INTERNATIONAL JOURNAL ON SMART SENSING AND INTELLIGENT SYSTEMS VOL. 10, NO. 2, JUNE 2017

www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

DESIGN AND DEVELOPMENT OF 3D PRINTED MYOELECTRIC ROBOTIC EXOSKELETON FOR HAND REHABILITATION

Ismail Ben Abdallah[1,2], Yassine Bouteraa[1,2], Chokri Rekik[1]
Control and Energy Management Laboratory (CEM-Lab) National School of Engineers of Sfax, Tunisia (1)
Digital Research Center of Sfax, Technopark of Sfax – Tunisia (2)
*Emails: ismaelbanabdallah@yahoo.fr; yassinebouteraa@gmail.com; chokri.rekik@enis.tn

Submitted: Feb. 6, 2017 ***Accepted: Apr. 16, 2017*** ***Published: June 1, 2017***

Abstract- The development of dynamic rehabilitation devices can be evaluated as a research fast-growing field. Indeed, robot-assisted therapy is an advanced new technology mainly in stroke rehabilitation. Although patients benefit from this enormous development of technology, including the presence of rehabilitation robots, the therapeutic field still suffering a lack in hand robotic rehabilitation devices. In this context, this work proposes a new design of a 3D printed hand exoskeleton for the stroke rehabilitation. Based on the EMG signals measured from the muscles responsible for the hand motion, the designed mechatronic system detects the intention of hand opening or hand closing from the stroked subject. Based on an embedded controller and five servomotors, the low cost robotic system is able to drive in real time three degrees of freedom (DOFs) for each finger. The real tests with stroked subjects showed that the designed hand exoskeleton architecture has a positive effect on the motion finger range and mainly in the hand ability to perform some simple tasks. The case studies showed a good recovery of the motor functions and consequently the developed system efficiency.

Index terms*: robotic exoskeleton; 3D printing; EMG control; features extraction; stroke rehabilitation.*

I. INTRODUCTION

Recently, the development of rehabilitation robotic system has received increased attention by many researchers [1-2]. Exoskeleton devices designed to physiotherapy and kinesiotherapy are being considered for numerous applications such as clinical [3] and at-home rehabilitation [4].

The most popular hand impairments which can affect the world population are spasticity, lack of control or muscle weakness in consequence of stroke, paralysis, injuries or muscular diseases. Cerebrovascular accidents (CVA) and spinal cord injuries (SCI) are currently the most common causes of paralysis. Stroke survivors often suffer impairments on their wrist, hand and paretic extremities. Recovery for the upper extremities functions is often limited for the person after stroke [5] related to the learned non-use of the impaired hand and the complex anatomical structure which implies the coordination of multiple muscles for majority of the hand functions [6].

Human hands are complex and versatile instruments which play an essential role in the person-environment interaction. Since it requires a smaller size and rich tactile sensing capabilities, hand exoskeletons still face many challenges for the rehabilitation community and many technical areas, including hand biomechanics, neurophysiology, rehabilitation, actuators and sensors, physical human-robot interactions and ergonomics. Inspired by theses, a comprehensive review of technologies used in hand exoskeleton [7] and dynamic hand orthoses [8] for rehabilitation and assistive engineering were presented for literature.

Several studies investigating the use of electromyographic (EMG) signals in robot-based stroke neurorehabilitation to enhance functional recovery [9]. Indeed, EMG is a high technology which has a definite potential to be used as control signal for multifunction prosthesis [10]. There is need to draw correlation between the physical, physiological factors and the EMG signal [11]. Demonstrating the feasibility of the EMG pattern classification technique to discern the intent of stroke survivors, a robust subject-specific electromyography (EMG) pattern classification technique has been developed to discriminate between the intended manual tasks from muscle activation patterns of stroke survivors [12]. Based on EMG signals from the hemiplegic side, an exoskeleton hand robotic training device dedicated for stroked person is designed [13]. In order to provide training on their impaired hand. In some context, [14] develop an effective human motion prediction method based on the EMG signals using a neuro-fuzzy technique for the control of power-assist exoskeleton robots.

The design and development of hand rehabilitation devices are increased in the research area for the scientific impact [15-23] as well as the industrial field for the commercial production [24-25]. Providing a continuous passive motion for the hand fundamental movements, Armadeo from the Tyromotion [24] and the Kinetec Maestra from the Sammons Preston [25] are the most developed commercial products. On the other hand, the developed search products are presented as robotic devices for hand grasping, such as Alpha prototype II [15] and HWARD (Hand and Wrist Assisting Robotic Device) [16], or as exoskeleton type such as hand motion assist robot [17] and Wearable Handling Support System [18]. The special training systems are also developed such as the Haptic Knob [19], reconfigurable robotic system [21], HEXORR device (Hand EXOskeleton Rehabilitation Robot) [22], Gloreha (hand robotic rehabilitation) [23] and HandCARE [20] in order to perform the special rehabilitation cases such as hand and finger function trainings. However, the majority of these systems are too expensive for personal use and at-home rehabilitation. Others are a static platform and then not portable. Moreover, some products are designed for some specific applications such as sensorimotor recovery in stroke rehabilitation and range of motion recovery after hand surgery. Covering a wide range of subjects is a great constraint in the design of hand exoskeleton devices.

In this paper, we envisioned that a portable hand rehabilitation mechatronic system would be more useful to the hand impaired patients for their activities of daily living and it would encourage them to use their impaired hand more often. Thus, we present a new design of low-cost 3D printed portable hand exoskeleton. The hand impaired subject can enable the hand motion from the desired hand intention in the healthy side as well as from the hemiplegic side. Our product is a novel mechatronic design of an EMG-controlled robotic system to meet the needs of the hand impaired subjects including the stroked cases (see Figure 1). The hand exoskeleton is designed using the low-cost 3D printing technology. The exoskeleton mechanism is designed specially to perform the finger fundamental movements that reproduces the therapy exercise by adopting a cable-actuated extension and spring-return flexion mechanism which is the main contribution of this work. Indeed, by using the spring-return flexion mechanism, the designed exoskeleton adapts with the object pattern. Therefore, stroked subject can grasp any object by a simple cable releasing mechanism without the need of high performance EMG classifier which requires a costly computing platform. Also, the low-cost designed system is very useful for both hand training and some daily living activities.

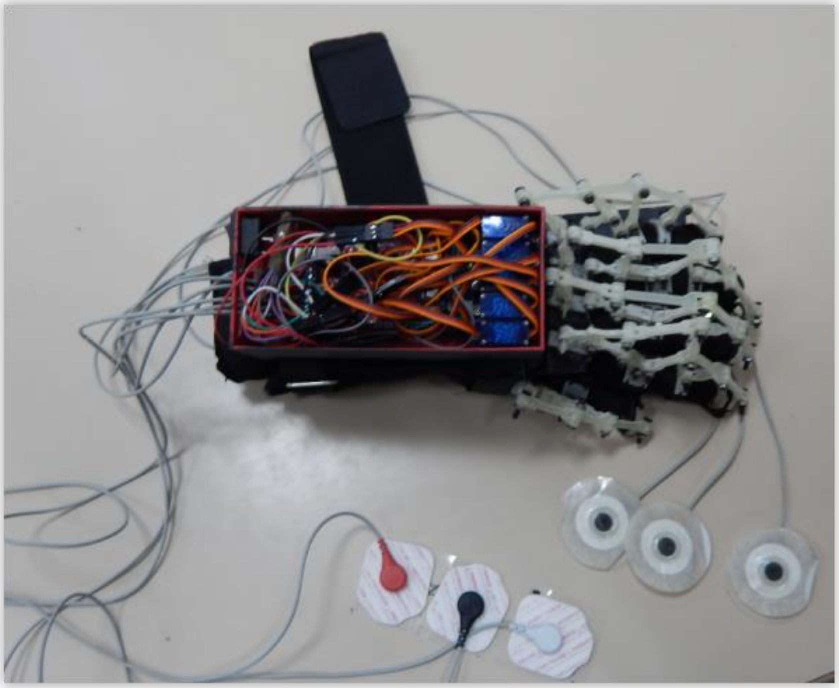

Figure 1. The designed hand rehabilitation robotic system

The present paper is organized as follows: hand rehabilitation theory is introduced in section II including the anatomical study of the hand and therefore the requirements of the hand exoskeleton device. Section III describes different steps of the robotic system design including the 3D model designed using solidworks software, rapid prototyping technique using 3D printer technology and the different electronic components responsible for powering, control and exoskeleton moving. Experimental results of the preliminaries tests with healthy and hand impaired participants are discussed in section IV. Finally, we conclude with a work summary and perspective.

II. HAND REHABILITATION THEORY

The rehabilitation exoskeleton device has been designed to perform the flexion-extension hand motion in rehabilitation training. The theoretical information about the anatomical structure, design requirements of a rehabilitation exoskeleton device are given in the following subsections.

1. Anatomy of the hand

Hand exoskeleton device is closely coupled with hand skeleton when it is worn. Hence, developing the hand exoskeleton requires the discovery of hand anatomy and biomechanics in order to ensure safe and effective operation. Indeed, knowing the degree of freedom (DOF) and range of motion (ROM) of each joint is highly recommended for the mechanical design and safe structure. Moreover, the main responsible muscles of the hand movement (intrinsic and the extrinsic muscles) as well as the connective tissues must be studied. Therefore, the systematic knowledge helps achieving proper functions for rehabilitation and assistance.

Figure 2 presents an overview of the biomechanics of the human hand including the bones and joints. There are 19 bones and 14 joints distal to the carpals. Each finger articulates proximally with a particular carpal bone at the Carpometacarpal (CMC) joint. For each finger, the metacarpal bone and the proximal phalanx are linked at the MCP joint which enables two degree of freedom permitting the flexion, extension, abduction, and adduction movements. The two remaining joints (PIP and DIP) are found between the phalanges of the fingers.

The different shapes of the finger joints result in varying DOF at each joint providing a large range of motion and greater flexibility of the digits. Range of motion is the overall motion used in a movement and can be specified by linear or angular motion of the hand digits. The MCP joints are flexed approximately 45°, the PIP and the DIP joints are flexed between 30° and 45° and between 10° and 20° at the resting posture, respectively. The extension varies widely among individuals. For PIP and DIP joints, flexion of about 110° and 90° occurs. Extension beyond the zero position is regularly observed and depends largely on the ligamentous laxity [26].

The rest of this section is the muscles responsible of hand motions which are accomplished by the coordinated action of groups of muscles. Generally, the principles muscle responsible for fundamental hand movements (flexion and extension of the digits) are the extrinsic muscles located in the arm and forearm while the intrinsic muscles are located entirely within the hand, and they permit the independent action of each digit.

According to the related study of the anatomical structure of the hand, the placement of the electrodes for EMG acquisition is chosen at the muscles responsible of the flexion and extension of the hand, they are the extrinsic muscles. This part is detailed in the next section.

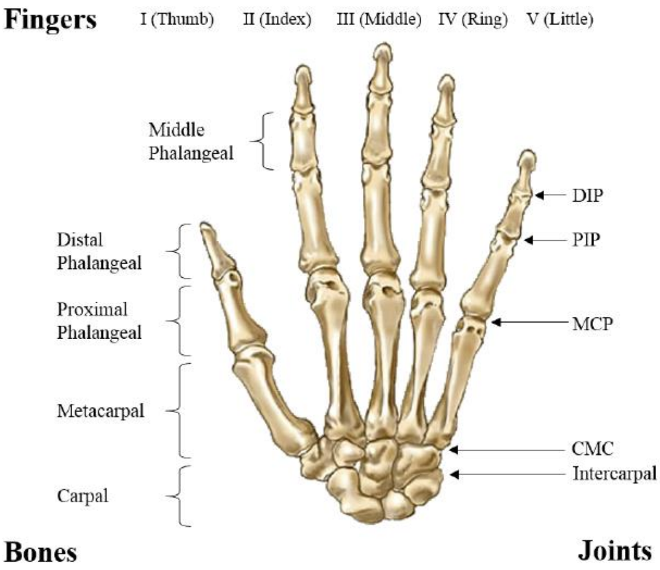

Figure 2. Bones and joints of a human hand

2. Requirements of the hand exoskeleton device

Since the wearer interact directly with the exoskeleton systems under close contact conditions, the safety constraint is one of the most important requirements in physical human-device interaction. Indeed, this physical interaction should be ensured without hazardous and unexpected movements because any malfunction can be seriously harmful to the user. Inspired by this, the unpredicted scenarios that can be due to controller part should be considered by the mechatronic architecture during the rehabilitation exercise. Hence, limits to the range of motion will be respected even in the case when the exoskeleton device want to force the wearer's body to move in an excessive range of motion. The workspace of a finger is shown in Table 1. As describing in the next section, the mechanical design avoids any exceeding of anatomical range of motion limits. In addition, despite the fact that the electrical actuators provide a sufficient torque to move the hand and perform the desired action but not capable to exceed the imposed mechanical constraints.

According to the kinematic model of the human hand [27], illustrated by Figure 3, the mechanical design must ensure the coincidence of the center of rotation because any conflict between the center of rotation of the user's hand and that of the exoskeleton device can damage both the user's hand as well as the mechanical structure. Next section details the mechatronic design by respecting the anatomical range of motion and center of rotation.

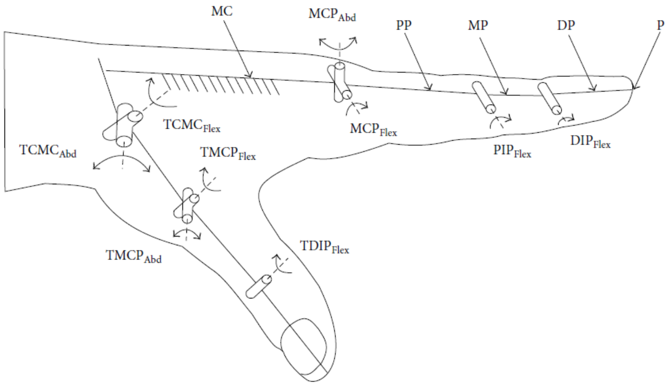

Figure 3. Kinematic model of hand: exception of thumb, the remaining digits are a fixed metacarpal.

Table 1. Normal values for range of motion of joints

Finger joint	**Angular motion range (°)**
MCP	[-90, 30]
PIP	[-120, 0]
DIP	[-80, 0]

III. MECHATRONIC DESIGN

As discussed previously, the anatomical constraints address the need of three inter-related factor that are ergonomics, performance and comfort-ability. In this section, according to these factors, we presented the mechanical architecture design as well as the electronic part and the control scheme.

As presented by [28-29], several rapid prototyping (RP) techniques are useful in the medical field. In particular, the use of 3D printer technology is broadcasting in the rehabilitation devices field specially in exoskeleton manufacturing [30]. Therefore, the use of additive manufacturing process allows attaining high level of customization which necessities only the geometric model of the robotic hand exoskeleton to be realized (3D printed). The tree main steps of the mechanical manufacturing of an exoskeleton device by 3D printing technologies can be outlined as follows:

- Modeling of the 3D geometry of the desired exoskeleton device using CAD software

- Processing of the acquired data through dedicated software
- Realization of the exoskeleton device using a 3D printer

The mold design of the device has been created using solidworks CAD software and subsequently printed using a 3D printer. Indeed, the possibility to realize highly customized hand exoskeleton is receiving a boost thanks to the widespread diffusion of low-cost 3D Printing technologies. Figure 4 and Figure 5 illustrate the CAD model of the designed device in rest and extension state, respectively. The different movements of model assembly are tested and animated using solidworks animation and motion toolbox.

The hand exoskeleton mechanism is composed of three basic elements: a splinting forearm, control unit, and five-finger mechanisms, as shown in Figure. 7. Table 2 lists the mass of each component of the hand exoskeleton (total mass is 310 g). Specially, the control unit box and the five finger mechanisms are 3D printed with PLA plastic called also polylactic acid which is a thermoplastic polyester. Indeed, PLA is a wonderful, easy to use, 3D printing material. As main advantage, it is a renewable and biodegradable resource because it is commonly derived from renewable resources, such as corn starch, tapioca roots or sugarcane. Thus, it naturally degrades when exposed to the environment. In addition, it is non-toxic and has a pleasant smell when printing. PLA filament comes in a wide range of colors and because of its thermal characteristics, is particularly easy to get great prints with.

The splinting forearm is chosen according to the size of the subject forearm. This support allows the exoskeleton to fit on different hand sizes easily. This support is considered as the “ground” link of the finger mechanisms, and the actuators and the control unit, including the battery, are all attached to the support.

Table 2. The hand exoskeleton component mass

Component	**Mass (g)**
splinting forearm support	115
Finger mechanism ×5	20×5
Control unit	108
Servomotor ×5	09×5
9V rechargeable battery	20
Total mass	388

Figure 4. CAD model: spring-return flexion mechanism (rest state)

Figure 5. CAD model: flexion state

The exoskeleton mechanism is designed specially to perform the finger fundamental movements that reproduces the therapy exercises, unlike to [31], by adopting a cable-actuated extension and spring-return flexion mechanism. Figure 6 proves the ability of the designed system to perform the flexion-extension of the digit and grasp an object.

The control unit is attached to the support through an adjustable elastic band which is routed around the forearm, making the actuators in correspondence with each finger mechanism. Each finger mechanism is attached to the support through three simple bands scratched with the links of each digit. This can enable the finger to move in flexion and extension directions freely. Each finger mechanism consists of three phalanges with interconnecting rotation joints. This configuration follows the model of human physiology and imitates basic human hand characteristics.

In the mechatronic design, we present the electronic part responsible for powering and moving the mechanical structure (see Figure 7). The control box, fixed on the splinting forearm, is responsible to exoskeleton control, containing Arduino mega 2560, fives micro servomotors sg 90. This system can be powered by rechargeable battery (9v) or by an external power supply (12v recommended). Each micro servo is capable to drive one digit, the sg90 is a low-cost solution for integrating in portable device because its low weight (9g) and reduced size (23.0 mm x12.2 mm x 29.0 mm). Arduino board is capable to control the rehabilitation exercise such us motor control and EMG acquisition and processing using E-health shield.

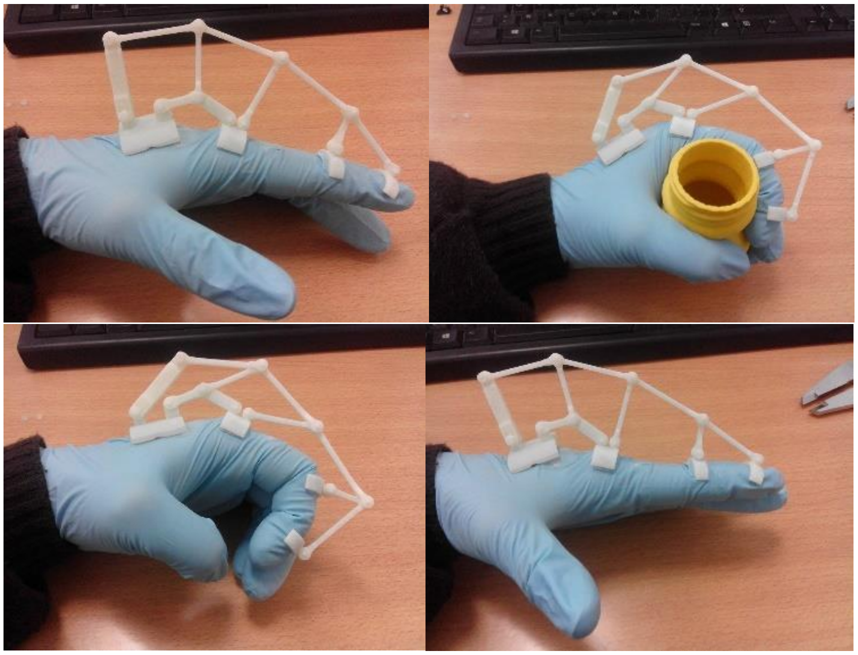

Figure 6. Preliminaries tests of the digit movements

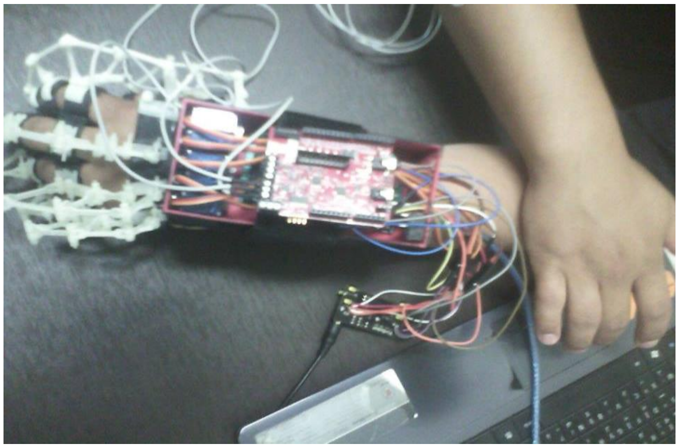

Figure 7. Mechatronic design: control unit components

IV. METHODS

1. Instrumentation and EMG acquisition

Myoelectric signal is an electrical potential generated by the muscles. Generally, EMG signals have been measured by two methods. The first is an invasive method using a needle electrode sensor, this method is not recommended in our case owing to need of more clinical skills, moreover, and the needle electrodes can cause pain for the patient. The second is a non-invasive method using a surface electrode sensor. This method can be easily applied and still give important information for use in several applications.

In this paper, we control the grasping task from surface electromyography (SEMG) signal during dynamic contraction of the hand muscles. The selection of the muscles, as well as the placement of the electrodes, were based on the related literature [32-33]. The first of the electrodes is placed at the Flexor Digitorum Superficialis (FDS) muscle to measure gross finger flexion as well as the grasping task, and the second at the Extensor Digitorum Communis (EDC) to measure gross finger extension and then the opening task.

Firstly, SEMG signals from patient are acquired using e-health shield for Arduino. The e-Health Sensor Shield allows Arduino users to perform biometric and medical applications using ten sensors which contains the muscle/electromyography sensor (EMG). This platform has a small form factor and full integrated. In fact, the EMG sensor will measure the filtered and rectified electrical activity of a muscle. Using the centered potentiometer in the shield, the EMG gain is adjusted to 1000.

This sensor use disposable pre-gelled electrodes. Resolution of the acquisition system ADC is 10 bits. Myoelectric signals are detected by placing three electrodes. Two of them for measurement with a distance equal to 3 cm and the third act as a reference electrode placed at the proximal end of the elbow.

In order to optimize the quality of the received signal, we design a Butterworth band pass filter [34] of range of 20– 400 Hz and a notch filter of 50 Hz to remove the power line noise [35]. This developed filter is implemented in the microcontroller-based Arduino board. Sampling frequency of the acquisition system is set at 1000 Hz.

2. Feature extraction approach

Tacking account of the very complex natures of the biomedical signals, feature extraction is very important issue in EMG signal processing. The main goal of this technique is to extract the useful information which is hidden in SEMG signal. In addition, the feature extraction focuses to remove the unwanted EMG parts and interferences. In the literature, EMG features can be decomposed into several groups which are: time domain, frequency domain or spectral domain, and time-scale or time-frequency domain (TFD). Based on the related library [36], we focused on time domain features. In fact, time domain (TD) features are extracted directly from raw EMG time series and do not need any additional transformation. Then, these features are usually quick and easy implemented. In our case, the feature extraction is mainly used to analyze the EMG data to extract the useful information for onset detection and estimation of applied grasping force in order to copy the desired hand pattern to the wearable hand exoskeleton in the hemiplegic side. Two feature extractions are used in this stage, one as onset detector for flexion and extension and other is considered as a power indicator to estimate handgrip force.

The onset detection feature is selected to evaluate the intension of hand opening and closing. Based on the related literature, one of the most popular used as an onset detection is the mean absolute value (MAV) [36]. This feature, similar to integrated EMG, can be called also with others names like: average rectified value (ARV), integral of absolute value (IAV), averaged absolute value (AAV). As mentioned in its name, it is the average of absolute value of the EMG signal amplitude in a given segment defined in (1). In order to improve the onset index, two modified versions of this feature were developed [37-38]. The first type of modified MAV (MAV1) is an extension of MAV feature. The weighted window function w_i is assigned into the equation for improving robustness of MAV feature as calculated by (2). The second modified version (MAV2) is an expansion of MAV feature which is similar to the first modified version. Improving smoothness of the weighted function, the weighted window function w_i that is assigned into the equation is a continuous function as defined by (3).

$$MAV = \frac{1}{N}\sum_{i=1}^{N}|X_i| \tag{1}$$

$$MAV1 = \frac{1}{N}\sum_{i=1}^{N} w_i|X_i| \tag{2}$$

Were $w_i = \begin{cases} 1, if\ 0.25N \le i \le 0.75N \\ 0.5, otherwise \end{cases}$

$$MAV2 = \frac{1}{N}\sum_{i=1}^{N} w_i|X_i| \tag{3}$$

Where $w_i = \begin{cases} 1, if\ 0.25N \le i \le 0.75N \\ \frac{4i}{N}, elseif\ i < 0.25N \\ \frac{4(i-N)}{N}, otherwise \end{cases}$

In our case, MAV2 feature was selected in order to improve the onset handgrip index and then determine the desired task. Hence, two MAV2 features are extracted from FDS and EDC muscle to detect the grasping and releasing onset, respectively. This method is very useful in case of exoskeleton control from the hemiplegic side. Indeed, this feature is dedicated to people with partially lost movements ability while the system can understand the subject volition and help it to perform the desired hand task. However, this system cannot be effective only in case where patient is already in the therapy advanced stage, i.e., able to provide some muscle power. On the other hand, if the patient wants to control the robotic exoskeleton from the healthy side, the MAV2 feature cannot well determinate the handgrip power and provide a vague idea of the EMG energy. In order to overcome this drawback, a second feature is used as input to estimate the handgrip power. Based on the related library [36], Root Mean Square (RMS) is the most popular feature in analysis of the EMG signal for both clinical and engineering applications. It is modeled as amplitude modulated Gaussian random process whose relates to constant force and non-fatiguing contraction and it can be used for handgrip force prediction. The mathematical definition of RMS feature can be expressed by (4). It is also similar to standard deviation method.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {X_i}^2} \tag{4}$$

Figure 8 shows an EMG raw processed by RMS and MAV2 features. After signal processing, both RMS and MAV2 features are considering as input of controller in order to detect the subject volition and estimate the handgrip force and then performing desired task in the rehabilitation exercise.

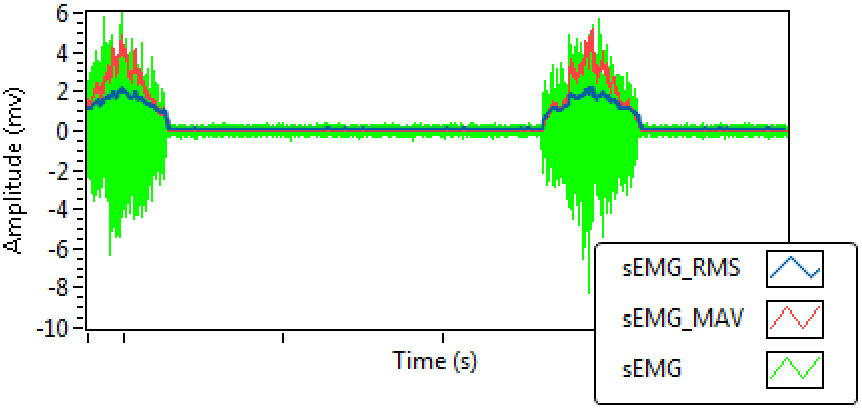

Figure 8. EMG raw processed by RMS / MAV2 feature extractions

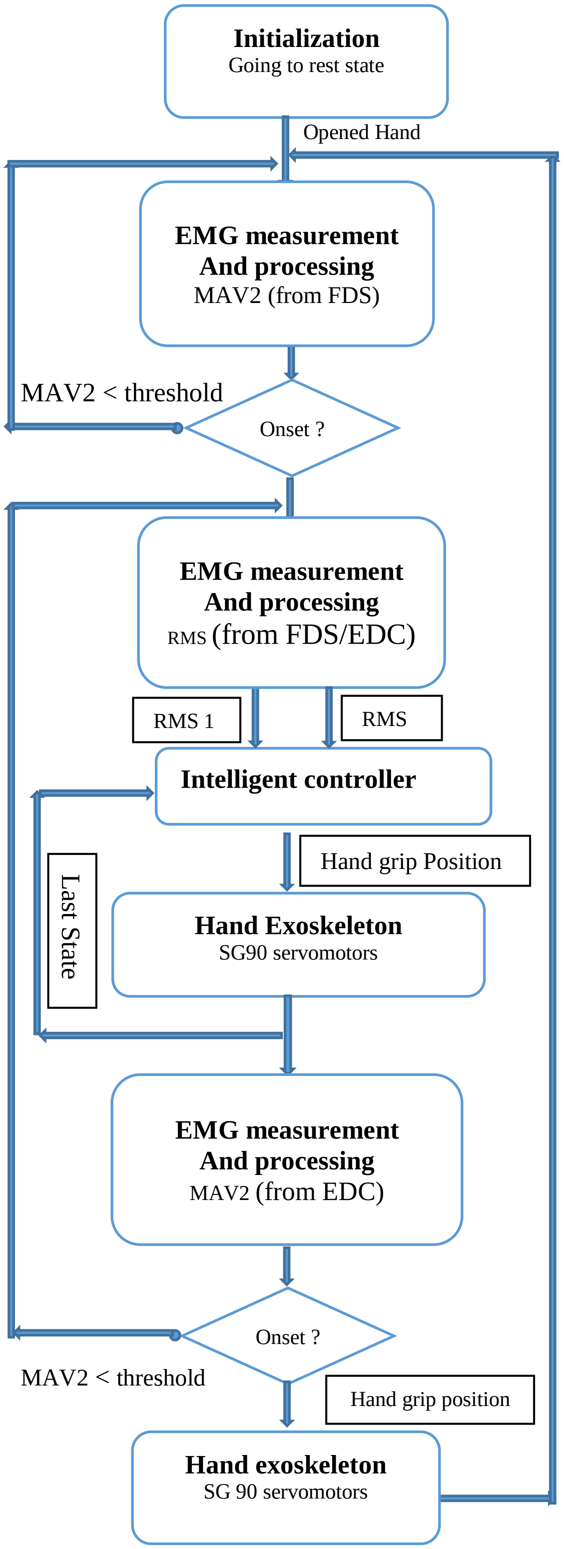

Figure 9. grasping task control process for pic and place cycle

3. Control scheme

The control scheme of each close-open cycle (similar to pic and place task) consists of three parts (see Figure 9), where first step deals with hand exoskeleton initialization to the rest state when it is opened. The second step takes care of bio signal acquisition and processing. In this part, a MAV2 feature was extracted from FDS to detect the onset, and therefore the intention, of grasping. Once this feature value exceeds a predefined threshold, an intelligent controller is executed to control the hand exoskeleton position similar to applied handgrip force. According to handgrip force evaluated by the two RMS features extracted from FDS and EDC muscles and tacking account the last state of the exoskeleton position generated as output, the developed controller performs the grasp and hold state for object (if any) moving. The user can release the grasped object (if any) by mean of MAV2 feature extracted from the EDC muscle. The final step is filled by returning to the rest state and testing the EMG signal for novel pic and place cycle.

Noting that the estimated handgrip force is mapped to angular position of each servomotor by releasing the wired finger mechanism. The force released by fishing wire is covered under the spring force. Therefore, by releasing all fishing wires, the hand exoskeleton adapts with geometric form of the grasped object. If any object exists, hand exoskeleton will be entirely closed respecting the defined mechanical ROM.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The myoelectric hand exoskeleton was evaluated in a preliminary user study with a healthy participant and a stroked patients with hand impairment. For both healthy and stroked participants, some control scheme is implemented. As shown in Figure 15, the muscles contraction is detected by EMG sensors and acquired by E-health shield for Arduino which ensures the analog filtering of the EMG raw. This filtered signal will be processed by the Arduino controller. Two features were implemented to determine the intention and therefore the handgrip force estimation. The signal processing results are mapped to control five servomotors in order to perform the desired hand pattern.

1. Experimental setup and tests with healthy participant

For experimental evaluation, an experiment with a healthy participant has been conducted to examine the ability of the hand exoskeleton to perform a simple activity such as grasping task. For this experiment two surface EMG electrode sensors were placed on the desired muscles of the user's right arm to control the robotic hand exoskeleton worn by his left hand. Third surface EMG electrode sensor of each muscle is placed on the elbow as a ground.

Before beginning, a preliminary adjustment should be configured. The fishing wires must be securely attached ensuring the ability of the servomotors to make moving the connected digits at time of actuating. To achieve this goal, we add a potentiometer which control the servomotor responsible to move the selected digit. The main role of this component is providing a variable input to the Arduino controller which maps the analog input value to a corresponding angle and then control the servomotor with regular velocity until the fishing wire will be securely attached. Figure 13 proves the fishing wires adjustment and electrode placement.

Firstly, the healthy participant is asked to simply open-close his hand in a few times. In the rest state, the springs ensures that the hand still closed and therefore in the flexion state. Moreover, the hand is fully opened under the action of the servomotors. This can ensure that the provided torque of each servomotor is capable to flex the wired finger. Secondly, the participant pass to perform some particular tasks in order to validate the developed feature extraction approaches. This can ensure the ability of tacking and manipulating an object.

The experiment with healthy participant had two objectives. First, to prove that the mechanical structure can accommodate the desired hand motion with high flexibility and second, whether the developed control system can, at least, understand the volition of a healthy participant which can provide a sufficient EMG power for hand exoskeleton control. While both objectives were achieved in this work, the second objective confirms also the ability of the stroked participant to control the robotic exoskeleton by the healthy side. Figure 14 proves the ability of the developed rehabilitation device to perform a simple hand flexion and extension for grasping task.

Based on these results, the next phase is to certify the developed system in the clinical environment by applying it with stroked subjects.

2. Experimental results with hand impaired participants

A preliminary evaluation of the designed rehabilitation system has been performed on two participants with impaired hand following the stroke during 26 days. Initially, the first participant demonstrated some muscle power from the hemiplegic side, i.e. able to provide some simple movements such us lift arm, flexion-extension of the wrist and some finger moving. However, he's suffering from hand control such us flexion and extension of all finger to grasp an object. Second subject is recently affected by stroke and cannot control his hand especially the extension of fingers.

Firstly, the subjects were given a brief explanation about the designed robotic exoskeleton until the subjects understand the overall procedure of the experiment. Since his high flexibility and low weight characteristics, both subjects provide a good feedback regarding the first impression on the devise. First step consists of testing the workability of the device without enabling power. This act provides the patient data including the initial range of motion and the angle limit of both flexion and extension movements for each digit. After that, le device was set based on the provided data. The surface electrodes are placed on the desired muscles. In the device setting, the fishing wires are securely attached ensuring the ability of the servomotors to make moving the wired digits at time of turning. After this step, the current state of the hand is fully opened respecting the ROM limit of each digits. The steps described earlier were repeated at each novel exercise. The duration of the configuration steps varies according to subject cooperation.

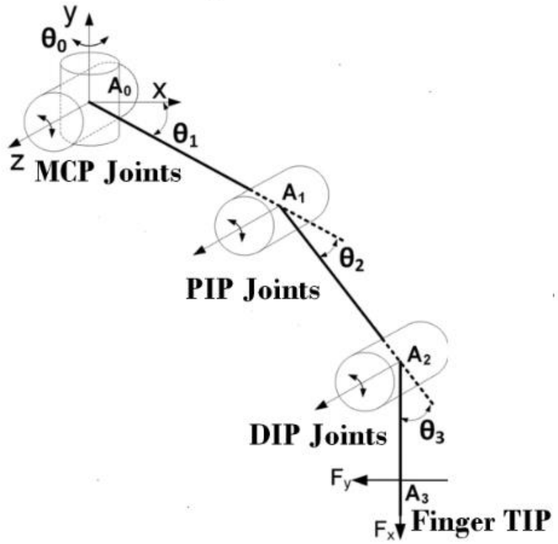

Figure 10. kinematic diagram of the finger

Beginning by the first subject that can produce a sufficient EMG power for intention detection. Inspired by his advanced rehabilitation stage, le EMG surface electrodes are placed in the hemiplegic side in order to apply the intention detection approach. In this case, subject performs the training exercise for both extension of the ROM of each digit and sensorimotor recovery. According to the kinematic diagram illustrated by Figure 10, the experimental results of the ROM evolution during the rehabilitation period are tabulated in the Table 3 and illustrated by Figure. 11. In addition, a progression factor has been calculated related to the ROM progress and it is included between 0 and 10. This factor indicates the current state of the rehabilitation level. Indeed, a healthy person will be assigned by a factor in average of 10.

Table 3. Evolution of the ROM of each finger of first participant

Fingers	**Joint angle**	**Initial ROM (°)**	**Final ROM (°)**	**ROM difference (°)**	**Progression factor (/10)**
Thumb	Θ_1	[-50,10]	[-65,20]	25°	7.08
	Θ_2	[-100, -25]	[-110, -05]	30°	8.75
	Θ_3	[-70, -10]	[-75,0]	15°	9.37
Index	Θ_1	[-45,05]	[-60,10]	20°	5.83
	Θ_2	[-95, -30]	[-105, -20]	20°	7.08
	Θ_3	[-65, -05]	[-70,0]	10°	8.75
Middle	Θ_1	[-65, -15]	[-80, -05]	25°	6.25
	Θ_2	[-80, -35]	[-95, -10]	30°	7.08
	Θ_3	[-70, -10]	[-80, -05]	15°	9.37
Ring	Θ_1	[-70, -20]	[-80, -10]	20°	5.83
	Θ_2	[-85, -40]	[-90, -30]	15°	5.00
	Θ_3	[-70, -10]	[-80, -05]	15°	9.37
Little	Θ_1	[-70, -30]	[-85, -15]	30°	5.83
	Θ_2	[-85, -40]	[-95, -20]	30°	6.25
	Θ_3	[-65, -05]	[-75,0]	15°	9.37
Average	Θ_1			24°	6.16
	Θ_2			25°	6.83
	Θ_3			14°	9.24

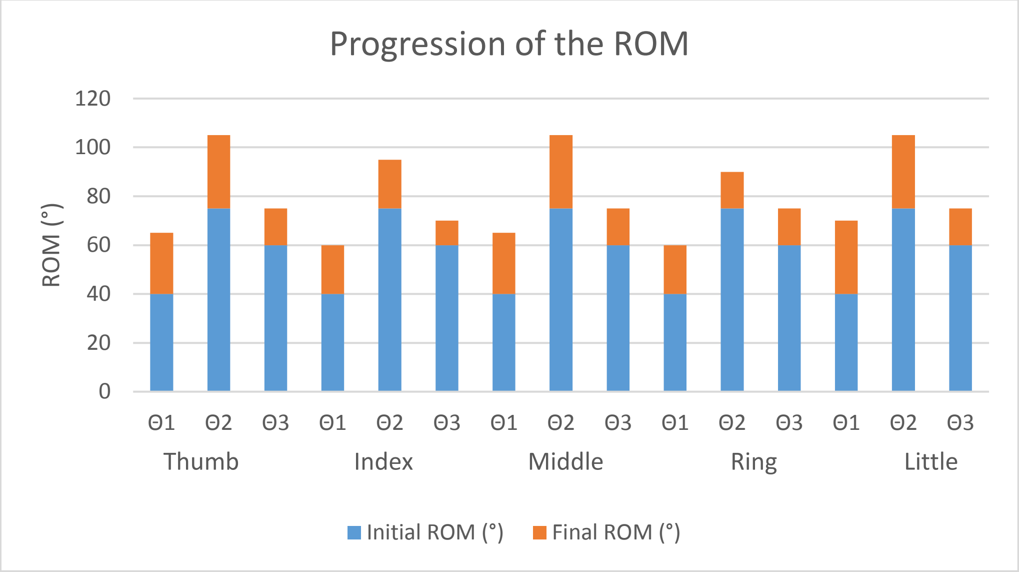

Figure 11. Progression of the ROM of each digit in the hand of first participant

Since the second participant is recently affected by stroke, the preliminaries tests provide that any measurable EMG power can be detected from the hemiplegic side. Inspired by his state, the EMG signal will be measured from the healthy side. In this case, only the EMG power is processed and then only MAV approach is used. It is not necessary to modify the algorithm in the embedded controller. However, we make such modifications according to the current state of the participant in order to validate each approach but, for therapist and at-home rehabilitation cases, a non-modifiable controller is provided since it can work well with a wide range of participants. Because the second participant is a newly stroked subject, his progression in lower regarding the results obtained by the firs subject, as indicates Table 4 and the related histogram in the Figure 12.

By comparing the results obtained by the two stroked subjects, we note that the designed robotic hand exoskeleton is a perfect rehabilitation device for the subjects which are in advanced stage of therapy. Thus, the high ability of the range of motion recovery can be applied in the postsurgery case. The extension of the developed device to other rehabilitation domains is a high challenge in the design of the rehabilitation devices. Therefore, we recommended that the newly stroked subjects may pass by the preliminaries conventional therapy under a professional therapist before using our designed device. This can make more efficiency of the rehabilitation impact.

Table 4. Evolution of the ROM of each finger of the second participant

Fingers	**Joint angle**	**Initial ROM (°)**	**Final ROM (°)**	**ROM deference (°)**	**Progression factor (/10)**
Thumb	Θ_1	[-45,05]	[-55,10]	15°	5.41
	Θ_2	[-90, -35]	[-100, -25]	20°	6.25
	Θ_3	[-55, -20]	[-60, -15]	10°	5.62
Index	Θ_1	[-40,05]	[-45,15]	15°	5.00
	Θ_2	[-90, -35]	[-100, -30]	15°	5.83
	Θ_3	[-55, -15]	[-60, -10]	10°	6.25
Middle	Θ_1	[-60, -10]	[-75, -05]	20°	5.83
	Θ_2	[-75, -35]	[-85, -30]	15°	4.58
	Θ_3	[-60, -15]	[-65, -05]	15°	7.50
Ring	Θ_1	[-75, -25]	[-80, -20]	10°	5.00
	Θ_2	[-80, -40]	[-90, -35]	15°	4.58
	Θ_3	[-50, -15]	[-55, -05]	15°	6.25
Little	Θ_1	[-70, -20]	[-75, -10]	15°	5.41
	Θ_2	[-75, -40]	[-85, -30]	20°	4.58
	Θ_3	[-55, -10]	[-65, -5]	15°	7.5
Average	Θ_1			15°	5.33
	Θ_2			17°	5.16
	Θ_3			13°	6.62

In conclusion, the real tests with stroked subjects showed that the designed hand exoskeleton architecture had a positive effect on finger range of motion, hand ability to perform some simple tasks and such motor recovery, demonstrating the potential of the developed rehabilitation system efficacy. However, we suspect that the treatment in short time of training, compared to average time needed in the stroke rehabilitation, was too short to differentiate the rehabilitation progress.

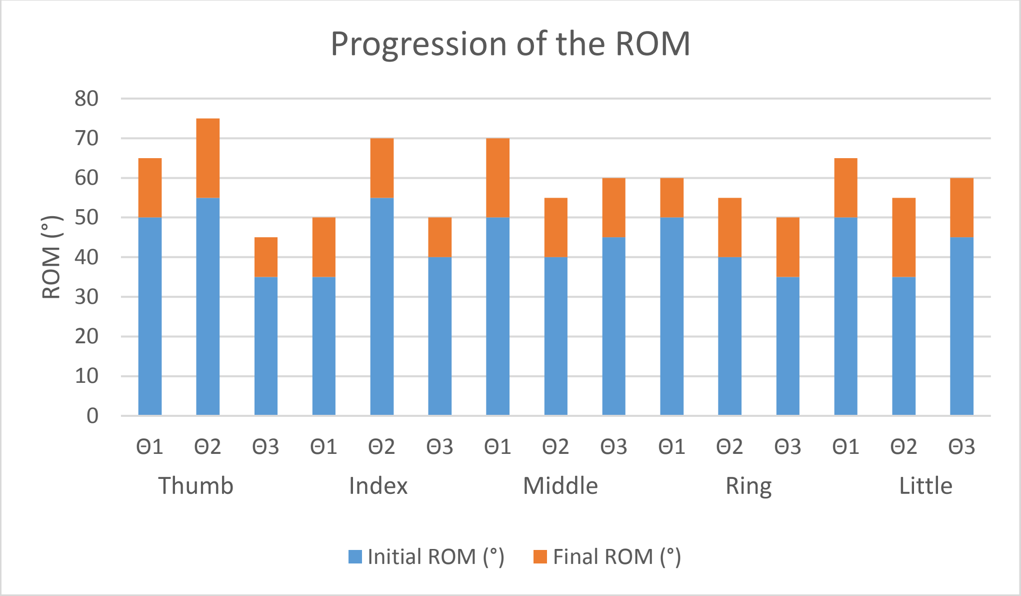

Figure 12. Progression of the ROM of each digit in the hand of the second participant

Overall, the high-friendly hand exoskeleton is very simple to use can be exploited in home rehabilitation. Indeed, subjects were able to use the system without difficulty even in the cases of elderly people unaccustomed to complications of electronic technology thanks to the embedded controller. However, periodic therapist contact was essential for evaluation of rehabilitation progress and motivating patients to complete the training protocol. In fact, periodic presence of the therapist provided sufficient motivation especially for the stroked subject to continue the treatment.

The major limitation of this experimental tests is the reduced number of participants involved. However, the main goal of this work was to apply a new design of hand exoskeleton in several applications including training in stroke rehabilitation which is successfully demonstrated. Another limitation is that, in this paper, the first stoked patient which uses the exoskeleton device is already in the therapy advanced stage. Therefore, he can produce a sufficient EMG power for intention detection. In addition, when our system will be applied with a new stroked subject, two EMG sensors are insufficient to conclude the desired intention. Thus, the number and quality of EMG sensor should be improved in order to guarantee a wide range of use.

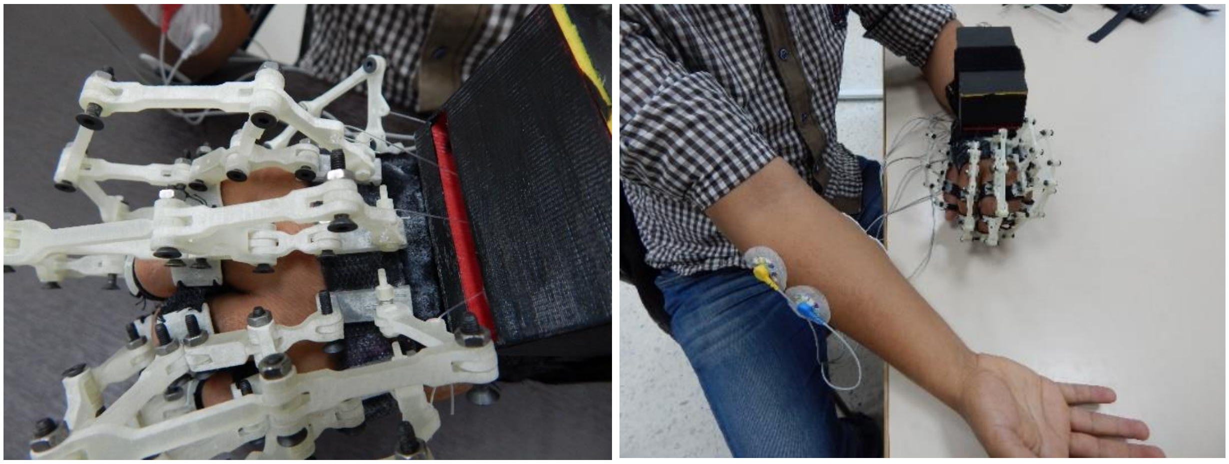

Figure 13. Fishing wire adjustment and electrodes placement

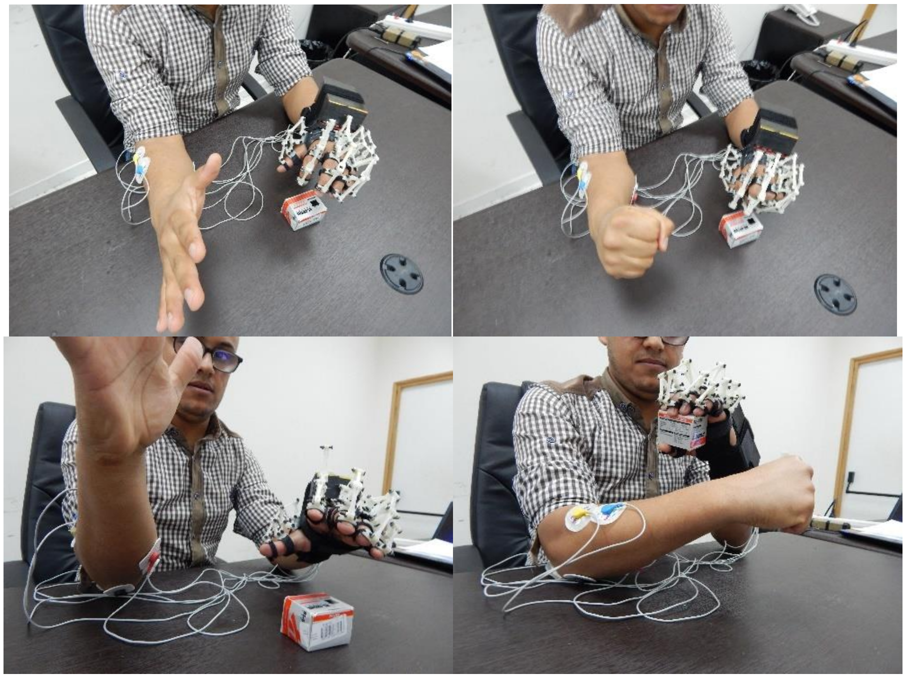

Figure 14. Tests with healthy participant: (1) a simple open-close task; (2) grasping an object

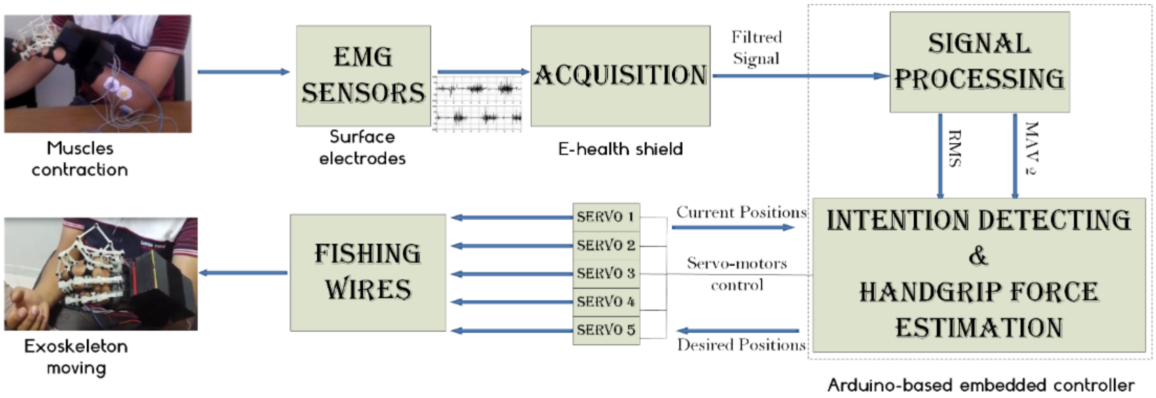

Figure 15. System overview

VI. CONCLUSIONS

We present a design for a developed system based on 3D printing technology. The characteristics of the developed rehabilitation system can help stroke patients to perform the rehabilitation exercises as presented in the results section. Under the presented design based essentially on a spring-return flexion-based finger mechanism, the system can be considered as a continuous passive motion (CPM) device. The exoskeleton for hand rehabilitation is actuated based on electromyography (EMG). The developed wearable low cost robotic system for hand rehabilitation has shown a great efficiency.

REFERENCES

[1] Aabdallah, I.B., Bouteraa, Y. and Rekik, C. (2016). ‘Design of smart robot for wrist rehabilitation’. International journal of smart sensing and intelligent systems. vol. 9, no. 2.
[2] Mehdi, H., & Boubaker, O. (2012). ‘Robot-assisted therapy: design, control and optimization’. International Journal on Smart Sensing and Intelligent Systems, 5(4), 1044-1062.
[3] Orihuela-Espina, F., Roldán, G. F., Sánchez-Villavicencio, I., Palafox, L., Leder, R., Sucar, L. E., & Hernández-Franco, J. (2016). ‘Robot training for hand motor recovery in subacute stroke patients: A randomized controlled trial’. Journal of Hand Therapy, 29(1), 51-57.
[4] Y. Bouteraa and I. Ben Abdallah, Exoskeleton robots for upper-limb rehabilitation, 2016 13th International Multi-Conference on Systems, Signals & Devices (SSD), Leipzig, pp 1-6.
[5] Mazzoleni, S., Sale, P., Franceschini, M., Bigazzi, S., Carrozza, M.C., Dario, P. and Posteraro, F. (2013). ‘Effects of proximal and distal robot-assisted upper limb rehabilitation on chronic stroke recovery’. NeuroRehabilitation, 33 (1) 33–39.

[6] Gerloff, C., Corwell, B., Chen, R., Hallett, M. and Cohen, L.G. (1998), ‘The role of the human motor cortex in the control of complex and simple finger movement sequences’. Brain, 121(9), 1695-1709.
[7] Heo, P., Gu, G. M., Lee, S. J., Rhee, K., & Kim, J. (2012). ‘Current hand exoskeleton technologies for rehabilitation and assistive engineering’. International Journal of Precision Engineering and Manufacturing, 13(5), 807-824.
[8] Bos, R. A., Haarman, C. J., Stortelder, T., Nizamis, K., Herder, J. L., Stienen, A. H., & Plettenburg, D. H. (2016). ‘A structured overview of trends and technologies used in dynamic hand orthoses’. Journal of NeuroEngineering and Rehabilitation, 13(1), 62.
[9] Cesqui, B., Tropea, P., Micera, S., & Krebs, H. I. (2013). ‘EMG-based pattern recognition approach in post stroke robot-aided rehabilitation: a feasibility study’. Journal of neuroengineering and rehabilitation, 10(1), 1.
[10] Song, R., Tong, K. Y., Hu, X., & Zhou, W. (2013). ‘Myoelectrically controlled wrist robot for stroke rehabilitation’. Journal of neuroengineering and rehabilitation, 10(1), 1.
[11] Ryait, H. S., Arora, A. S., & Agarwal, R. (2009). ‘Study of issues in the development of surface EMG controlled human hand’. Journal of Materials Science: Materials in Medicine, 20(1), 107-114.
[12] Lee, S. W., Wilson, K. M., Lock, B. A., & Kamper, D. G. (2011). ‘Subject-specific myoelectric pattern classification of functional hand movements for stroke survivors’. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 19(5), 558-566.
[13] Ho, N. S. K., Tong, K. Y., Hu, X. L., Fung, K. L., Wei, X. J., Rong, W., & Susanto, E. A. (2011, June). ‘An EMG-driven exoskeleton hand robotic training device on chronic stroke subjects: task training system for stroke rehabilitation’. In Proceedings of the 2011 IEEE international conference on rehabilitation robotics (pp. 1-5).
[14] Kiguchi, K. (2007, June). ‘A study on emg-based human motion prediction for power assist exoskeletons’. In Proceedings of the 2007 International Symposium on Computational Intelligence in Robotics and Automation (pp. 190-195).
[15] Masia, L., Krebs, H. I., Cappa, P., & Hogan, N. (2007, June). ‘Design, characterization, and impedance limits of a hand robot’. In Proceedings of the 2007 IEEE 10th International Conference on Rehabilitation Robotics (pp. 1085-1089).
[16] Takahashi, C. D., Der-Yeghiaian, L., Le, V., Motiwala, R. R., & Cramer, S. C. (2008). ‘Robot-based hand motor therapy after stroke’. Brain, 131(2), 425-437.
[17] Kawasaki, H., Ito, S., Ishigure, Y., Nishimoto, Y., Aoki, T., Mouri, T. & Abe, M. (2007, June). ‘Development of a hand motion assist robot for rehabilitation therapy by patient self-motion control’. In Proceedings of the 2007 IEEE 10th International Conference on Rehabilitation Robotics (pp. 234-240).
[18] Hasegawa, Y., Mikami, Y., Watanabe, K., Firouzimehr, Z., & Sankai, Y. (2008, September). ‘Wearable handling support system for paralyzed patient’. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 741-746).
[19] Lambercy, O., Dovat, L., Yun, H., Wee, S. K., Kuah, C., Chua, K. & Burdet, E. (2009, June). ‘Rehabilitation of grasping and forearm pronation/supination with the Haptic Knob’. In Proceedings of the IEEE International Conference on Rehabilitation Robotics (pp. 22-27).
[20] Dovat, L., Lambercy, O., Gassert, R., Maeder, T., Milner, T., Teo C. and Burdet, E. (2008), ‘HandCARE: A cable-actuated rehabilitation system to train hand function after stroke’, IEEE Transaction in Neural Systems and Rehabilitation Engineering, 16(6), pp. 582–591.

[21] Felipe, J., Pereyra, A. and Castillo-Castaneda, E. (2016), ‘Design of a Reconfigurable Robotic System for Flexoextension Fitted to Hand Fingers Size’, Applied Bionics and Biomechanics, vol. 2016, Article ID 1712831, 10 pages.

[22] Schabowsky, C. N., Godfrey, S. B., Holley, R. J., & Lum, P. S. (2010). ‘Development and pilot testing of HEXORR: hand EXOskeleton rehabilitation robot’. Journal of neuroengineering and rehabilitation, 7(1), 1.

[23] Borboni, A., Mor, M. and Faglia, R. (2016), ‘Gloreha-Hand Robotic Rehabilitation: Design, Mechanical Model, and Experiments’ J. Dyn. Sys., Meas., Control 138(11), 111003.

[24] The Amadeo® System, Tyromotion. [Online]. Available: http://www.tyromotion.com/en/products/amadeo/.

[25] Maestra Hand and Wrist CPM, Sammons Preston. [Online]. Available: http://www.sammonspreston.com/app.aspx?cmd=get_product&id=91378.

[26] Heo, P., Gu, G. M., Lee, S. J., Rhee, K., & Kim, J. (2012). ‘Current hand exoskeleton technologies for rehabilitation and assistive engineering’. International Journal of Precision Engineering and Manufacturing, 13(5), 807-824.

[27] Aguilar-Pereyra, J.F. and Castillo-Castaneda, E. (2016) ‘Design of a Reconfigurable Robotic System for Flexoextension Fitted to Hand Fingers Size’. Applied Bionics and Biomechanics, vol. 2016, Article ID 1712831, 10 pages.

[28] Negi, S., Dhiman, S., & Kumar Sharma, R. (2014). ‘Basics and applications of rapid prototyping medical models’. Rapid Prototyping Journal, 20(3), 256-267.

[29] Hieu, L. C., Sloten, J. V., Hung, L. T., Khanh, L., Soe, S., Zlatov, N., ... & Trung, P. D. (2010, September). ‘Medical reverse engineering applications and methods’. In 2ND International Conference on Innovations, Recent Trends and Challenges in Mechatronics, Mechanical Engineering and New High-Tech Products Development, MECAHITECH (Vol. 10, pp. 232-246).

[30] Baronio, G., Harran, S. and Signoroni, A. (2016), ‘A critical analysis of a hand orthosis reverse engineering and 3D printing process’, Applied Bionics and Biomechanics, vol. 2016, Article ID 8347478, 7 pages.

[31] Yeow, C. H., Baisch, A. T., Talbot, S. G., & Walsh, C. J. (2014). ‘Cable-Driven Finger Exercise Device With Extension Return Springs for Recreating Standard Therapy Exercises’. Journal of Medical Devices, 8(1), 014502.

[32] Cram, J. R., Kasman, G. S. and Holtz, J. (2010), ‘Introduction to Surface Electromyography’, 2nd ed. Jones and Bartlett Publishers, 2010.

[33] Phinyomark, A., Phukpattaranont, P., & Limsakul, C. (2012). ‘Fractal analysis features for weak and single-channel upper-limb EMG signals’. Expert Systems with Applications, 39(12), 11156-11163.

[34] Mello, R. G., Oliveira, L. F., & Nadal, J. (2007). ‘Digital Butterworth filter for subtracting noise from low magnitude surface electromyogram’. Computer methods and programs in biomedicine, 87(1), 28-35.

[35] De Luca, C.J., Donald, L.G., Mikhail, K. and Serge, H.R. (2010). ‘Filtering the surface EMG signal: Movement artifact and baseline noise contamination’. Journal of Biomechanics, 43 (8), pp. 1573–1579.

[36] Phinyomark, A., Phukpattaranont, P., & Limsakul, C. (2012c). ‘Feature reduction and selection for EMG signal classification’. Expert Systems with Applications, 39(8), 7420–7431.

[37] Oskoei, M. A., & Hu, H. (2008). ‘Support vector machine-based classification scheme for myoelectric control applied to upper limb’. IEEE transactions on biomedical engineering, 55(8), 1956-1965.

[38] Phinyomark, A., Limsakul, C., & Phukpattaranont, P. (2009a). 'A novel feature extraction for robust EMG pattern recognition', Journal of Computing, 1(1), 71–80.