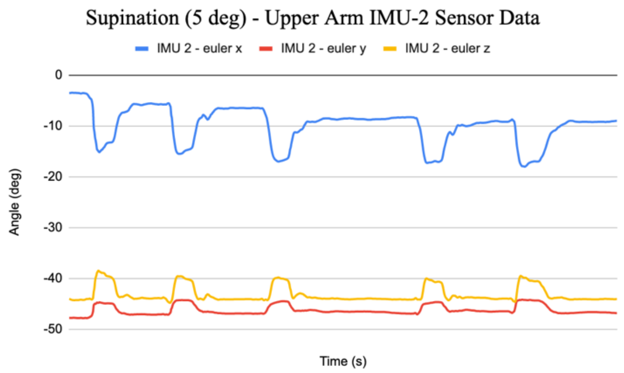


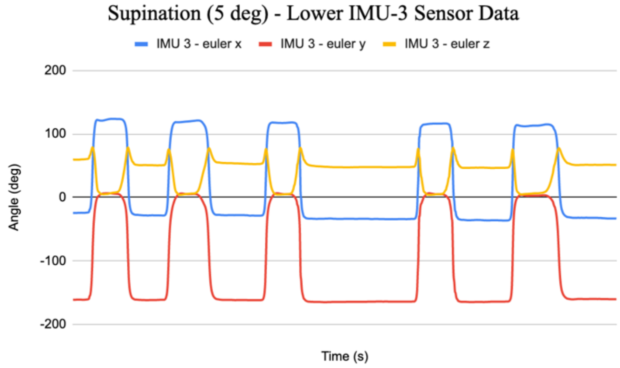


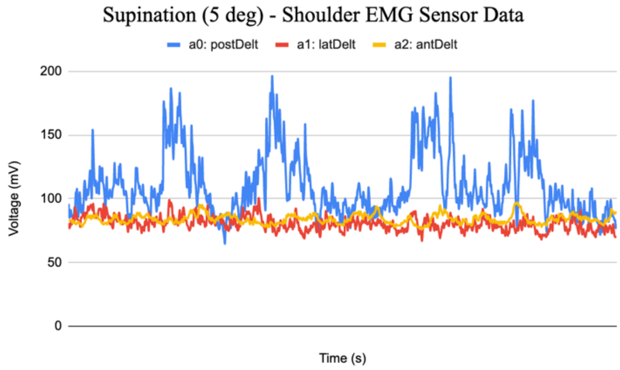


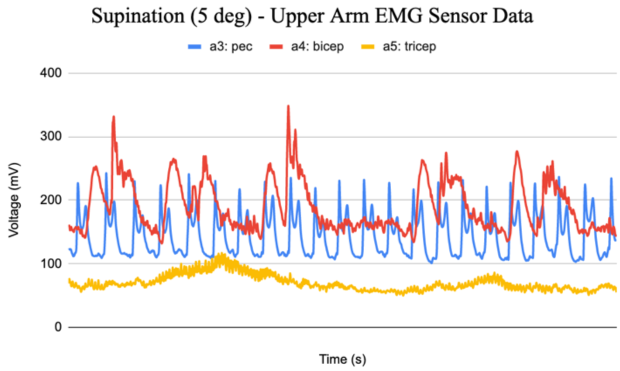
8. *Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table*

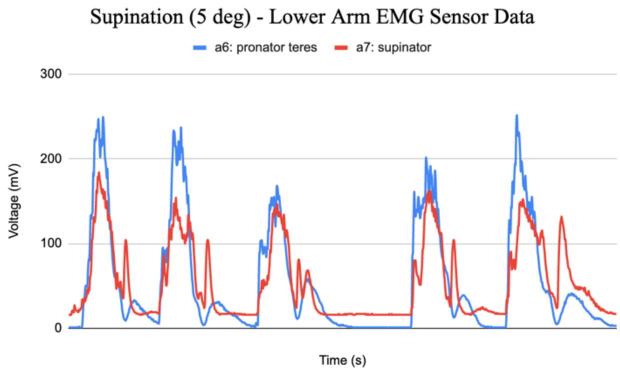






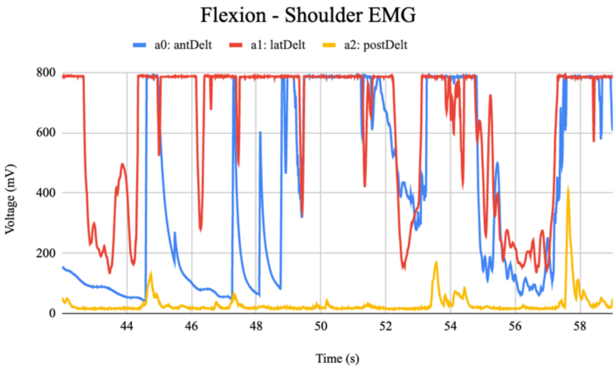


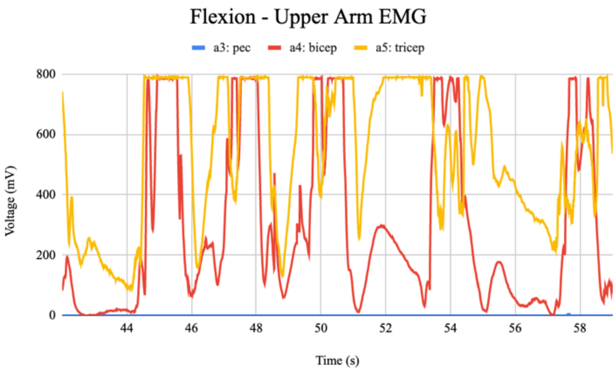


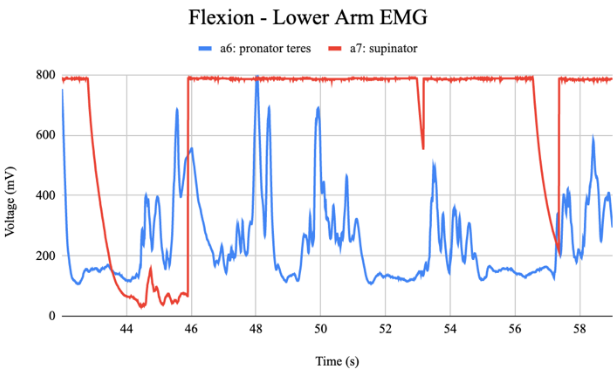


Appendix D:
Experiment 3 - Full-Arm Eight EMG Textile Sensor Array

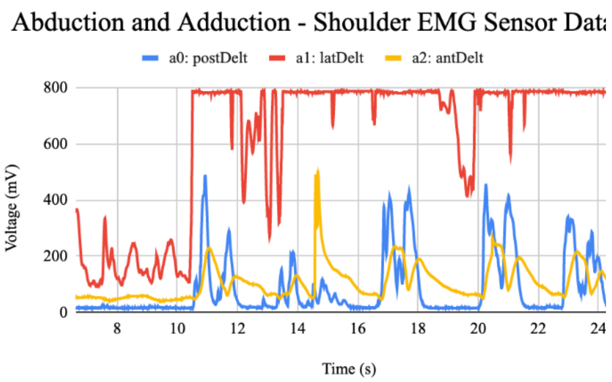
1. *Upper Arm/Shoulder Flexion*

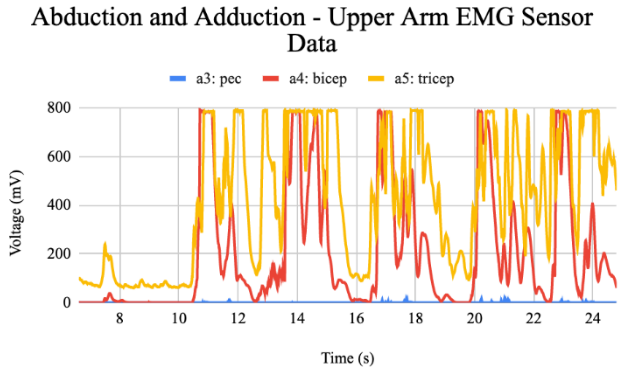


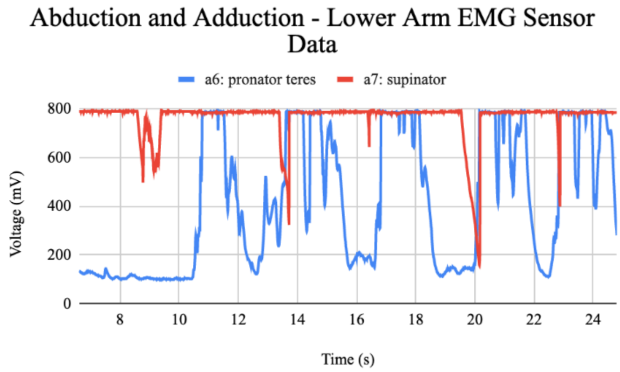




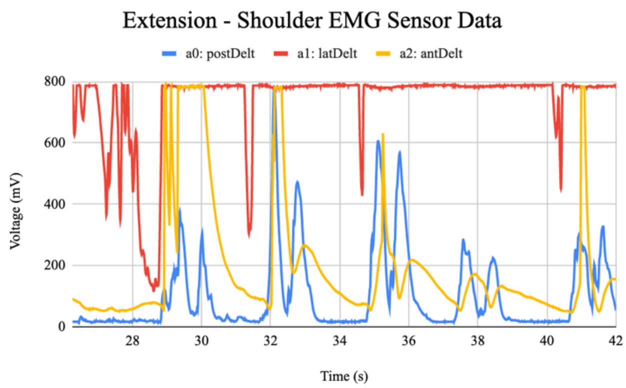
2. *Abduction & Adduction*

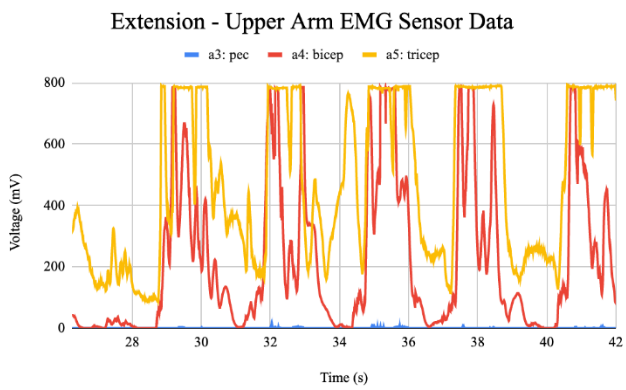


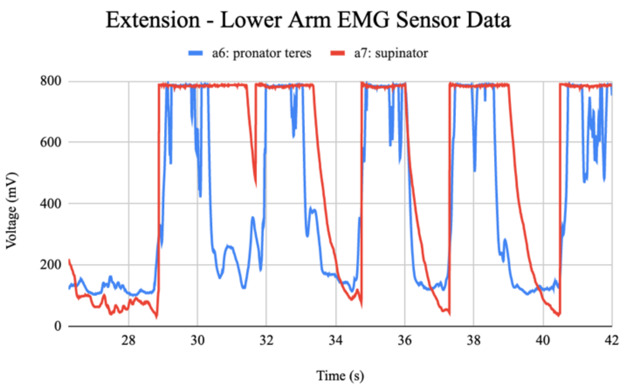




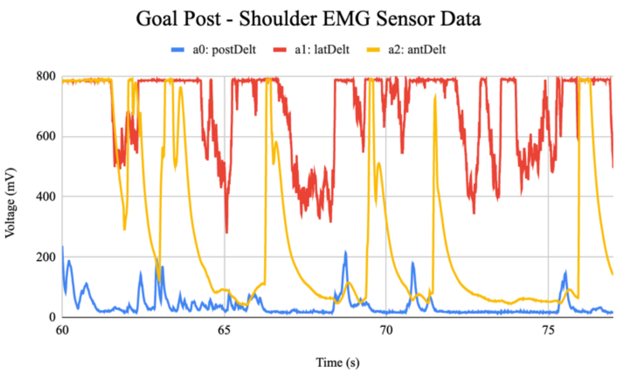
3. *Upper Arm/Shoulder Extension*

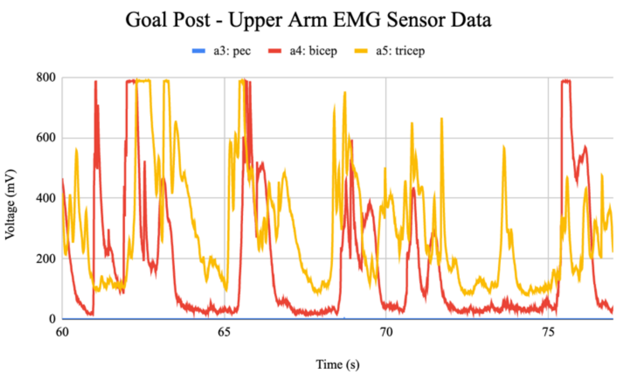


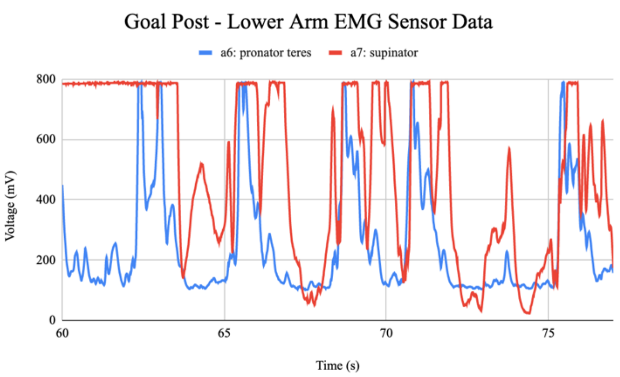




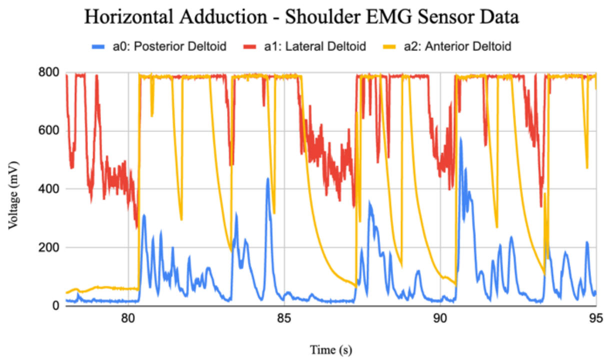
4. *Upper Arm Internal/Medial Rotation with Arm Held Anterior to the Body (Goal Post)*

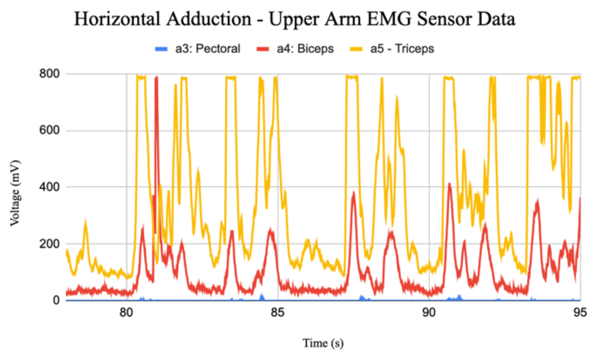


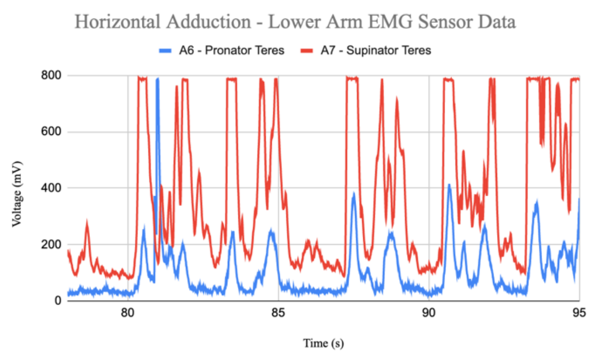




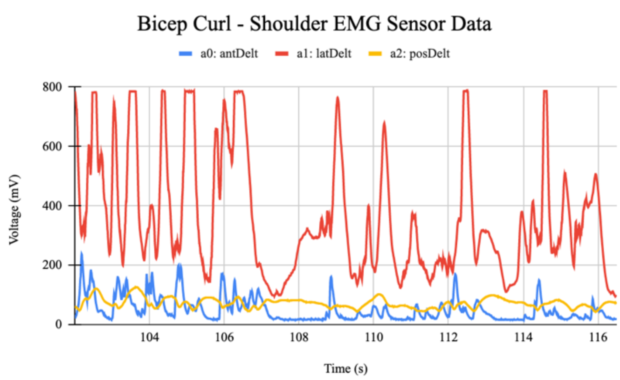
5. *Horizontal Adduction with right-angle upwards arm bend*

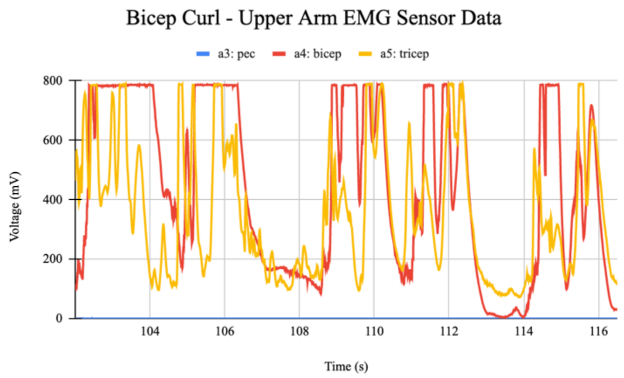


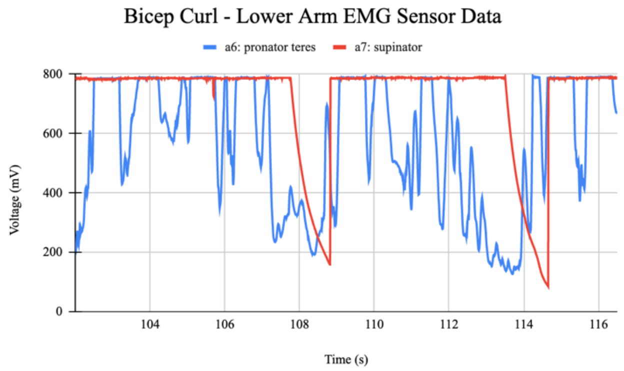




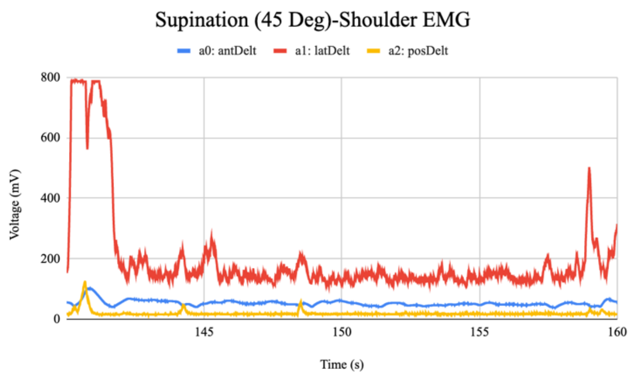
6. *Bicep Curl*

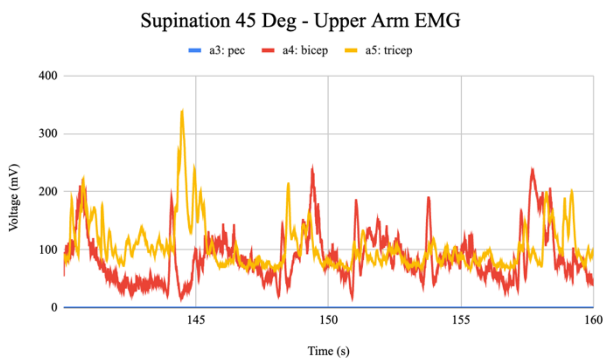


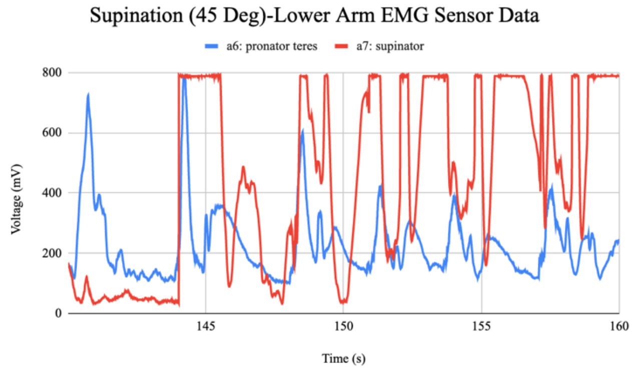




7. *Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 45 degrees between the wrist and table*







8. *Pronation and supination of the lower arm (forearm) with the elbow resting on a table and 5 degrees between the wrist and table*