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Design and Development of an Exoskeleton Prototype Arm Utilising Electromyography

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Abstract

Individuals who lack or have significant difficulties utilizing their arms and hands may benefit from having an exoskeletal arm to gain some independence in their daily lives. This paper outlines the design and implementation of a prototype electro-mechanical arm. The mechanisms utilised cable drawn pulleys to provide controlled angles 3-degrees of freedom (DOF) for index, middle and ring and the shoulder. The elbow has a single DOF. The aim was to build a prototype, wearable prosthetic mechanism for the whole arm that could perform some basics daily tasks.

Furthermore, it was intended the prosthetic mechanisms assist with some physiotherapy activities which might be helpful for individuals with muscle degenerative diseases. The arm was controlled by either utilising electromyography (EMG) signals recorded by placing sensors on the arm or by utilising a Joystick Interface. The actuation of its DC motors was programmed to reflect the user's muscle activities and to allow the user to control the modules smoothly and accurately. A Graphical 3D animation was implemented in MATLAB© Simulink© to demonstrate the arms' operation while the hardware was interfaced through LabVIEW©. The components were designed in Solidworks and 3D printed.

The prosthetic mechanism was able to lift object up to 2 kg. The mechanism provided accurate position control for moving objects and physiotherapy. The basic daily activity of drinking was achieved however this required development.

1. Introduction

In this study, a prototype exoskeleton arm was developed for patients who may not be able to use an arm as a result of a condition such as Muscular dystrophy. Muscular disorders (MD) are diseases that affect the human muscle system, these can be categorised as muscular dystrophy or neuromuscular conditions. A finding published in 2016 indicated around 70,000 people are affected by Muscular dystrophy or related neuro disorders in the UK (1). A study in 2008 reported that the number of muscle disorders and limb loss will more than double by 2050 (2). While there is no cure for muscle disorders, supportive care can help to keep the strength and flexibility and improve the quality of life. Muscular dystrophy is a rare disease that weakens muscle tissue over time (3).

The main function of the exoskeleton is to share a portion of the external load with the user. The exoskeleton arm prototype designed in this study is cost-effective and easy to use. It can with further developments help patients, in achieving useful daily tasks activities such as picking an object and eating and can be part of simple physiotherapy activities. Particular attention was paid to include electromyography (EMG) as a method of control for each mechanism. The perspective in using EMG as an intuitive and natural control interface for the robotic arm was previously reported (4). They measured an EMG signal in the last stage of the Muscular dystrophy patients.

Prosthetic hands vary in features from the points of view of their capabilities, weights, complexity, cost, and method of control. This area of design has adapted technologies such as mechatronics, robotics, neural and Artificial intelligence. An elbow rehabilitation device has been proposed (5). They estimated the torque from the EMG signal and also carried out a clinical trial. A 5- degrees of freedom (DOF) exoskeleton arm has been reported that emphasised the importance of EMG signal processing(6) (6). Techniques for extracting relevant EMG features were suggested (7).

In this study, the main method of control is based on EMG, however, an alternative method was also investigated that may be more suited for physiotherapy activities. This method of control was based on a joystick interface and it was completely independent of the EMG control.

As the arm mechanism is worn, its structure and biomechanics must provide a correct amount of natural movement while avoiding any discomfort or harm. The natural range of motion of the arm was extrapolated from the results obtained from information associated with shoulder movement (8), the elbow (9) and hand (10). The proposed range of movement of the exoskeleton arm was simplified to ensure the functionality of the prototype. The kinematic of the hand was evaluated from the discussions of a related work that also provided a literature review of the current exoskeleton hand technologies (11). It has been shown that linear actuators could assist in making a hand module more comfortable and portable (12).

In a study, Matlab© was used to graphically simulate a hand module thus validating the design (13). In this study, it was considered appropriate to conduct a graphical simulation to prove the feasibility of the proposed approach and evaluate any problem associated with EMG control, before hardware implementation. Some of the previous designs were had complex design (14) therefore in this study the aim was to reduce the complexity, enhance portability and affordability. The introduction of the pulley mechanism was effective in reducing the overall weight of the exoskeleton (15). Their method of drive allowed relocation of heavy motors which effectively reduced the weight of the exoskeleton. Most previous designs focused on torque control; the novelty of the proposed design is mapping the EMG activity into accurate position control for each mechanism. The methodology utilised in this study was assisted by a related publication (16).

In the following sections, the methodology followed in the design is outlined, mechanical and software components of the system are described, and the evaluation results are discussed.

2. Methodology

2.1 Concept study

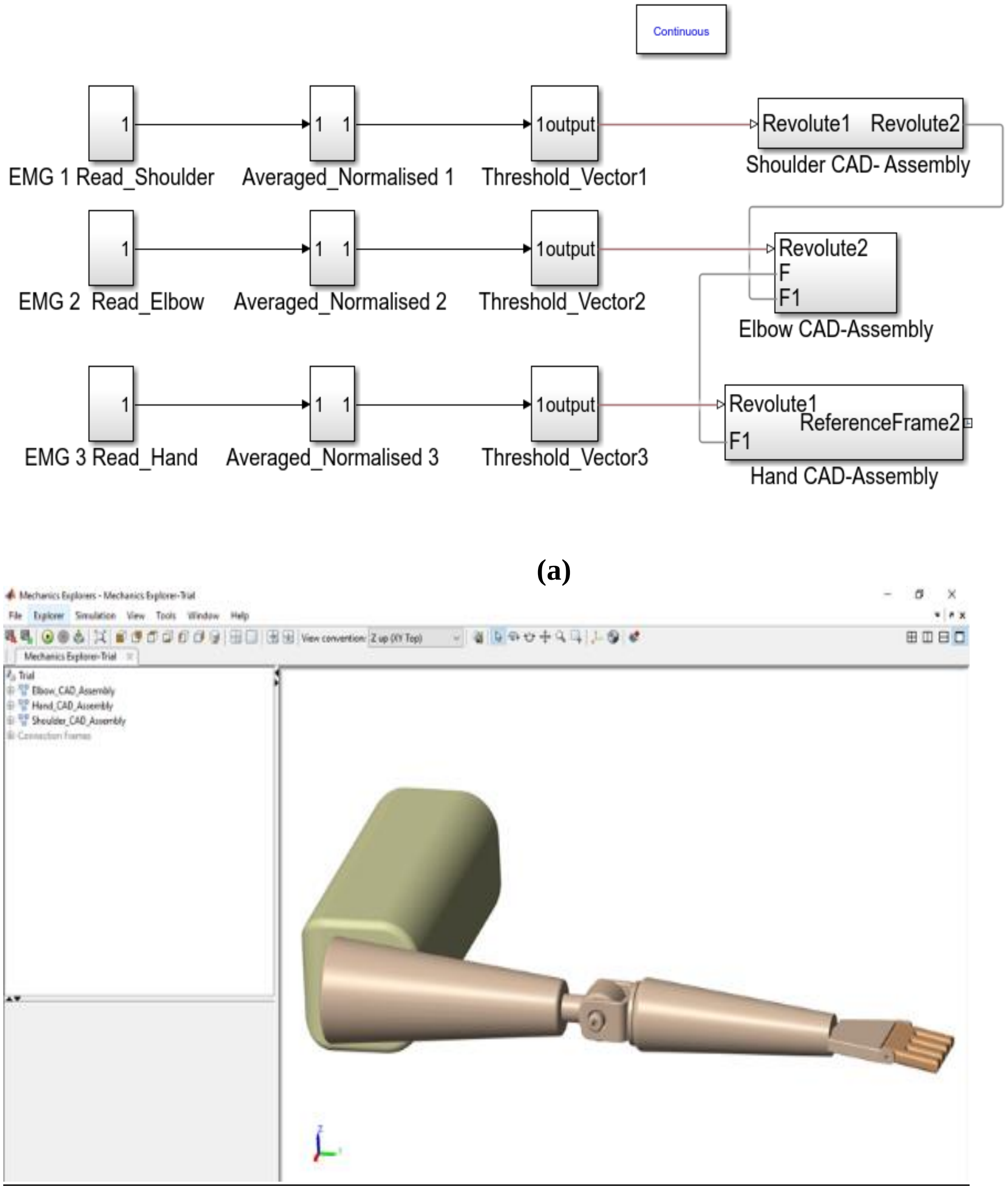
A review of the literature was conducted to identify the customer needs of MD patients when using exoskeleton products. It was found that typically, the current exoskeleton technologies can be large, heavy and unpractical for everyday activities. With this in mind, a scope and product design specification were created, prioritizing on designing a lightweight design that is easy to use control. The House of Quality function was utilised to analyse conflicting and collateral technical requirements. In this function, the degree of freedom was found to impair the weight and the detection of the EMG signal of the system design. Therefore, a trade-off was proposed to simplify the range of movement of the upper limb, as shown in Table 1.

Table 1 Simplified range of movement of the upper limb

Part	Natural DOF	Proposed DOF	Proposed Range (Degrees)
Hand	3	3 - Hand opening & Closing	90
Elbow	2	1 - Vertical Flexion	110
Shoulder	3	1 - Horizontal Flexion	100

2.2 Validation model

The practical potential of the EMG sensors was tested using a SimMechanics/Solidworks(c) model shown in Figure 2. This simulation was visualised by interfacing both the computer-aided design (CAD) model and its associated microprocessor board (Arduino UNO) with the EMG sensors. Three MyoWare EMG sensors were utilised to control the movements of each joint. The EMG sensors were positioned on the deltoid, biceps brachii and extensor carpi muscle.



(a)

(b)

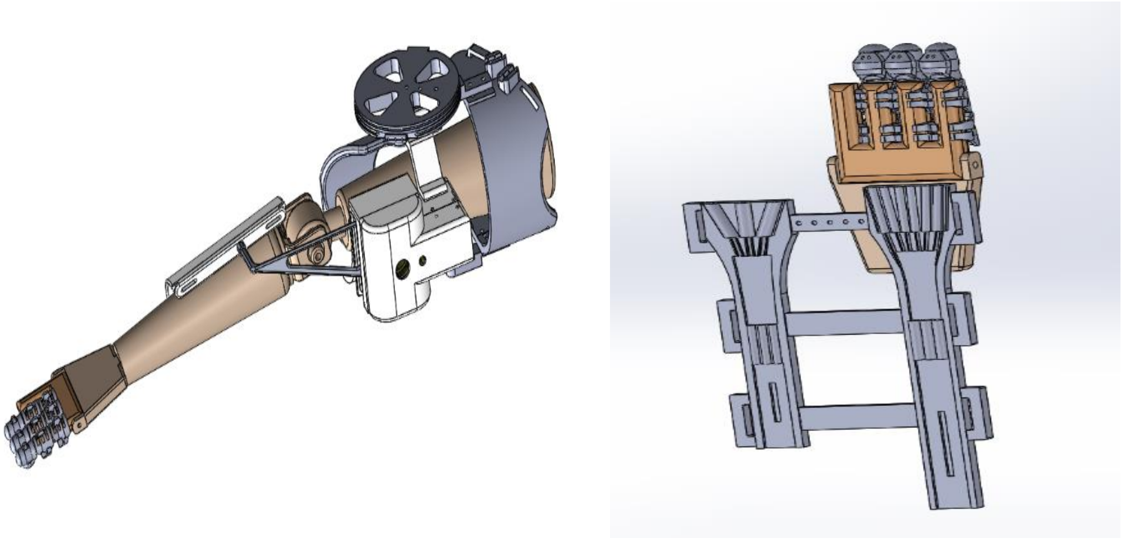
Figure 1 Design setup of the Simulink© model: (a) operation, (b) design.

The simulation confirmed the feasibility of the proposed approach by correctly reflecting the real-time movements of the arm based on the EMG muscle activity. However, it also showed some of the problems associated with EMG based design. The EMG was found tiring on the user when operated for a long time.

2.3 Mechanical design

The torque and power were analysed for the selected actuator. The weight was considered a key factor to satisfy the portability requirement. Attention was paid to the type of motor based on performance and weight and cost. In some previous designs, brushless DC motors were used. However, in this study, due to reduce cost, three different alternative motors were utilised as follows: Servo (for elbow), Stepper (for shoulder) and linear actuator (for hand).

Three transmission systems were utilised to transfer the power from the DC motors to the mechanism. The type of system depended on the torque required and other conflicting design constraints. In the shoulder mechanism, the wire was looped around the DC stepper motor and a second wheel was used to drive the flexion/extension of the shoulder mechanism. In the elbow mechanism, the transmission relied on direct linkage. The shaft was connected directly to the DC servo motor. Additionally, the gearing amplified the output torque. For the hand mechanism, the transmission relied on two 12V linear actuators which pulled the prosthetic fingers utilising a metal cable. The pulley system reduced the weight on the arm by shifting some of the system components to the back of the human body. Particular attention was paid to reduce the angular displacement of the cable caused by bents and friction.



(a) **(b)**

Figure 2 CAD model of the shoulder and elbow mechanism (a); Hand mechanism design (b)

For the hand module, the finger's grip was facilitated using the mentioned pulley system with a spring return mechanism. The force of the actuators was utilised to grip the object and a spring mechanism aided in returning the fingers to the rest position. In the kinematic analysis, a finger was divided into three segments, matching the proximal, middle and distal phalanx of the natural movement. The analysis was performed to calculate the force required by the actuator to hold an object weighing 2 kg. This was utilised as the main parameter for the linear actuator selection. The three chosen fingers were those that gave the highest grip. The index and middle fingers provided the highest grip and the ring finger provided some additional support.

2.4 EMG Processing

EMG sensors were utilised to detect muscle movement. The MyoWare© muscle sensor was chosen as it has a built-in signal amplifier, two high-pass filters (cutoff frequency 0.16 Hz), an operational amplifier with regulated gain and a 3rd order Bessel filter with a cut-off frequency of 40 Hz. The signal activity was mathematically manipulated into a "Desired Angle" for the arm to reach. The three EMG sensors were placed on the deltoid, the biceps brachii and the extensor carpi muscle. To utilise the EMG signal as an input for each motor system a lowpass filter and the moving average were employed. The lowpass filter with a cutoff of 0.02 Hz was used to reduce the noise produced by the sensor and smooth the signal, and the moving average to further smooth out the data. Feature extraction is crucial when implementing EMG in the medical system (17).

2.5 Software/Hardware Implementation

Two microprocessor boards (Arduino Uno) were employed during the implementation. Pulse width Modulation of the motor can cause distortions and power fluctuation in the microprocessor. Therefore it is important to place the sensors on a separate board with a separate power supply. The physical implementation was conducted in LabVIEW©, utilising the LIX library by installing the following package, LINX by Digilent/LabVIEW© Maker Hub**.** The designed software provided smooth motor control that was directly dependent on the user's muscle activity. The EMG signal guided the direction and extent of the hand movements by actuating the motors at each joint.

The PID controller was applied to operate the motor to the desired angle. Three different motors were employed in the system. The EMG control was adapted appropriately to the motor type, as shown in the flowchart in Figure 3. A toggle button was also added to switch between the EMG and Joystick control. The joystick was mapped into the desired Motor angle by implementing the linear mapping and scaling feature available in LabVIEW. The EMG and Joystick control method were independent. The operating power supply 12 volts.

2.6 Prototype construction

The proposed range of movement was achieved, and mechanical locks were also included to ensure the user's safety. The components were 3D printed in ABS plastic, carbon fibre and silicone rubber which were found practical for prototyping. However, the ABS plastic was weak and required extra thickness on high-stress areas which compromised the weight of the overall system. The weight was approximately 3kg, slightly over the design expectation; however, further FEA optimization and the use of aluminium parts could further reduce the weight of the arm. A chassis was produced to hold the elbow and the shoulder mechanism together. The Hand mechanism was independent and could be used on its own.

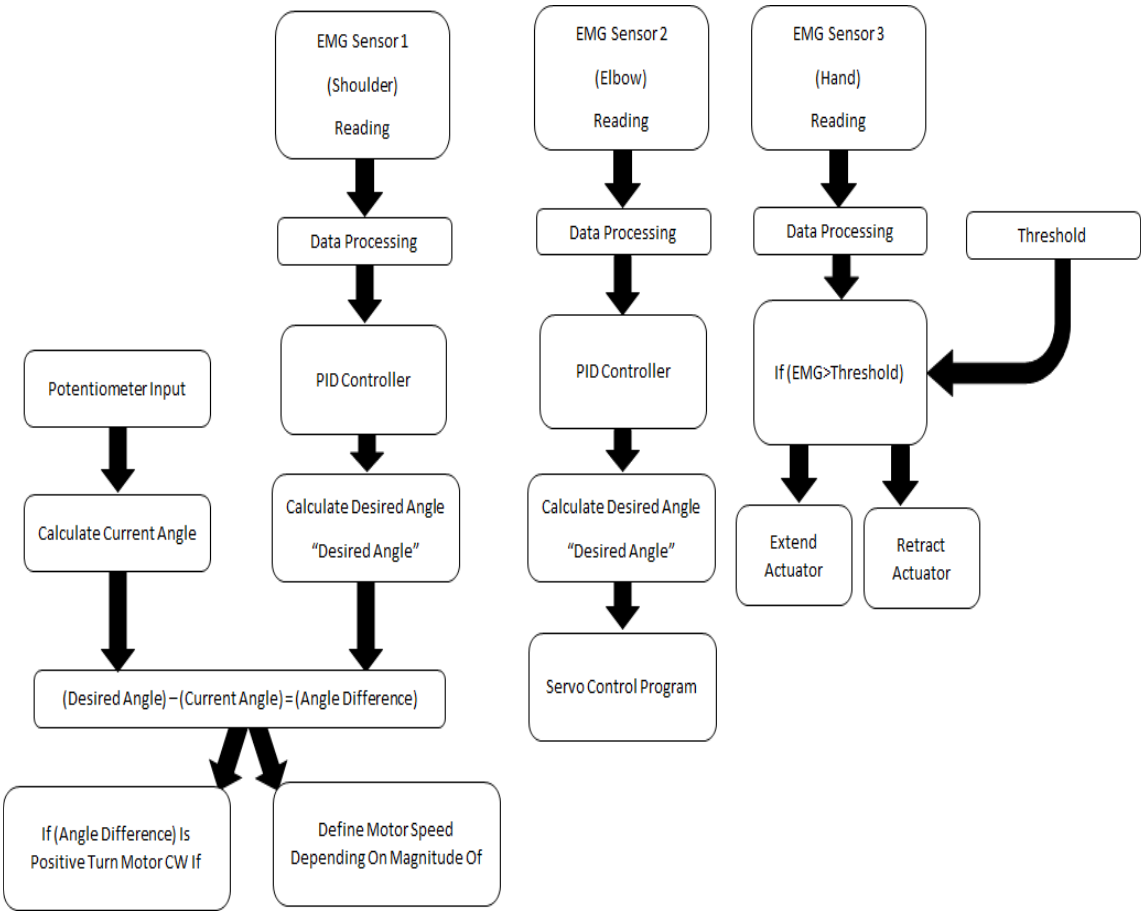


Figure 3 Flow chart of the EMG control method

3. Results and discussion

Figure 4 shows the developed prototype arm.

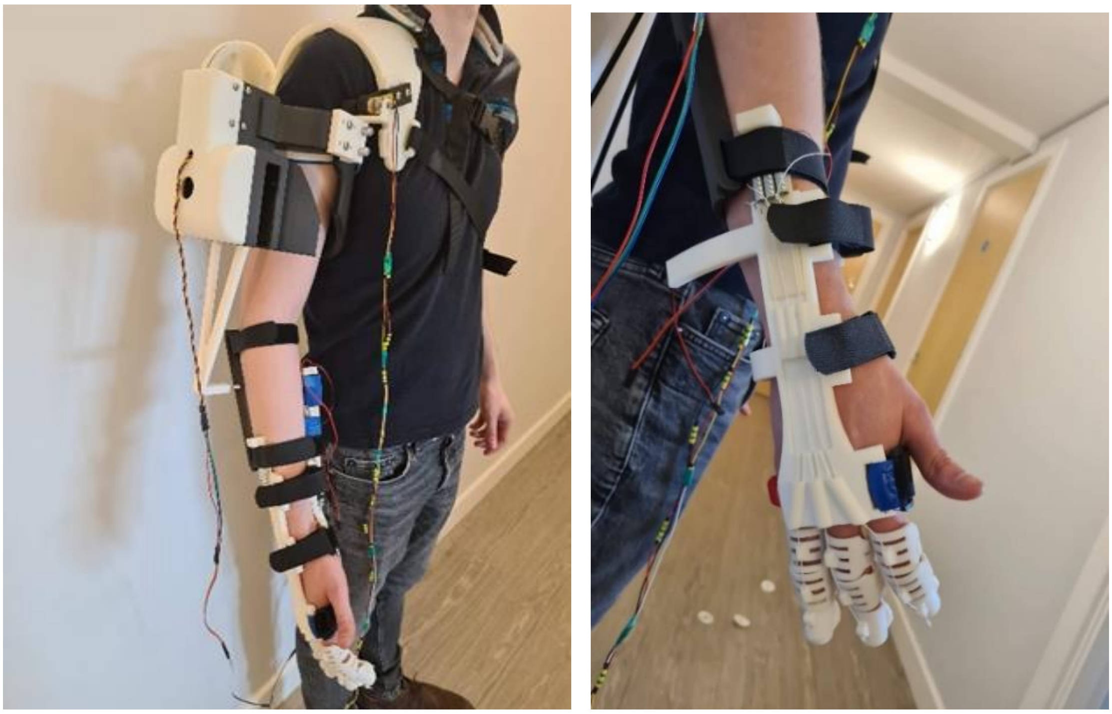

(a) (b)

Figure 4 Prototype arm: (a) shows shoulder and arm testing, (b) shows hand testing.

The valuable feature of the design was its EMG control mechanism. The system was assessed to determine if it could detect EMG signals correctly and perform the movement's functions accordingly. The system was tested by lifting small objects such as cups and cans.

The mechanism was able to lift 2 kg objects, thus, reducing fatigue of the user. The gripping system of the hand mechanism provided adequate gripping and successfully lifted objects of different shapes. The fingers' rubber material provided sufficient friction to hold objects with different shapes and materials. The use of rubber silicone on the prosthetic hand allowed it to be waterproof so it could be washed after use. The actuation time taken for full contraction of the whole mechanism was around 3 seconds. In the validation model constructed in MATLAB$^{©}$, the EMG control was found tiring, especially for a long time. This issue was solved in the prototype design by decreasing the mapping range of the EMG activity, i.e. there was no need to fully contract the muscle to fully rotate the mechanism.

The EMG was considered effective in capturing the intended motion of the user. However, to ensure appropriate accuracy, the user required training.

The training was found particularly effective for performing some daily activities. During testing, the user tended to contract involuntary the biceps and the extensor carpi muscles together. The involuntary muscle activities misled the mechanism of different movements. However, the user quickly learnt to use the appropriate muscle by practising in few hours. Practising also improved the ability of the user to control muscle activities. It was involuntary for the user to contract the muscle more than needed, and therefore, rotate the mechanism further than intended. The user quickly adapted to this issue. At the end of the training session (about 5 hours), the user was able to control the mechanism effectively and also perform a basic daily activity of drinking. This study proved that EMG can be successfully mapped into position control.

In addition to assisting the movement of the patient, the prosthetic arm may be valuable for physiotherapy training a joystick interface positioned at the hip of the user. The user could switch between the joystick and EMG control by using a toggle switch.

The main limitation of the devised hand mechanism was that it could not lift objects heavier than 2 kg. This was attributed to the type of motor and the absence of torque control. The proposed prototype was tested on physically fit adults who presented healthy muscles. Muscle disorders can reduce muscle activity, and therefore, the range needed for this mechanism to work. The proposed EMG control method should work on others, as long as muscle activities are present. Literature research indicated that patients with late-stage Duchenne muscular dystrophy could still operate analogue EMG outputs, and therefore, prove the feasibility of the proposed approach.

4. Conclusions

The design, construction, and testing of a fully functional EMG controlled exoskeleton arm consisting of shoulder, elbow, and hand modules were outlined. The mechanism worked successfully in the evaluation tests. However it had some limitations, and therefore its further improvement is needed to be used routinely. The prototype indicated that EMG activity can successfully be mapped into an effective position control. Future work could include the inclusion of greater more degrees of freedom in the shoulder, elbow, and hand modules. In addition to position control, torque control shall be added where needed. The inclusion of artificial intelligence such as neural network, deep learning and fuzzy logic could further enhance the operation of the prototype. It is also necessary to perform EMG testing on patients with muscular dystrophy, to determine program modifications needed to adapt the current prototype.

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