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Designing and Construction a Low Cost Robotic Exoskeleton for Wrist Rehabilitation

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ABSTRACT: Several causes may result in motor impairment that affects or causes the motions disabilities of the upper limb, among them are spinal cord injury, stroke and wrist drop. Various causes result in the above conditions, so the need for rehabilitation therapy was of most importance. Generally, the researchers interested in and focus on the designing and construction of the lower limb systems for rehabilitation purposes rather than that for upper limbs. This paper focuses on designing and construction of a low cost, two degree freedom (DOF) (including flexion/extension and adduction/abduction), a portable robotic exoskeleton for wrist rehabilitation which designed and constructed with 3D printer technique using polylactic acid (PLA) material and Solid Works software program and controlled with EMG myoware and gyroscope sensors. A significant accurate range of motion and velocity is provided. Moreover, the proposed design of the robotic exoskeleton is comfort, lightweight, simple and economic as well.

KEYWORDS: Electromyography (EMG); Exoskeleton; Rehabilitation; Robotic; Wrist

INTRODUCTION

Motion disorders among patients is one of most problem that limited or impaired the activities of daily living (ADL). Although the stroke is mostly the leading cause of upper limb impairments, other causes of such disabilities may result from spinal cord injuries, wrist drop which in turn is considered the most resulted condition of radial nerve palsy [1]. It is known that the rehabilitation therapy and post traumatic care regimes have significant effect on restoring the functional activities of the disabled patients [2,3]. It has been showing that physical therapy with a frequent exercise can restore the muscle stretch and therefore provide the motors with benefits from promoting the rehabilitation of the brain functional models [4]. Traditional therapy put large efforts on physiotherapists in terms of manually intensive and repetitive exercises, this leads to ineffective and uncontrolled therapy. Also, it is lack of feedback performance and assessment of the process of the therapy for patients, therefore, it is relatively difficult to evaluate the level of motion of upper limb abilities which the patient reaches during the rehabilitation therapy, thus, the need for alternative rehabilitation ways received wide attention [5].

Rehabilitation therapy is associated with several restrictions involving the cost and long therapy duration in which the patients required a long time therapy to restore their functional activities of daily living [6].

Rehabilitation robotics have been widely introduced and developed from which it puts several benefits include: 1) An intensive, accurate, repetitive and controllable therapy [7,8], 2) Give an evaluation of the rehabilitation process besides of its fast therapy, thus the patients become more motivated and regain their activities as fast as possible in comparing with the conventional therapy, 3) Their role of reducing the effort on therapists in hospitals and rehabilitation centers which received a large number of patients, therefore, this will effectively increase the number of rehabilitative patients [9,10], 4) rehabilitation robots may be integrated with virtual reality to provide an interacting and motivating background environment thus encouraging patients to procure their tasks intensively [11].

Rehabilitation systems especially those that are dedicated for the upper limbs are available only in a limited number mostly in developed countries that involve the research in this field and stay for a long period of time under the clinical research level [12]. In addition to its limitedness, most of the rehabilitation systems come with high costs making them only recede in specific rehabilitation centers. In an appropriate form, the rehabilitation devices must be accessible for all patients through their existent in hospitals and rehabilitation centers. However, often the devices are existing in hospitals in their fixed states may be due to their bulky size or its high cost. These limitations offer a significant burden on patients in terms of their living away from hospitals and rehabilitation centers, which leads to making treatment more expensive and reduce their visiting times to the hospitals, thence, minimizing their opportunity to get the rehabilitation process well.

As a result, many researchers have been interested in this field in which they developed and introduce new rehabilitation devices aiming to override the problems as much as possible. In terms of upper limb rehabilitation devices especially those that are dedicated for rehabilitating the wrist joint, extensive researches have been carried out to help the impairment patients restoring their activities of daily living and increase their independence [13-18]. However, the proposed devices still need several enhancements and reinforcements in terms of the technology usage in the design and manufacturing of them, in addition to the utilization of the electronic components and actuators that may uncomfortable for interaction with patients besides of possibility of making the devices bulky in size and decreases the opportunity of home-based therapy.

This paper presents novel robotic exoskeleton goals to excesses the limitations and increase their availabilities in order to positively reflect on the rehabilitation process and empower the patients to attain their activities completely. The presented exoskeleton offers two degrees of freedom (flexion/extension, adduction abduction movements) for wrist rehabilitation. It involves the employment of an EMG myoware and gyroscope sensors for the overall controlling of the exoskeleton in one hand and for evaluation the progressing in the rehabilitation process during the therapeutic sessions on the other hand. The proposed device focus on rehabilitation a range of disabilities including the stroke, spinal cord injuries and wrist drop cases. Such the device has been evaluated and examined in terms of its range of motion and velocities. The assessment of the device has been carried out lonely as well as with normal subjects.

The device was designed with SolidWorks software program and manufactured using 3D printer technology as it shows high accuracy of final construction with facilities of being deals and compatible with wide range of materials such as the plastic one. The proposed exoskeleton has been constructed with polylactic acid (PLA) material. Choice of this construction material comes into its characteristics of being lightweight and costless which are the considerable situations in this research to provide a lightweight and portable device at once, also it reduces the cost of the device as well. As a result, these facilities making the device more available and augmented the opportunities to be used by patients which in turn increases rehabilitation therapy for more patients.

The next sections of this paper is arranged as follows, Sections II and III shows the overview of the anatomy and biomechanics of wrist joint and the requirements for designing purposes. Section IV addresses the overall system mechanical design. Section V processed the control system, electronic components and their compatibility with the mechanical structure. Section VI presents the results of exoskeleton evaluation and its application with normal subjects. The final section details the conclusion of this research.

ANATOMY AND BIOMECHANICS OF THE WRIST JOINT

The wrist joint is a complex musculoskeletal joint consists of distal end of radius and ulna and the proximal end of metacarpal bones and the proximal and distal rows of eight bones known as carpal bones [19]. The wrist joint has the ability to move in the sagittal (flexion/extension) and frontal (adduction/abduction) planes as shown in Figure 1. The ligamentous and bony structure of wrist joint allows it withstands a load greater than 10 times the load that can maintain the fingertip during grip [20]. The axes of wrist rotation is not fixed due to the complex bony structure involving in it [21]. Several muscles are responsible for movements of the wrist joint which involved in the posterior and anterior compartments of the forearm.

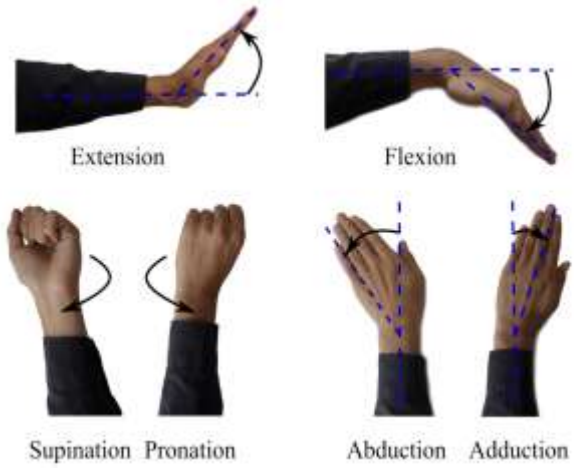

Figure 1. Range of Motion of the Wrist Joint [12]

WRIST REHABILITATION SYSTEM REQUIREMENTS

Wrist motion analysis

In order for the design to be compatible and comfortable to use for rehabilitation, it must permit the same range of motions and velocity strategies as that of the human one. The movements of the human wrist joint are flexion/extension, adduction/abduction and pronation/supination. The degree of which the joint move different with different movement, the normal subjects can flex/extend and adduct/abduct their hand roughly 80°, 75°, 40° and 35° respectively. In addition to their ability to pronate and supinate their hand at approximately 80° and 75° in a subsequent way.

The required torque to achieve the wrist movements is ranged between 2 to 4 Nm, this range is based on normal activities of daily living [22].

System design considerations

Rehabilitation device involves a specific requirement represented in their range of motion, safety, their degree of freedom (DOF), comfortability and its cost. In order to achieve the such requirements, several considerations must be taken into account which involve the biomechanical and anthropometrics human parameters, the links and joints of the mechanical structure must be designed in such a way that matches the human anatomical structure since the wrist joint provides movements around an axes naturally not fixed. Moreover, it is appropriate to be adjusted for all people regardless of age, sex, length, weight, in this way, the rehabilitation process can be accessible for all patients without any restrictions. The rehabilitation device must also be safe as possible to be used without any unexpected defect. The safety consideration represented in the restricted range of motion to avoid the excesses motions, also the mechanical structure must be accurately designed to obviate undesirable structures that may limit the patient's range of motion and causes pain to them which may lead to unaffected therapy, in addition, the device must be integrated with electronic components not causes any electrical feedback, and integrated with reinforced structures to provide a comfortable and reliable robot.

The 3D printer additive manufacturing technology is an easy and widely used technique providing a quick construction and small scale, accurate, low cost, time saving manufacturing process. This technique is targeted in the construction of the proposed rehabilitation exoskeleton [23].

The electric motors are most commonly used due to their facilities of providing a linear motion as compared to pneumatic actuators and have a sufficiently high power to weight ratio in addition to its large existence and small in size where making the devices compact in sizes and increases the possibility to be portable as well, thus, it was found it is the appropriate choice for actuated the presented robotic exoskeleton.

SYSTEM MECHANICAL DESIGN

The mechanical design of presented exoskeleton was done through 3D CAD SOLIDWORKS software program, choosing of this software program comes into the considerations of its simplicity, allowing the designer to make modification and changing of the design in a way that reduces the inaccuracies, solving the design problems, assigning the visualization of the overall design parameters before the final decision, in addition to its facility of converting and storing the design in a form that compatible for every 3D printer type allowing manufacturing of each piece then using 3D printer technology.

Following the considerations presented in Section (3.2), the robotic exoskeleton was designed and constructed with the 3D printed technique using polylactic acid (PLA) thermoplastic material which is a low cost, lightweight and doesn't affect with the existing environment, consequently, these properties augmented the manufacturing design to be lightweight and costless as a result.

Forearm design

The design process of the presented robotic exoskeleton started with design a structure that compatible with the human forearm in order to permit the patients rest their forearm during therapy, the designed forearm mechanical structure breakdowns into several components (see Figure 2,) include 1) structural mechanism which consists of two links being articulated with a circle structure which in turn provide a rigid-complex part. This main mechanism is connected with the wrist part at its distal end, 2) fastener circular structure designed such that one end is connected with the cylindrical structure and the other end has a curve to avoid the possibility of making a pain to the patients while entering their lower arm, the main function of this structure is to keep the overall forearm structure from getting out during the operation of the exoskeleton in a way that locked the proximal end of the cylindrical structure, 3) wrist holder for hold the patient's lower arm during the therapeutic strategy and exhibits more comfortability for them,4) cylindrical structure act as a bearing and carrier for the forearm components.

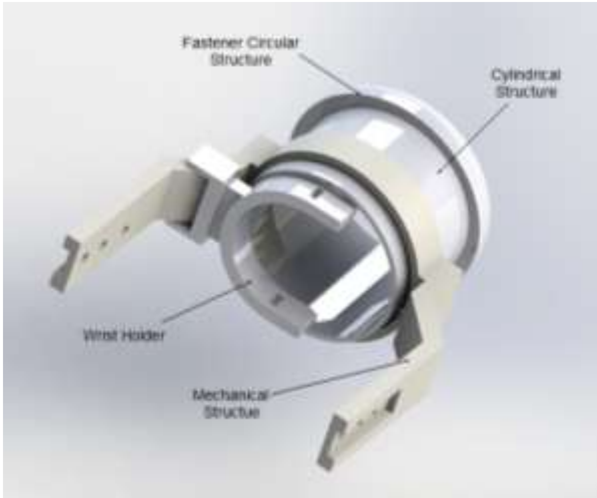

Figure 2. Forearm Design

Wrist design

The wrist design was done as two separate parts. The first one is the flexion/ extension part (see Figure 3) which designed as three links connected with each other to provide more rigid and compact structure.

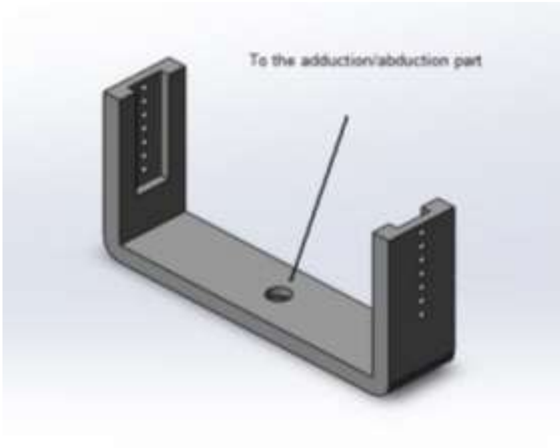

Figure 3. CAD Model of the Flexion /Extension Part.

The second part of the wrist exoskeleton is the adduction/abduction part (see Figure 4), which consists of two main parts, the first one consists of two subdivisions being compact and reinforced with springs to allow more flexibility and resilient during the adduction/abduction movement. The second one is the handle part representing the palm holder in which the patient rest his palm on it, it also reinforced with the strip passing through the two sides of the holder thus make the patient's hand more stable and prevent it from drop while the exoskeleton performs the rehabilitation process. The previous handle is utilized during the first level of therapy (passive exercises). When the patient progressed in his rehabilitation process or has the ability for holding with their hands this handle replaced with the second type such the rehabilitation process be more impressive and fairly quick.

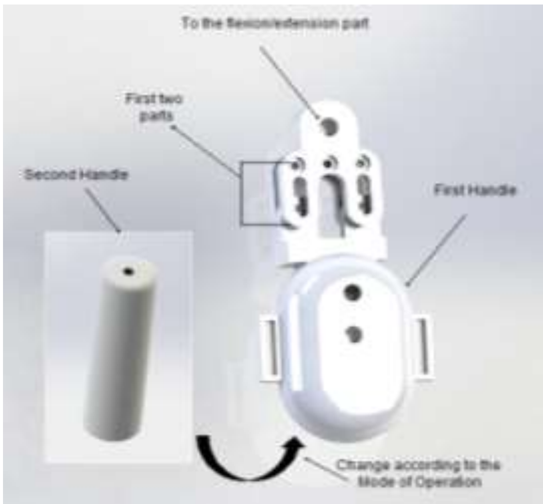

Figure 4. CAD Model of the Adduction/Abduction Part

Moreover, both the structural mechanism of the forearm design and the flexion/extension part of the wrist design (See Figures 2 and 3) were reinforced with holes exist on the sides of their distal ends functions to permit the exoskeleton be adjusted according to the patient's rotational axes by elevating /lowering , progressing/delaying these parts respectively.

Other mechanical structures involving the base for stabilizing and resting of the overall exoskeleton components, its design is shown in Figure 5.

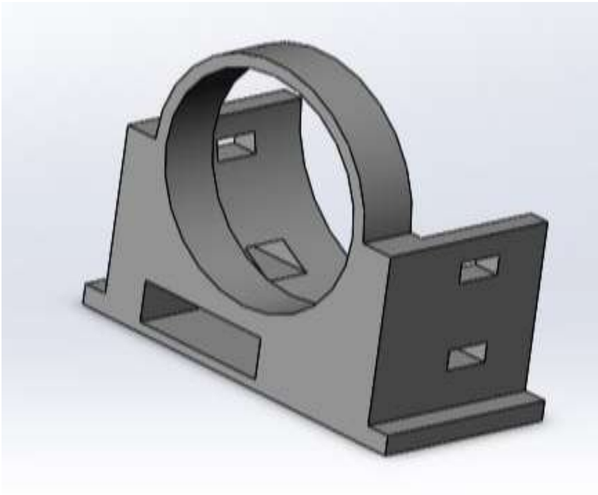

Figure 5. CAD Model of the Base

The exoskeleton parts are then assembled and ready for print with a 3d printer. Its assembly is shown in Figure 6.

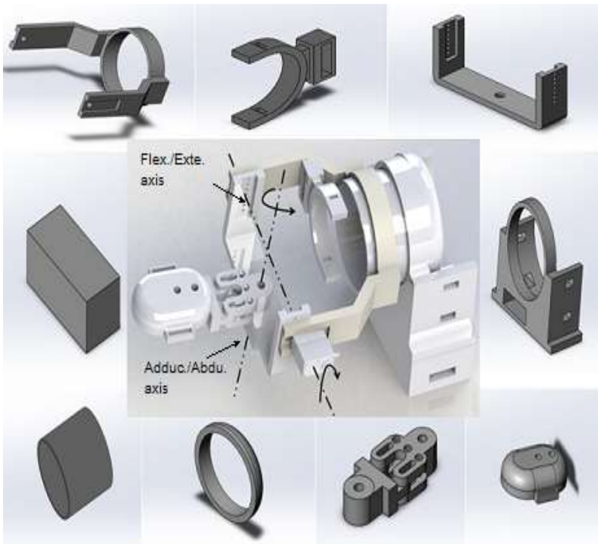

Figure 6. Parts Constructing the Exoskeleton and their Assembly

Final Parts and assembly of the robotic exoskeleton

The proposed design of the exoskeleton was interred in the printer software so that the exoskeleton parts can be manufactured. The printing technique promises a very high accuracy when it comes to dimension; i.e, there was not much difference between the final shape dimensions and the cad design. Figures 7-9 illustrate how the final printing parts and their assembly appear.

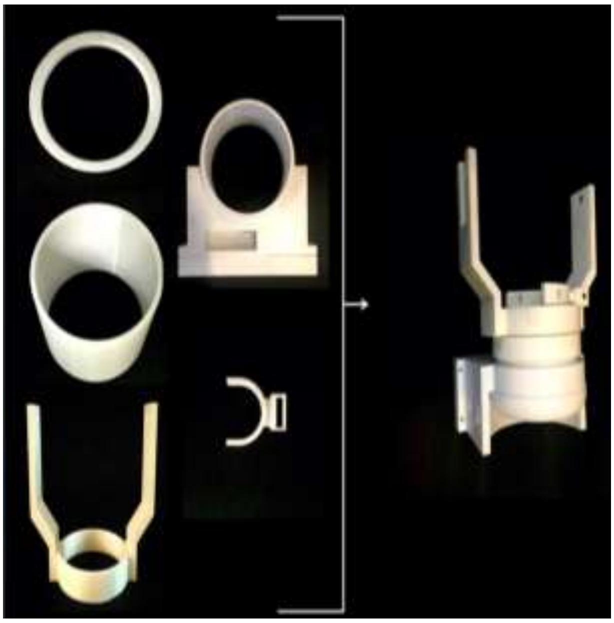

Figure 7. Forearm Design

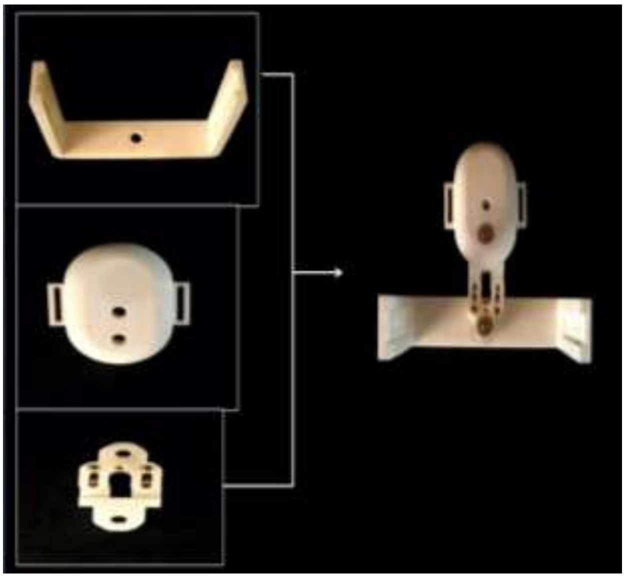

Figure 8. Wrist Design

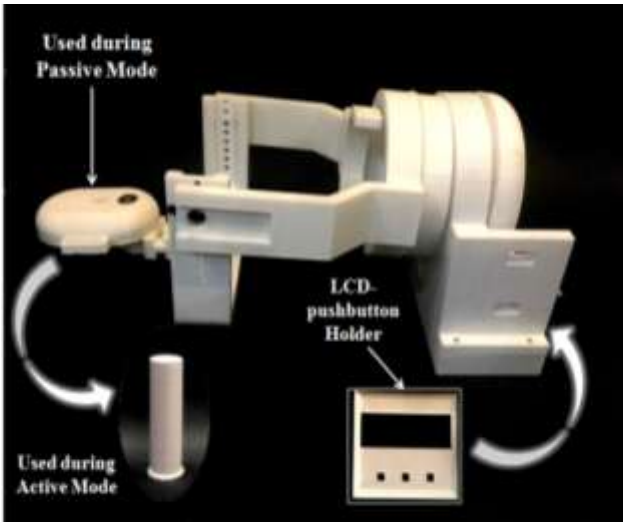

Figure 9. Exoskeleton Assembly

ELECTRONIC DESIGN

The overall electronic circuit of the proposed exoskeleton design consists of the following components: 1) an EMG myoware sensor for pick up the muscular activity superficially, 2) gyroscope sensor for acquiring the instance position of the hand,3) employment two mg995 tower pro servo motors for actuation the exoskeleton in which each motor is responsible to achieve a specific movement, 4) liquid crystal display and buzzer in order to display the state of mode of operation, type of movement, defect case, and angle readings during rehabilitation process, in addition to use a buzzer to alarm the patient about the current status of therapy and move their hand during the active-assistive mode before the exoskeleton exhibit its movements. Moreover, the design involves the use of pushbuttons to translate between different mode of operation and for different cases. All of these components are programmed and controlled with an Arduino mega2560 as microcontroller.

Control System

The control system of the presented exoskeleton was achieved through using the EMG myoware and gyroscope sensors. The EMG signal proposed to be extracted from the extensor carpi ulnaris exploiting its responsibility of adduction and extension of the hand at wrist joint. This signal was utilized to control the 2DOF of the exoskeleton movements with position information being feedbacked from the gyroscope sensor. Based on this information, the servo motors motions were controlled in terms of their direction, speed and range of motion. Figure (10) presents the muscle activity and angle measurements for normal subject.

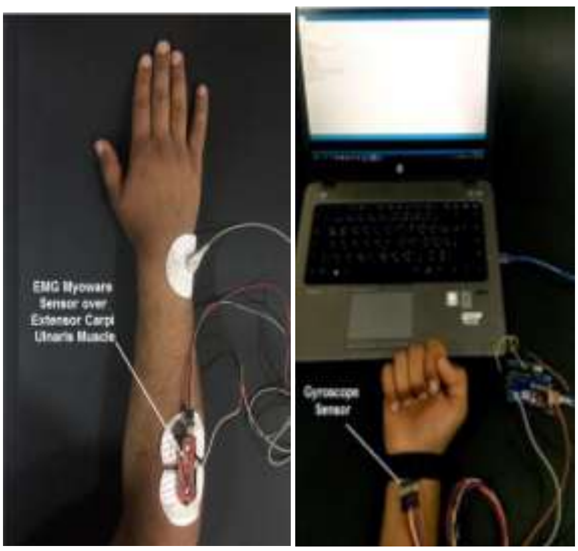

Figure 10. Muscle Activity and Angle Measurements

Two mode of operations have been included in this study represented in passive and active-assistive modes of operation. The first mode of operation performed during the primary stage of rehabilitation process i.e, when the patient has no muscle activity. While the active-assistive mode of operation included wherever the patient's muscle exhibits a level of activity as well as a specific angle information.

Pushbuttons have been used to change the mode of the exoskeleton operation as desired by the patient's case. Three pushbuttons were used, two of them have been used for passive and active operations indicated for stroke and spinal cord injury cases, while the third one has been employed for wrist drop case. Figure 11 illustrated the LCD-Pushbutton holder with exoskeleton and function for each button.

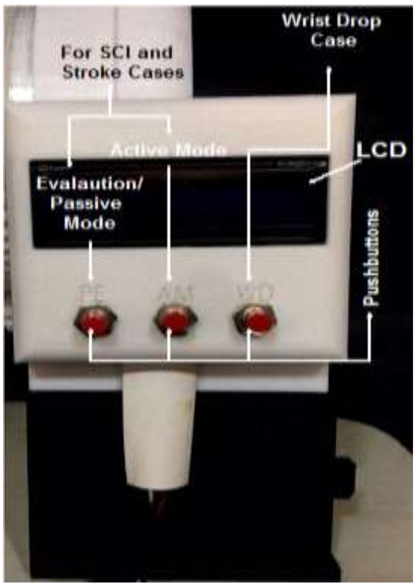

Figure 11. Assembly of LCD and pushbuttons with exoskeleton

The overall working principle of the exoskeleton is shown in Figure 12 below.

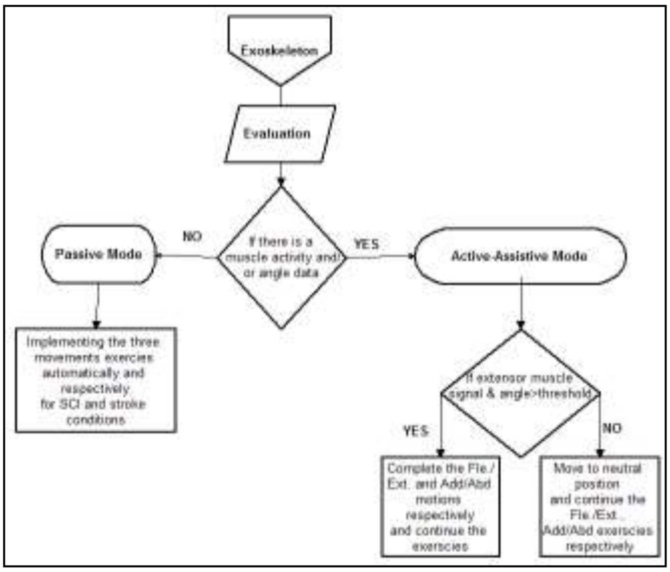

Figure 12. Schematic Diagram of the Exoskeleton Working

RESULTS

The wrist exoskeleton has been tested for a range of motion, velocity, safety, prolonged battery lifetime, servomotors statues and their ability to provide the torque requirements for different persons. It was tested with and without normal subjects. Table (1) shows the range of motions and velocity information for the normal subject and exoskeleton.

Table 1. Range of Motions and Velocity Information.

Type of motion	Normal angle **(deg)**	Exo-skeleton angle **(deg)**	Normal Velocity **(deg/s)**	Exo-skeleton Velocity **(deg/s)**
Flexion	75°	70°	1970.168	1332.645
Extension	70°	65°	2175.768	1528.402
Adduction	25°	25°	27496.58	1908.026
Abduction	35°	35°	22955.46	1826.868

Figures (13 - 16) show the movements of the exoskeleton in addition to their corresponding curves denoting the reflected range of motions and velocities.

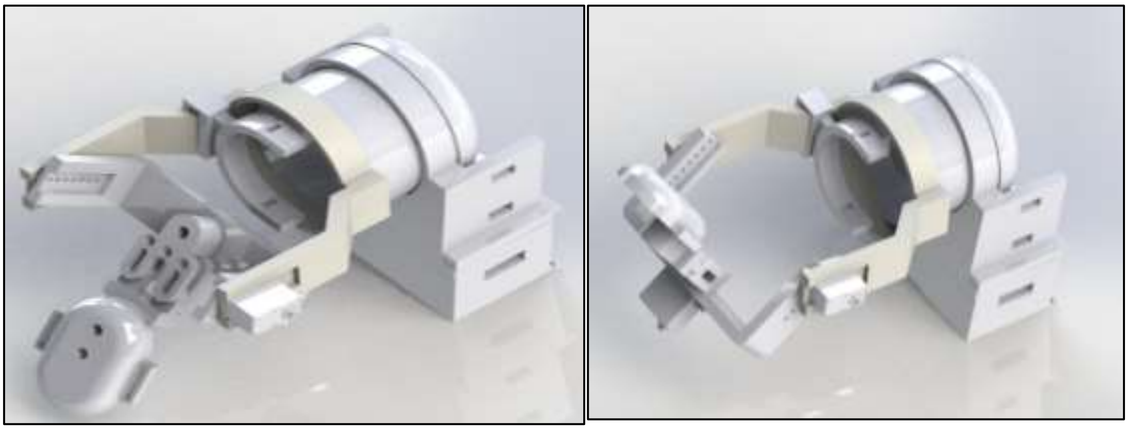

Figure 13. Flexion (above) and Extension (below) Movement of the Exoskeleton

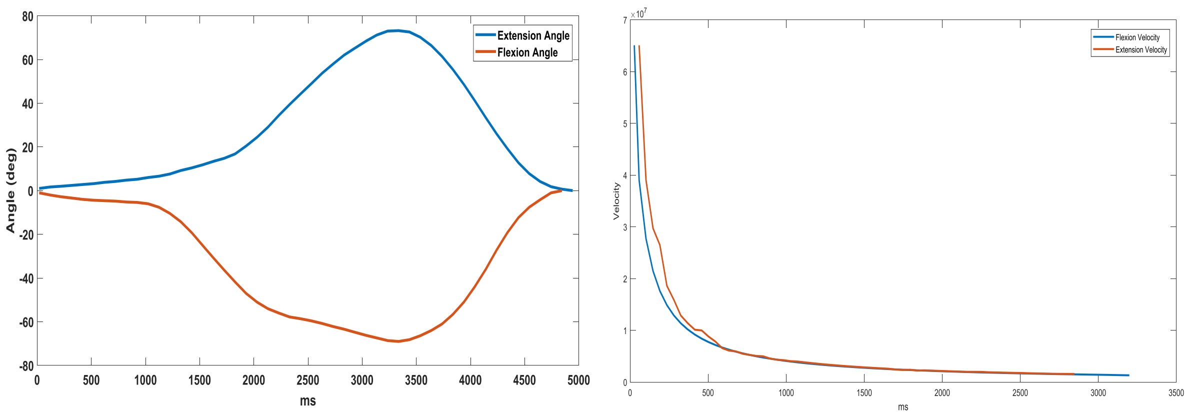

Figure 14. Flexion/Extension Motion Range (above) and Velocity (below) of the Exoskeleton

Figure 15. Adduction and Abduction Movement of the Exoskeleton

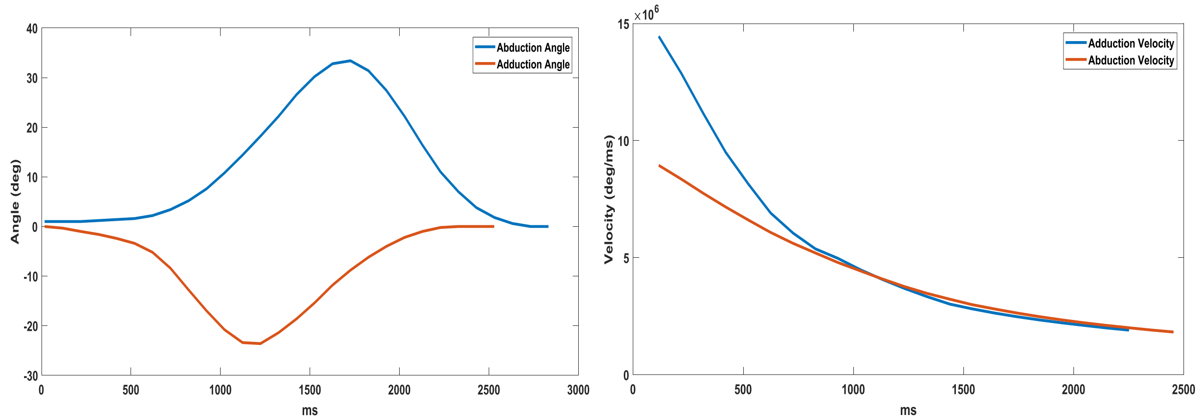

Figure 16. Adduction/Abduction Motion Range (above) and Velocity (below) of the Exoskeleton

CONCLUSION

Impairment of motor function is of most problem that must be taken into account due to their associated difficulties of increasing the dependency, weaken or deteriorate the motions, and limit the activities of daily living. Most of the rehabilitation devices have several limitations in terms of their DOF, the efficiency of the controlling systems and most of them not applied for testing purposes on normal subjects. The proposed exoskeleton has been tested for its ROM, velocity lonely and with normal subjects. The presented exoskeleton was achieved with several specifications include; 1) required little maintenance, 2) the structural mechanism, including links and joint match that of the normal human anatomical one, 3)low-cost material has been included in its manufacturing process, as well as it was reinforced with costless and accurate electronic components which increase the accessibility and availability of the exoskeleton for a large number of patients and rehabilitation centers as well, 4) support the home-based therapy service as it designed with compact size such making it portable and facilitate its transition, 5) comfortable to use and compatible for all patients regardless of age, sex, and other parameters. Furthermore, it was shown from the table (1) that the exoskeleton range of motions approximately the same as the normal ones, while the velocity is nearly half of that of the corresponding normal velocities because the exoskeleton was programmed to work primarily with lower velocities, then the proposed velocities will be increased as the patient enhanced with the rehabilitation process.

The exoskeleton application with normal subject shows better results such it reflects the same ROMs and velocities as tested. So, it is believed that this device can replace the role of the physiotherapist and affect the rehabilitation process more effectively whence more comfortability, fasten the rehabilitation process, more accurate, easiest with costless treatment.

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