3D-Printed Hand Controlled by Arm Gestures to Verify the Robustness and Reliability of a Low Cost Surface Electromyography System

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Abstract: - The study focuses on the development of a low-cost surface electromyography and 3D-printed hand gesture-recognition system. The complete system captures four (4) channels of EMG data through sEMG amplifier circuits interfaced to an Arduino prototyping board. This data is sent to a workstation wherein the graphical user interface shows the pre-processed signal. The gestures are used as control for the movements of the 3D-printed arm.

Key-Words: - Electromyography, Surface Electromyography, Prosthesis, Myoelectric Prosthesis, Gesture Recognition, Thresholding, 3D-Printing

1 Introduction

In the Philippines, the two largest government hospitals have at least one amputation related surgery per day [1]. However, not all amputees use prosthesis because of inconvenience brought about by the weight and high cost of about USD 100,000 [2].

Myoelectric technology uses sensitive electrodes to read activity in specific muscle groups and send signals to processing units that employ a specific function in electric motors in the prostheses [2]. Myoelectric prostheses are often used to effectively treat upper limb amputations. [2] For this study, focus will be given on transradial or below the elbow prosthesis.

This study aimed to develop a low-cost alternative to these devices. Four (4) gestures made by the upper limbs will be identified. To be able to test the muscle sensors, the specified output must be obtained through the 3D-printed hand. A specified hand gesture corresponds to a specified arm gesture. Threshold is the minimum intensity or value of a signal that will yield a response or specified effect [3]. The system primarily serves as a platform for research that does not deal with health-related risks and precision data.

2 Problem Formulation

In 2002, approximately 1.2 million Filipinos were recorded to be born with a missing limb or other body part. There are no current statistics regarding the situation of amputations (both upper and lower limb) in the Philippines but an extrapolated study made by the U.S. Census Bureau in 2004 shows an estimated number of amputees per country [1]. On a 1:142 ratio, 603,691 people are predicted to have amputations here in the Philippines [2].

There is an increasing number of amputees and thus the increasing need for prosthesis in the Philippines. People may be born with the amputation or it may be induced by trauma and disease [1]. Prosthesis is an artificial device attached to the body that can be used to replace the missing body part [3]. However, not all amputees use prosthesis because of inconvenience due to the weight and high cost. Cosmetic prostheses are used mainly for aesthetic purposes and cost around USD20,000. Body-powered prostheses which are mechanically powered using other body parts cost around USD30,000 while myoelectric prostheses which are controlled by the residual muscles cost around USD100,000 [2].

Myoelectric technology uses sensitive electrodes to read activity in specific muscle groups and send signals to processing units that employ a specific function in electric motors in the prostheses [2]. Myoelectric prostheses are often used to effectively treat upper limb amputations. Lower limbs require subtle articulation which better suit mechanical solutions due to motion artifacts.

With the increasing research interest in the applications of EMG, particularly surface EMG in the medical field, and the increasing number of amputees in the Philippines, the group decided to focus on the control of myoelectric prosthesis using gesture recognition. Myoelectric prosthesis was found to be the most preferred prosthesis over cosmetic prosthesis and body-powered prosthesis due to the intuitive control it provides the users. Myoelectric prosthesis also provides more dexterity. Using this type of prosthesis is less strenuous for a person because it is wired or attached to muscles that would normally control the same action [2]. Using the knowledge the group obtained on surface EMG, interfacing, and gesture recognition throughout the study, they aimed to come up with an alternative, low-cost myoelectric prosthesis that may be easily accessible to amputees.

3 Problem Solution

This study aimed to develop a low-cost alternative to these devices. Four (4) gestures made by the upper limbs will be identified. These gestures were biceps flexion, wrist extension (hand moving backwards towards the shoulder), triceps flexion, and wrist flexion (hand moving upwards while keeping the arm straight). The four (4) muscle groups chosen were biceps brachii, extensor digitorum communis, triceps brachii, and flexor carpi radialis.

To be able to test the muscle sensors, the specified output must be obtained through the 3D-printed hand. A specified hand gesture corresponds to a specified arm gesture. Threshold is the minimum intensity or value of a signal that will yield a response or specified effect [3]. The system primarily serves as a platform for research that does not deal with health-related risks and precision data.

The graphical user interface of the system can also provide the user with visual information, numerical information, as well as simple indicators, which may be a useful platform for starting research on medical fields such as rehabilitation and biomechanics. The low cost surface electromyography system primarily serves as a platform for research that does not deal with health-related risks and precision data.

This development of a low-cost system is particularly beneficial as an alternative to medical equipment for non-medical-related fields because of similar commercially available systems which are costly.

3.1 sEMG-Capturing System

The hardware components used to create the surface electromyography system were readily available. The system was composed of muscle sensors, electrodes, Arduino Pro Mini, EGBT-045MS Bluetooth shield, perforated circuit board (PCB), and battery packs.

Three (3) 9 V batteries were used to power the sEMG-amplifier circuit. The four (4) muscle channels were connected to the analog inputs of the Arduino board which converts the analog data to digital data. The signals from the muscles have values ranging from 0 to 5 V. These voltage values were set to correspond to a number between 0-255 which was represented by eight (8) bits. The Arduino Pro Mini and EBGT-045MS were wired and soldered to a small perforated circuit board (PCB) to allow wireless transmission of the obtained data to a workstation or laptop. The following figures show the circuit schematic diagram for the connections of the Arduino board and Bluetooth module and the simplified graphical representation of the sEMG-capturing system.

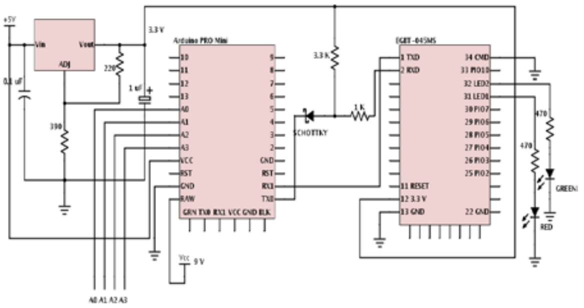


Fig. 1 Arduino Pro Mini and Bluetooth Module Schematic Diagram

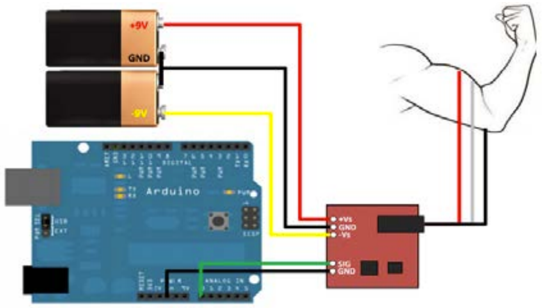


Fig. 2 sEMG-Capturing System [4]

Comparison between a typical EMG system and the group's low-cost sEMG-capturing system was done. The following table shows the hardware specifications of the two (2) systems. The table shows that the hardware specifications of the sEMG-capturing system fit with the typical EMG system hardware specifications. The entire sEMG-capturing system was packaged in a small 3D-printed box for easy mounting to test subjects.

Table 1 Comparison of EMG System Hardware Specifications

Specification	Hardware	Hardware Specifications	Typical EMG
Channels	Arduino	6	(arbitrary: 4)
Sampling Rate	Arduino	10 kHZ analog	1000 Hz to 1500 Hz
ADC Resolution	Arduino	10 bits	12 bits for RAW
Gain	Amplifier Circuit	0.002x to 20,700x (typ. 10,350x)	At least 1000x
Voltage Range	Amplifier Circuit	0 mV to 4.83 V	2 to 3 mV for un-amplified signal
Cut-off Frequency	Amplifier Circuit	19.75 kHz	10 Hz HP to 500 Hz LP
Baud Rate	Arduino	152,000	(arbitrary)

3.1.1 Electrodes

Nine (9) sets of 3M Foam Monitoring sensors were used. One (1) pair per muscle part was attached, one (1) to the middle of the muscle belly using the red cable and the other one (1) cm away using the blue cable. Four (4) muscle groups were used, and then the last electrode was attached to the elbow as ground using the black cable. These electrodes come per ten (10) in each strip. They have three (3) day wear time and are made of foam and stainless steel. The dimension of each electrode was 4x3.3cm.

3.1.2 Muscle Sensor V3

The muscle sensor v3 kit from SparkFun contains the 1.0 x 1.0 inch muscle sensor board, 24” cables with six (6) possible inputs and adjustable gain. The power supply voltage has a minimum of +-3.5V. The muscle sensor kit is breadboard compatible [4]. Four (4) of these were used for each of the four (4) channels. Since the sensors are designed to be used with microcontrollers, these devices already do the amplification, rectification, and smoothing of the raw EMG signal [4]. This will work well with the analog-to-digital converter of the Arduino. The following table shows the circuit parameters of the muscle sensors.

Table 2 Muscle Sensor V3 Circuit Parameters [4]

Parameter	Min	Type	Max
Power Supply Voltage	±3V	±5V	±30V
Gain Setting, Gain = 207*(X/1kΩ)	0.01 Ω (0.002x)	50 kΩ (10,350x)	100 kΩ (20,700x)
Output Signal Voltage (rectified and smoothened)	0V	--	$+V_s$
Differential Input Voltage	0mV	2-5mV	$+V_s$/Gain

3.1.3 Arduino Pro Mini

Arduino Pro Mini is a microcontroller board based on ATmega168 that has fourteen (14) digital input or output pins, eight (8) analog inputs, a resonator, reset button, and holes for mounting pin headers [5]. Arduino Pro Mini has two (2) versions: one runs at 3.3 V and 8 MHz, the other runs at 5 V and 16 MHz [5]. For the interface of the sEMG-amplifier circuits, the Arduino Pro Mini used was the one running at 3.3 V and 8 MHZ. The inputs were connected at pins A0, A1, A2, and A3. The microcontroller is wirelessly connected via the Bluetooth module to the workstation where the data obtained from the muscle sensors were sent.

Table 3 ATmega168 Circuit Parameters [5]

Operating Voltage	3.3V or 5V (depending on model)
Input Voltage	3.35 - 12 V (3.3V model) or 5 - 12 V (5V model)
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	8
DC Current per I/O Pin	40 mA
Flash Memory	16 KB (of which 2 KB used by bootloader)
SRAM	1 KB
EEPROM	512 bytes
Clock Speed	8 MHz (3.3V model) or 16 MHz (5V model)

3.1.4 EGBT-045MS Bluetooth Module

EGBT-045MS was the Bluetooth module used for the thesis project. This Bluetooth module was pre-configured as slave but may be configured as either master or slave as desired by the user. It operates in Data mode when the CMD pin or pin 34 is pulled to logic low or left unconnected. Only when the Bluetooth module is in Data mode that it performs transparent UART data transfer with a connected remote device. When the CMD pin is in logic high, it is in Command mode [6]. Set-up and configuration of the Bluetooth module may be done when it is set in Command mode. Configurations made in the Bluetooth module are retained when it is turned off therefore there is no need to reconfigure when switched on unless changes are to be made.

3.2 3D-Printed Hand

The robotic hand was designed using Solidworks CAD software, and then formed using a 3D-printer. Thermoplastic material was used for the additive process of 3D-printing. The hand was divided into multiple small parts as the printer cannot accommodate big designs. The three (3) phalanges were printed per piece then attached together using nails, nylon, and rubber band. A rubber band was attached to the top of the outer distal phalanx, located directly in the central axis of the finger and passed through the three (3) pieces. The band made passive extension possible for the index, middle, ring, and pinky fingers. The following figure shows the components used for the fingers of the hand.

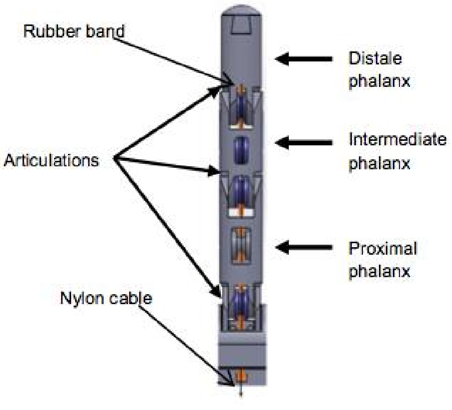


Fig. 3 Finger Components

A nylon cable was attached to the top of the inner distal phalanx and was directed towards the base of the motors inside the arm. This made the active flexing of the aforementioned fingers possible. The three (3) articulations are guided by like-sized pulleys, which control the motion sequence.

The thumb was created in a similar fashion. However, the axis of freedom between the proximal and the middle phalanges was made perpendicular to the axes of the fingers to improve the quality of the grasp movement and to allow a lateral movement of the thumb. The intermediate articulation was bent 25 degrees to the axes of the fingers.

Five (5) servo motors were used to control the passive opening and active closing of the fingers. These motors were controlled by an Arduino UNO board and powered by a 5 to 5.5 V power supply. The grasping motion is able to contour to the shape of the object.

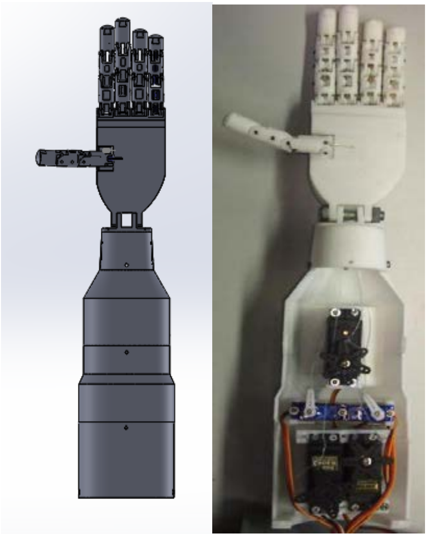


Fig. 4 3D-Printed Hand Model and Actual

3.2.1 Thermoplastic

The hand was 3D-printed using thermoplastic which was heated and formed layer upon layer to yield the design modelled using Solidworks. Thermoplastic is a material commonly used for additive processes of 3D-printing.

3.2.2 Nylon

Nylon is the most common polymers used for different purposes [7]. For mechanical applications, it is used in machine screws, gears, and different low- to medium-stress components [7]. For the 3D-printed hand, nylon was used to control the active closing movement of the fingers.

3.2.3 Rubber Bands

Rubber bands are highly elastic materials commonly used to hold things together [8]. Rubber bands come in different sizes depending on its width, length, and thickness [8]. Different rubber band sizes may be used for desired applications. Rubber bands were used to control the passive opening movement of the fingers.

3.2.4 Nails

Nails are pin-shaped metal materials used for fastening. Small nails were used to attach the three (3) different phalanges of each finger.

3.2.5 Servo Motors

Servo motors were used to control the movement of each finger. One (1) servo motor was attached to each finger to allow five (5) degrees of freedom (DOF). These servo motors required low voltage levels therefore they were easily powered to perform the desired outputs. Two (2) different servo motor models were used for the fingers. TowerPro 9g motors were used for two (2) of the fingers and TowerPro MG996R 10kg motors were used for the remaining three (3) fingers.

3.2.6 Arduino UNO

The Arduino UNO board is based on the ATmega328 microcontroller board [9]. It has fourteen (14) digital input or output pins where six (6) of which may be used as PWM outputs [9]. This board also has a 16 MHz ceramic resonator, USB connection, power jack, ICSP header, and reset button [9]. An Arduino UNO board was used to control the servo motors for each finger.

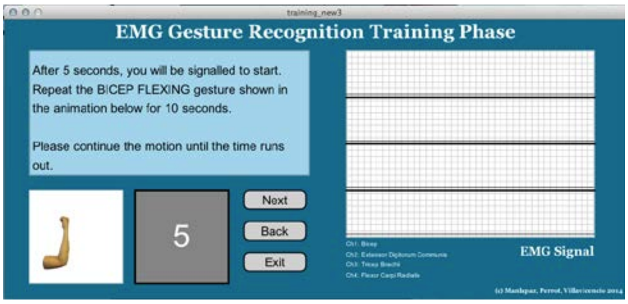
3.3 Graphical User Interface

The development environments used for the study are Processing IDE and Arduino. Both microcontrollers, for the 3D-printed hand and the sEMG capturing system, use the Arduino to process the data. The Graphical User Interface (GUI) is designed using the Processing IDE. This also provides a graphical representation of the data and step-by-step indicators.

The Processing IDE was used to graph the rectified and smoothened signal acquired from the sEMG-capturing system. This was the interface used in order to instruct the user how to obtain their EMG muscle signatures. It signals the user to perform certain actions, with a visual animation and timer to guide them. The data is further processed through this environment and a signal is sent to the 3D-printed hand in order for hand actions to be made.

3.3.1 Training Phase

The Training GUI essentially graphs and displays numerical data for each gesture and saves this to a CSV file. It explains and shows what the user has to do for ten (10) seconds. For each segment, one (1) text file containing the acquired data is created and the user is able to rest before beginning the next segment.



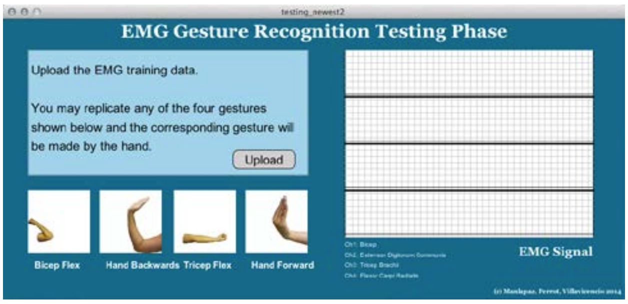
After 5 seconds, you will be signalled to start. Repeat the BICEP FLEXING gesture shown in the animation below for 10 seconds.

Please continue the motion until the time runs out.

Fig. 5 Training Phase GUI

3.3.2 Testing Phase

The Testing GUI was very similar to the Training GUI. The same classes were used to display the GIFs, the oscilloscope, and the text. There was only one screen frame thus the buttons to change the view were no longer used. Instead, four (4) GIFs were shown and labelled to show which gesture it is.



Upload the EMG training data.

You may replicate any of the four gestures shown below and the corresponding gesture will be made by the hand.

Fig. 6 Testing Phase GUI

3.4 Data Gathering and Analysis

The four (4) chosen gestures were performed repeatedly for ten (10) seconds. The values obtained from the performance of the gestures were saved in a text file. These values were plotted to show the general appearance of the muscle signals. The following figures show the graphs of the muscle signals. Four (4) subjects performed the four (4) gestures, two (2) males and two (2) females. It was observed that the EMG signals from male subjects have higher magnitudes as compared to those from female subjects. This proved that better EMG signals are obtained from male subjects because they have less body fat and bigger muscles compared to females. This means that the females garner noisier signals and thus affecting the resolution of the signal. The patterns for each gesture however, are still very similar. This information was used in order to set the conditions for specified outputs.

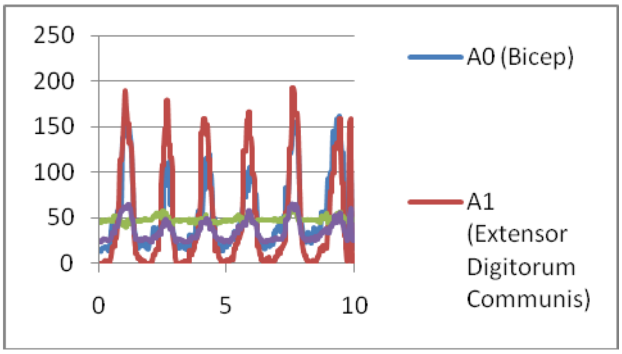


Fig. 7 Gesture 1 (Male Subject)

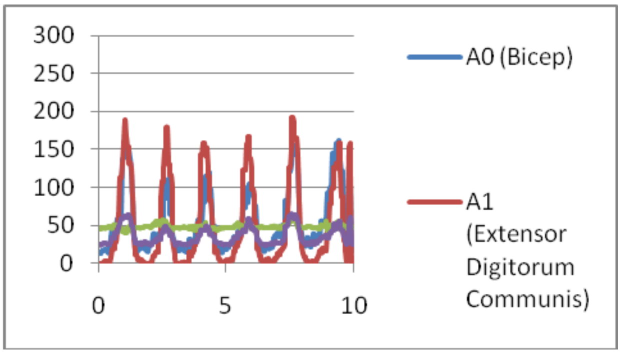


Fig. 8 Gesture 1 (Female Subject)

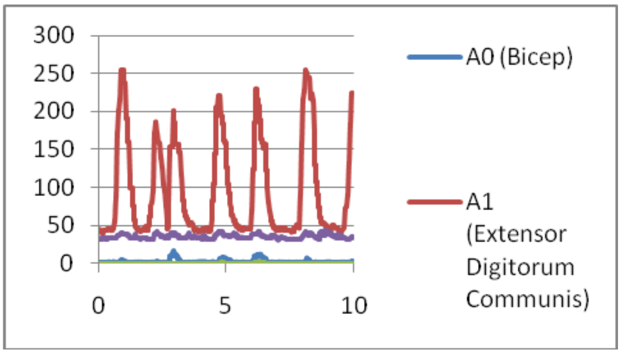


Fig. 9 Gesture 2 (Male Subject)

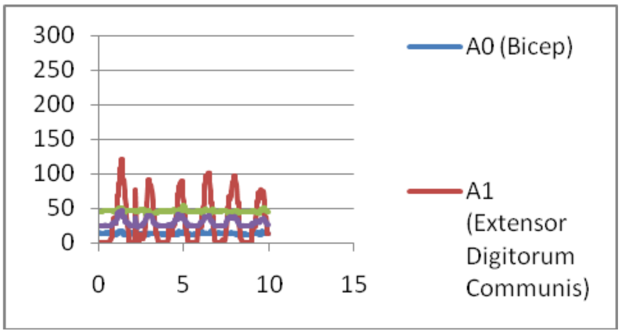


Fig. 10 Gesture 2 (Female Subject)

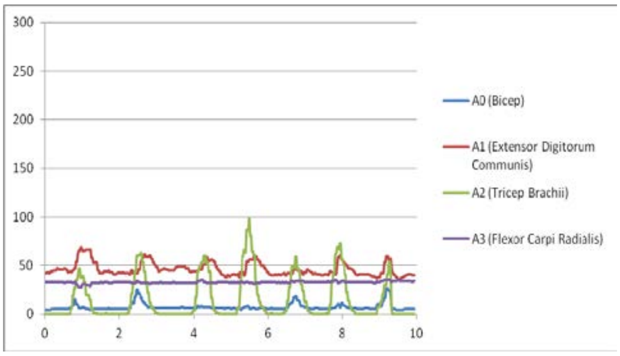


Fig. 11 Gesture 3 (Male Subject)

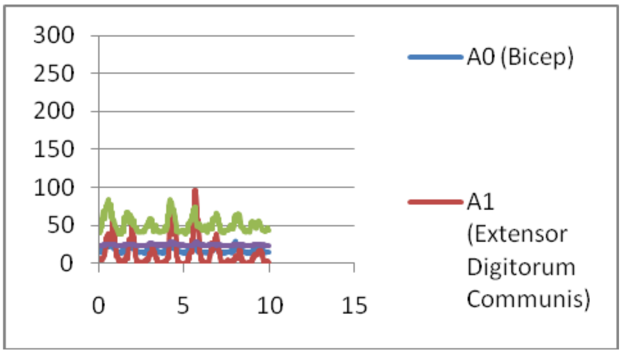


Fig. 12 Gesture 3 (Female Subject)

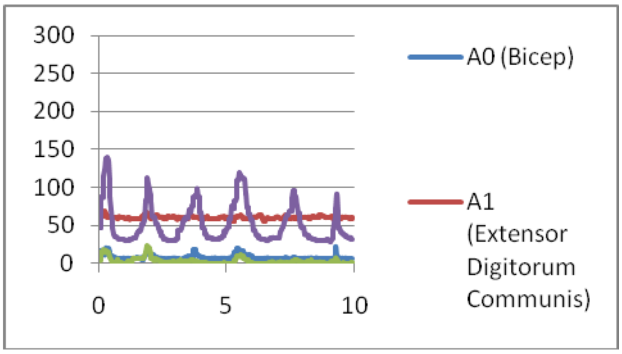


Fig. 13 Gesture 4 (Male Subject)

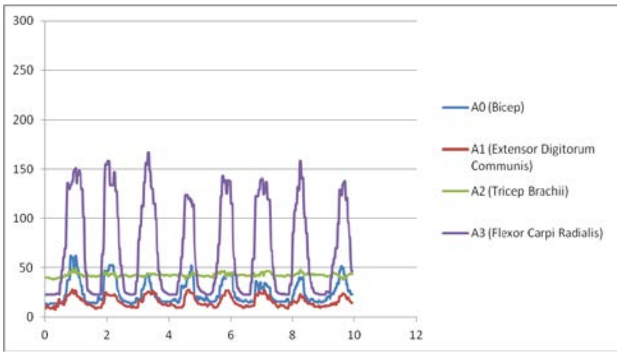


Fig. 14 Gesture 4 (Female Subject)

A maximum voluntary contraction file was also created which stored the highest and lowest values obtained from the gestures performed. The threshold values for the gestures were obtained and these determined the state of the muscles, which was either high or low, for each gesture. When upon performance of the gesture, the values obtained from a specific muscle exceeded the threshold value, then that muscle was said to be in a high state, else it was said to be in a low state. The following table shows the states of the muscles for each gesture performed.

Table 3: Muscle States

Gesture	Biceps Brachii	Extensor Digitorum Communis	Triceps Brachii	Flexor Carpi Radialis
Biceps flexion	HIGH	HIGH	LOW	LOW
Wrist extension	LOW	HIGH	LOW	LOW
Triceps flexion	LOW	LOW	HIGH	LOW
Wrist flexion	LOW	LOW	LOW	HIGH

These muscle states per gesture were used as control for the actions of the 3D-printed hand. When a gesture is performed, the active muscles or those in the high state were determined using the obtained threshold values. To verify the identification of the gesture by the sEMG-capturing system, the corresponding hand action must be performed by the 3D-printed hand. The following table shows the input gesture and output action correspondence of the system.

Table 4: Input Arm Gesture and Output Hand Action

Input	Output
Biceps flex	Rock
Wrist extension	Okay
Triceps flex	Peace
Wrist flexion	Pinky

4 Conclusion

Surface electromyography is highly studied in the academic and medical field for multiple applications such as human-computer interface, myoelectric prosthesis, and the like. The study conducted was able to show that the identification of the signals for the chosen gestures was accurate using thresholding method and these may be used for control such as the 3D-printed hand. The system was used as an interactive motion detection platform.

The group was able to establish a wireless communication system with the muscle sensors and the workstation via Bluetooth. The signals were identified in Processing IDE and the arm gestures performed were used to output rock, okay, peace, and pinky on the 3D-printed hand. The output hand actions may be changed choosing from the thirty two (32) possible hand actions as desired by the users. Furthermore, the group was able to make all possible hand combination actions using the 3D-printed hand by programming it to show in binary numbers 0 to 31.

The objectives of the study were achieved as the signals for the four (4) gestures were successfully obtained and classified from four (4) different subjects, and the same pattern in the signals were noted. The data was shown on the workstation through the interactive GUI and was further processed in order to show an output on the 3D-printed hand. This study may therefore serve as a sufficient platform for further developments on myoelectric prosthesis.

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