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An Electromyography Recording and On-Line Driving System for a Robotic Wrist

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ABSTRACT

Rehabilitation for individuals suffering from motor disabilities caused by conditions such as spinal cord injuries, neuromuscular disorders, or stroke-related complications remains a significant challenge in both clinical practice and the daily lives of patients. As the global incidence of such conditions continues to rise, the need for effective and accessible rehabilitation solutions has become more urgent. In particular, the development of home-based assistive technologies, which enable patients to undergo therapy without frequent visits to medical centers, has become a key area of interest in biomedical engineering. Among these technologies, exoskeleton robots have emerged as promising tools for restoring lost motor functions. Recent advancements have shifted from predefined motion execution toward intelligent systems capable of recognizing the user's movement intentions. This study presents the design and implementation of a wrist exoskeleton prototype controlled by electromyographic (EMG) signals. The system uses an Arduino microcontroller integrated with EMG modules to detect muscle activity in the forearm and drive a servo motor, enabling wrist movements such as flexion-extension and abduction-adduction. EMG signals were recorded in a controlled laboratory environment following standard motor task protocols. Signal preprocessing and movement classification were carried out using MATLAB, utilizing its serial communication toolbox to interface with the Arduino board. The developed algorithm generates three-state control commands to drive the motor, allowing smooth, real-time imitation of voluntary wrist movements. The results demonstrate the feasibility of this approach for future application in wearable, intelligent rehabilitation systems tailored to individual users.

1. INTRODUCTION

Rehabilitation robotics is a crucial domain in robotics that employs robots and intelligent systems to aid the rehabilitation and enhance the motor function of individuals with disabilities. This innovative technology has garnered attention in various fields, including medicine, physiotherapy, industry, social communications, and support for daily life. Rehabilitation robotics enables a return to normal life and improves the quality of life for

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individuals with disabilities. Intelligent orthoses and prosthetics, robotic exoskeletons for mobility assistance, public and home-based rehabilitation tools, and biofeedback-based systems are among the achievements in this field [1].

Detecting the user's intention in performing a movement and executing it correctly by an assistive robot is one of the most significant challenges in this domain. The use of biological signals from the body, called "biofeedback", is an effective solution to this issue, especially the recording of muscle signals or electromyography (EMG). EMG, abbreviated for electromyography, is sometimes referred to as myoelectric activity, indicating the electric signals produced due to muscle activity and measurable on the skin's surface for superficial muscles [1-3]. Recording EMG signals, processing them, and converting them into control commands for the movement or actuation of motors in a robotic device are the essence of what is known as "EMG-driven" motion [4-5], as we will refer to it.

Various and intricate movements of the wrist, palm, and fingers are orchestrated by multiple muscle groups, primarily originating from the elbow and forearm region. Beyond the muscle count, the contribution of different muscles in executing each movement, and each muscle's responsibility in various movements are some of significant challengs in electromyography of forearm muscles. Numerous researchers have delved into recognizing wrist and hand movements [6-9], with some focusing on recognition EMG patterns of individual forearm muscles during different functionalities [10-11]. Therefore, the discussion of forearm electromyography becomes particularly crucial, especially when the goal is to recognize a broad range of movements with the fewest EMG signal channels.

This article addresses the design of an EMG-driven robotic system for manipulating a two-degree-of-freedom robot with anatomy resembling the human wrist. As explained further, the EMG signal originates from the bioelectrical mechanism of muscle contraction. When electrodes are attached to the skin surface, they enable the reception of electric voltages produced by muscles located in proximity to the skin. Naturally, this electric voltage is very weak (in the millivolt range) and prone to noise, requiring amplification and filtering for interpretation. Hence, a two-channel EMG signal recording system is designed as the heart of this article. In the middle segment of this design, a computer program is necessary to receive and process the acquired EMG signals, converting them into control commands to actuate the robot's motors. This processing is carried out through code programmed in MATLAB software. Finally, the flexion and extension as well as abduction and adduction movements of the user's wrist are mimicked in real-time by the two-degree-of-freedom robot.

2. WRIST ANATOMY

The wrist is formed by the articulation of the lower surfaces of the Radius and Ulna bones (upper and lower forearm bones) on one side and the carpal bones (wrist bones) on the other side, in this way connecting the forearm to the hand.

Carpal Bones Structure: The wrist, known as the Carpus, is formed by the alignment of eight bones termed carpal bones. These carpal bones are arranged in two rows: the proximal row, situated closer to the forearm bones, and the distal row, located near the palm bones (see Fig. 1). In the proximal row, moving from the thumb side to the little finger side, the carpal bones are Scaphoid, Lunate, Triquetrum, and Pisiform. In the distal row, also moving from the thumb side to the little finger side, the carpal bones are Trapezium, Trapezoid, Capitate, and Hamate.

The carpal bones are positioned together to form an arch, with the concavity of this arch facing the anterior or volar side. The Radius bone, also known as the radial bone or the thumb side bone (articulating with the wrist on the side of the thumb), features a widened and thickened part near the wrist known as the Styloid Process. Most of the carpal bones of the proximal row are adjacent to the articular surface of the radius bone and articulate with it. In fact, the Radius bone articulates with the Scaphoid, Lunate, and Triquetrum. The Ulna bone (located on the side of the little finger), narrows near the wrist and articulates with a smaller portion of the carpal bones. The lateral surfaces of each carpal bone are covered with cartilage to facilitate articulation with their neighboring bones.

The carpal bones of the distal row articulate with the metacarpal bones, which comprise the palm and correspond to the five fingers. Therefore, the wrist is composed of an arrangement of carpal bones forming various primary and secondary joints. These joints include (see Fig. 1):

- **Distal Radioulnar Joint:** The joint between the lower ends of the Radius and Ulna bones.
- **Radiocarpal Joint:** The joint between the lower end of the Radius bone and the carpal bones.

- **Ulnocarpal Joint:** The joint between the lower end of the Ulna bone and the carpal bones.
- **Intercarpal Joints:** Joints between the carpal bones.
- **Carpometacarpal Joints:** Joints between the distal row of carpal and the metacarpal bones in the palm.

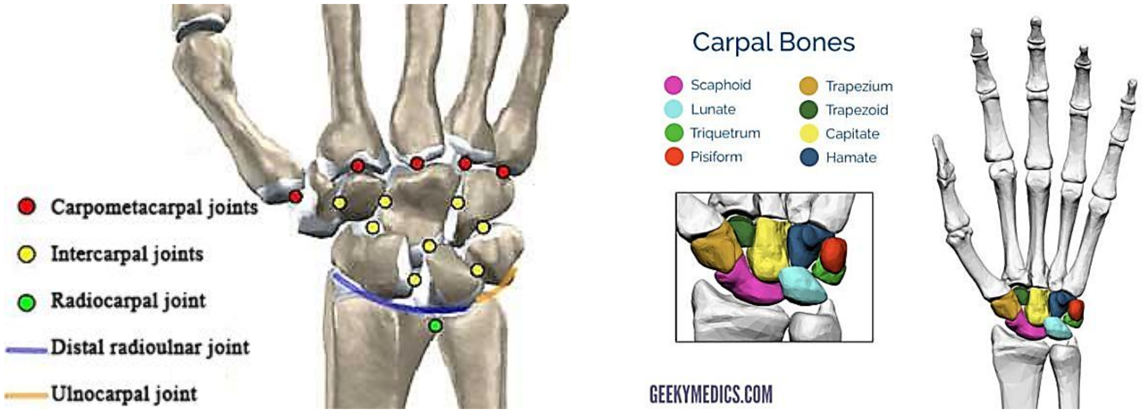


Fig. 1. Bones (Right Image) and Joints (Left Image) of the Wrist Region

Surface and Movements of the Wrist: Terminologically, the front surface of the wrist is referred to as the volar surface, which corresponds to the palm side. Conversely, the back surface of the wrist is termed the dorsal surface, corresponding to the back of the hand. The most significant anatomical movements of the wrist include (see Fig. 2):

- **Flexion (Palmar flexion):** In this movement, the palm moves forward towards the forearm.
- **Extension (Dorsi flexion):** In contrast to flexion, this movement involves bending the hand backward towards the dorsal side. The total range of flexion and extension of the wrist is approximately 170 degrees.
- **Abduction (Radial deviation):** In this motion, the plane parallel to the palm moves towards the radius bone on the side of the thumb, deviating away from the body's midline. Its natural range is about 15 degrees.
- **Adduction (Ulnar deviation):** Unlike the abduction, the plane parallel to the palm moves towards the ulna bone on the side of the little finger, approaching the body's midline. Its natural range is about 40 degrees.
- **Pronation:** involves during a left-handed rotation of an object, such as turning to open a water tap.
- **Supination:** Conversely, involves during right-handed rotation, such as turning to close a water tap.

Fig. 2. Anatomical Movements of the Wrist

3. ANATOMY OF THE FOREARM MUSCLES

The diverse movements of the wrist result from the involvement of 25 muscles categorized into three groups. The first group consists of muscles originating from the elbow region and attaching to the wrist or fingers. The second group comprises muscles originating from the forearm and attaching to the palm and fingers. The third group includes muscles connecting from the palm to the fingers, responsible for finger movements.

The muscles in the first group are total eight, with four of them categorized as wrist flexors and remaining four are wrist extensors. The carpal flexors share a common origin from the medial epicondyle of the humerus, that is their fixed end attaches to the inner (medial) epicondylar prominence. The carpal extensors possess a common origin from the lateral epicondyle of the humerus. These eight muscles, which are all long and superficial in the forearm include (see Figs. 3 and 4):

Palmaris Longus: This relatively small muscle is active solely during wrist flexion, becoming visibly prominent when the hand is clenched, forming a palpable mass in the forearm region. Originating from the medial epicondyle of the humerus, it superficially adheres to the retinaculum overlying the bones of the palm (specifically, the sheaths of the second to fifth metacarpal bones). Due to the fact that the attachment point of the moving head of this muscle is far from the wrist flexion-extension axis, thus it is considered one of the most effective flexor muscles of the wrist.

Flexor Carpi Radialis: A two-headed muscle originating from the medial epicondyle of the humerus (its origin) and extending through a long tendinous insertion to attach to the base of the second metacarpal bone on the palm and the ridge of the third metacarpal bone (its insertion). This muscle is a flexor of the wrist as well as plays a role in radial deviation of the wrist. Therefore, it is involved in both flexion and abduction of the wrist. It is innervated by the median nerve.

Flexor Carpi Ulnaris: Located on the ulnar aspect of the forearm, this muscle originates from the medial epicondyle of the humerus and has a broad attachment to the undersurface of the ulna. It then attaches with a long tendinous insertion to the pisiform bone and the hook of the hamate bone, ultimately connecting to the fifth metacarpal bone on the palm. This muscle is involved in the movements of wrist flexion and ulnar deviation.

Flexor Digitorum Superficialis: This muscle originates from the medial epicondyle of the humerus and possesses atachments to the upper surfaces of the radius and ulna bones (in other words, at the own origin has attachments to the humerus, ulna, and radius). It forms connections through four tendons to the bases of the second and fourth fingers. It contributes to the flexion of the second finger and wrist.

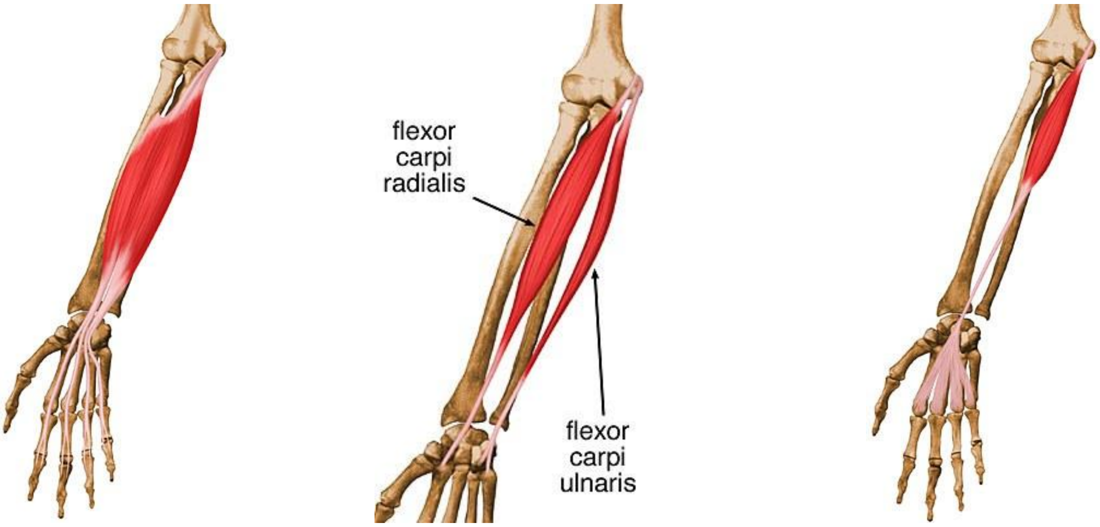
Extensor Carpi Ulnaris: Originating from the lateral epicondyle of the humerus and the posterior surface of the ulna, this muscle extends down to attach to the base of the fifth metacarpal on the palm. Its function involves participation in wrist extension and adduction (deviation towards the ulnar side).

Extensor Carpi Radialis Longus: This elongated muscle begins from the lateral epicondyle of the humerus and attaches at the posterior base of the second metacarpal on the palm. Its innervation is provided by the radial nerve. Its role encompasses wrist extension and abduction (radial deviation). This muscle is considered one of the five primary muscles regulating hand-wrist movements.

Extensor Carpi Radialis Brevis: Situated in the forearm, this shorter, thicker muscle, sharing the name with the Extensor Carpi Radialis Longus, extends from the lateral epicondyle of the humerus to attach to the base of the third metacarpal on the palm. Its function involves extending the wrist and radial deviation. It is distinguishable from the long extensor by its origin from the outer epicondyle of the humerus.

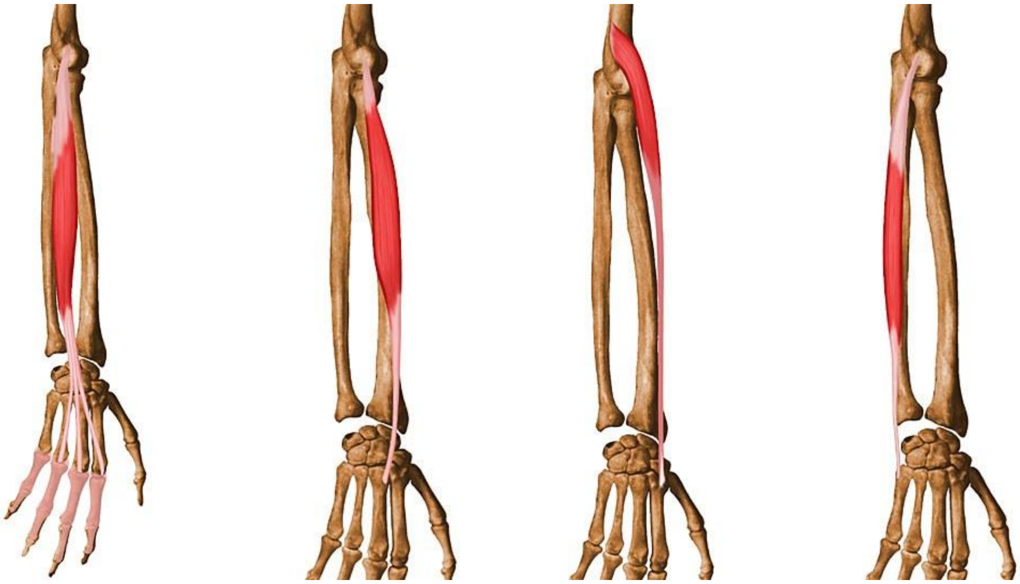
Extensor Digitorum Communis: This muscle, located in the posterior forearm, is responsible for extending the wrist and finger joints. It originates from the lateral epicondyle of the humerus and connects via a common tendon to the extensor tendons of the second and third fingers, contributing to the extension of these fingers.

Note: In literal terms, *Epicondyle* means “above the condyle”. Condyle refers to the protrusions at the ends of long bones. In the lowermost part of the humerus, there are two prominences, one on the medial side and the other on the lateral side, referred to as condyles. On the medial condyle, there is a smaller prominence called the epicondyle or supracondylar process. The medial epicondyle of the elbow is palpable on the inner surface of the elbow, and the ulnar nerve passes behind it.



Flexor Digitorum Superficialis FCR & FCU Palmaris Longus

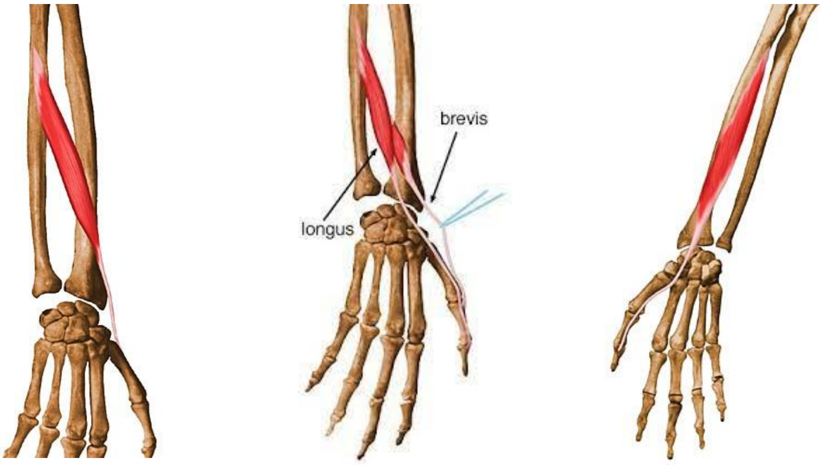
Fig. 3. The first group muscles originating from the elbow medial epicondyle and are responsible for wrist flexion.



Extensor Digitorum Communis Extensor Carpi Radialis Brevis Extensor Carpi Radialis Longus Extensor Carpi Ulnaris

Fig. 4. The first group muscles originating from the elbow medial epicondyle and are responsible for wrist extension.

The second group of forearm muscles comprises 7 muscles that origin from an area on one of the two bones of the forearm, and are responsible for the movements of the fingers. Four muscles are assigned to the movements of the thumb, the tendons of their moving ends are connected to the bony ligaments of the thumb after passing through the wrist, and they are (Fig. 5): Flexor Pollicis Longus, Extensor Pollicis Longus, Extensor Pollicis Brevis, Abductor Pollicis Longus. The fifth muscle is the Flexor Digitorum Profundus and is responsible for flexing the four fingers. The other two muscles are the extensor of the index finger, Extensor Indicis, and the extensor of the little finger, Extensor Digitiminimi.



Abductor Pollicis Longus   Extensor Pollicis, Longus & Brevis   Flexor Pollicis Longus

Fig. 5. Muscles of the second group originating from the middle of forearm bones and are responsible for thumb movements.

The third group of forearm muscles comprises 10 muscles, all of which are small muscles located on the back and palm of the hand, contributing to finger movements. These muscles include: Palmar Interossei, Dorsal Interossei, Lumbricals, Flexor Digiti Minimi Brevis, Opponens Digiti Minimi, Palmaris Brevis, Adductor Pollicis, Abductor Pollicis Brevis, Opponens Pollicis, and Abductor Digiti Minimi. These small muscles, as illustrated in Fig. 6, have no involvement in wrist movements; therefore, we won’t delve into their description in this context.

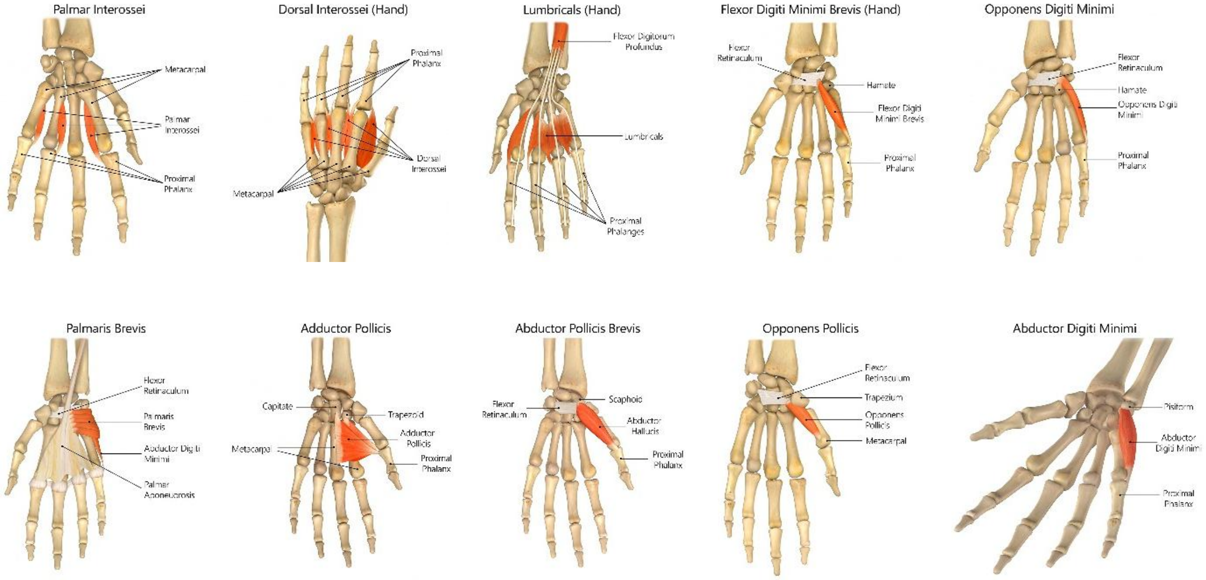


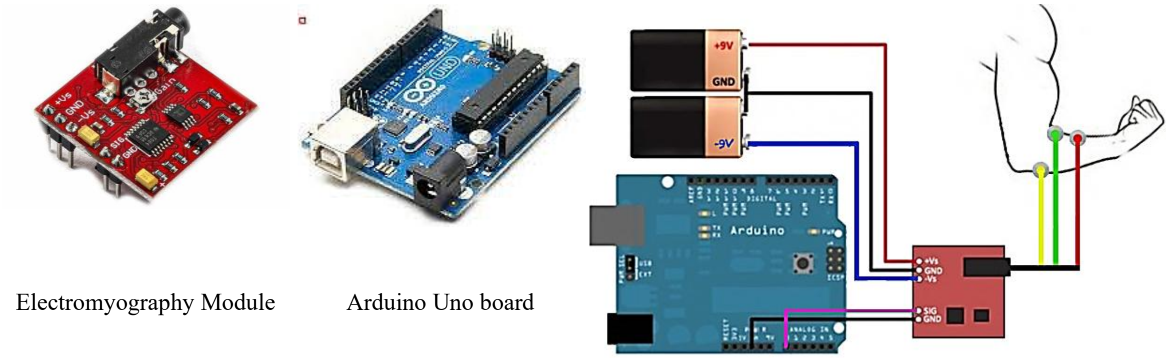
Fig. 6. Muscles of the third group Involved in Fingers Movements. (images are taken from www.rehabmypatient.com)

4. HARDWARE COMPONENTS

The hardware components utilized in this work encompass a bipolar Electromyography Module, an Arduino Uno board, a handcrafted robot mimicking the human wrist’s anatomy with degrees of freedom for flexion-extension and abduction-adduction movements, actuated by R.C. servo motors.

A bipolar Electromyography Module, which is embedded on Arduino, is employed for recording and registering signals, as shown in Fig. 7. This module utilizes a two-pole system for signal recording and, following amplification, outputs an analog signal of 0~5 volts. The module utilizes three electrodes, one for reference and two for recording muscle signals, connected via a three-wire cable through an audio jack. As illustrated in Fig. 7, the module requires a positive and negative 9-volt power supply along with ground. Instead of using battery packs, we opted for a 9-volt adapter for power, and an inverting op-amp was employed to generate the negative 9-volt supply. Two EMG module along with their power supplies, are mounted on a custom-printed circuit board attached to the Arduino, sending their analog signals to the Arduino board's analog terminals (Fig. 8 - Right).

A robotic wrist with two orthogonal joints capable of mimicking flexion-extension and abduction-adduction movements was constructed (Figure 8 - Left). The joints incorporate standard servo motors (R.C. servos) actuated by PWM signals, controlled by the same Arduino board used for the Electromyography Module. These motors typically cannot perform full rotations and have a motion range between 0 to 180 degrees, consistent with the motors used in this robot. The schematic in Fig. 9 outlines how the robot wrist motors are actuated. This figure illustrates the Electromyography Module and the Arduino Uno board along with their connection through serial port to send and receive data in MATLAB.



Electromyography Module

Arduino Uno board

Fig. 7. Electromyography Module and Arduino Uno board.

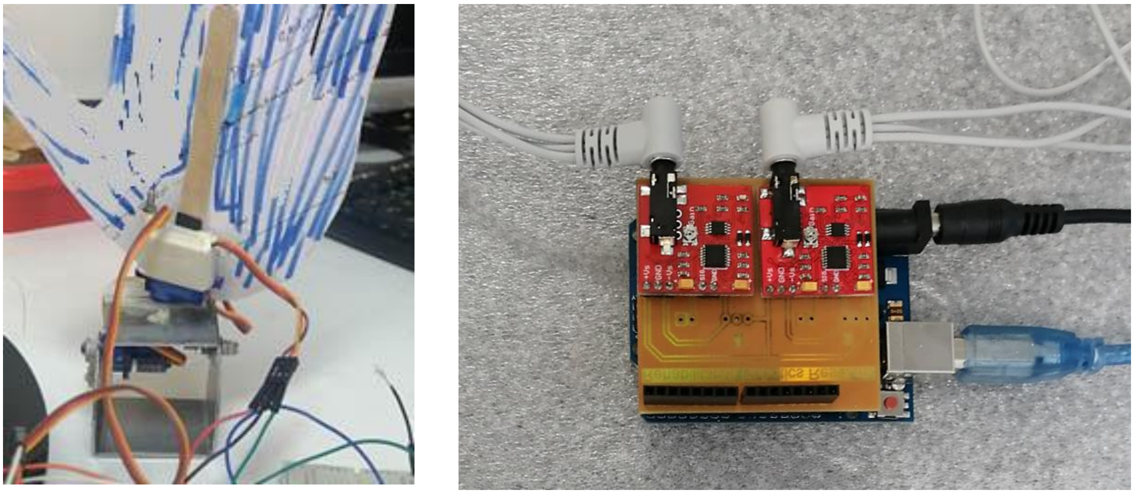


Fig. 8. Exprimental setup; right: Two EMG Module mounted on the Arduino Uno board, left: 2-DoF robotic wrist.

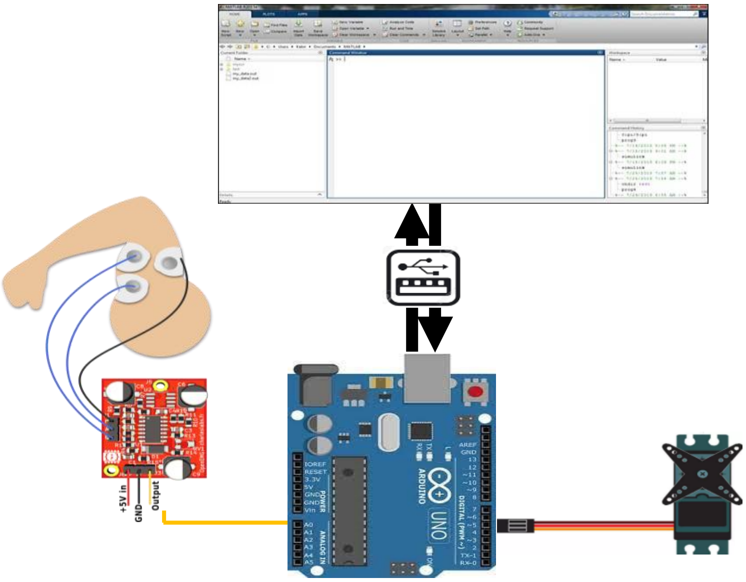


Fig. 9. EMG signal processing and online activation of robot motors with MATLAB software interface

In accordance with literature recommendations, the skin surface is cleaned and shaved before attaching the electrodes. A gel is used to increase conductivity between the skin and electrodes. The electrodes are placed parallel to muscle fibers, and the distance between electrode centers, as per the SENIAM standard for forearm muscles, is set at 2 centimeters. The electrode placement protocol for attaching the chestleads on the skin is detailed in Fig. 10.

For the convenience of code writing necessary for preprocessing of the recorded electromyography signal and the development of the algorithm detecting motion initiation, an additional toolbox related to the “communication with the Arduino board” was installed on MATLAB software was utilized for communication with the Arduino board through the serial port, as shown in Fig. 9. Accordingly, after recording the signal by the Electromyography Module, the signal is transferred to the Arduino board through its analog ports. This signal enters a microcontroller programmed directly from the MATLAB software. If observed, the data exchange between Arduino and MATLAB occurs online. After decision-making, the execution of the movement is accomplished by sending PWM waves from the digital ports to the servo motors controlling the joints of the robot wrist.

Fig. 10. Attaching the chestleads on the skin according to Electrode Placement Protocol.

5. CONCOLUSION

In this paper, the activation of motors in a two-degree-of-freedom robotic wrist using recorded and processed electromyographic signals was investigated. Our goal was to record EMG signals from some of the forearm muscles and convert them into a control command that could be used to drive the robot. An example of recorded signals from the FCU and ECU muscles during abduction-adduction movement and the calculated control command for launching the robot's motors is shown in Fig. 11.

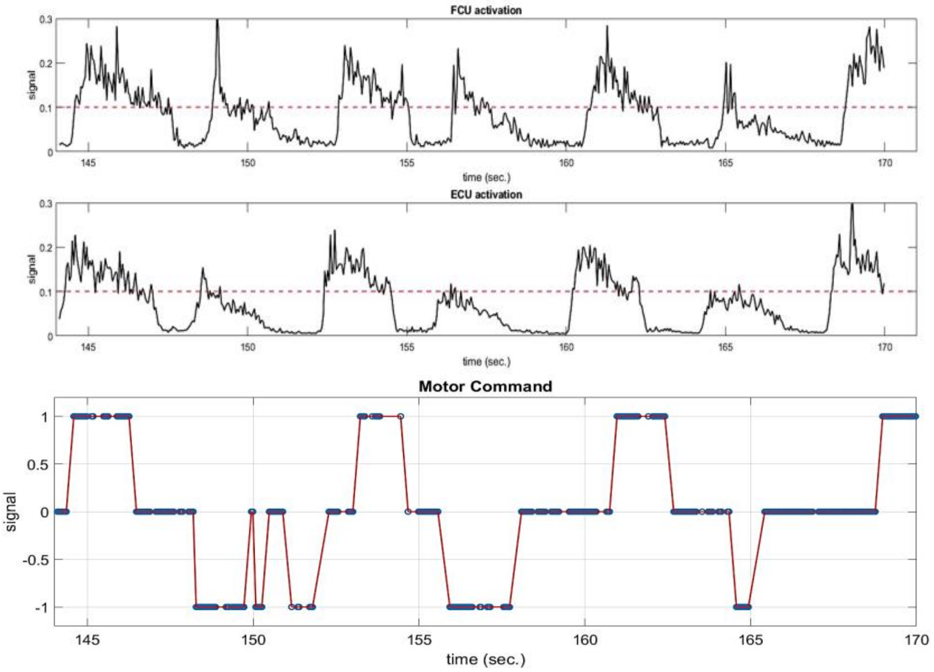


Fig. 11. EMG signals of FCU and ECU muscles in abduction-adduction movement and motor control command launch.

Declaration

We acknowledge that we used ChatGPT to enhance the academic writing of our manuscript while ensuring the originality and integrity of our work.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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