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Smart Robotic Exoskeleton: A 3-DOF for Wrist-Forearm Rehabilitation

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Key words: Exoskeleton, robotic, wrist, stroke, SCI, rehabilitation

Abstract: In order to regain the Activities of Daily Living (ADL) for patients suffering from different conditions such as stroke and spinal cord injury, they must be treated with rehabilitation process through a programmed exercises. The human motor system can learn through motor learning. This study concerned on rehabilitation of wrist and forearm joints to restore the ADL through designing and constructing a robotic exoskeleton. The exoskeleton was designed to rehabilitate the patients by providing a 3 Degree of Freedom (DOF) include the flexion/extension, adduction/abduction and pronation/supination movements. It is specified of being portable, comfortable, lightweight and compatible with the human anatomical structure in addition to providing a speed and Range of Motion (ROM) as that of a normal subject. It was designed with Solid Works software program and constructed with 3D printer technique using Polylactic Acid (PLA) plastic material. The overall exoskeleton was controlled with electromyography and angle information extracted using EMG myoware and gyroscope sensors, respectively. It was applied for evaluation with 5 normal subjects and 12 subjects of stroke and Spinal Cord Injury (SCI). The results were found that the exoskeleton has a strong effect on regaining the muscle activity and increasing the ROMs of wrist and forearm joints. These results give a proof of this exoskeleton to be used for performing physiotherapy exercises.

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INTRODUCTION

Muscle weakness and spasticity (resistance to muscle stretch) have their significant effect on impact the Activities of Daily Living (ADL). Several conditions have lead to such effects including Stroke and spinal Cord Injury (SCI)[1]. Upper limb disorders limited the motions of patients being conditioned with a specific defect which leading to increase the dependency of them in addition to restrict their motions to a limited degree[2]. One of the human's brain properties is the self-arrangement. Through an excitation to the afferent and efferent nerves, the neural pathways can be readvancement to regaining the activities of daily living. To recover or enhance functions of motor units, rehabilitation has been introduced which its history back to thousands of years ago. In hospitals and rehabilitation centers, conventional treatment for disabled patients was presented. This sited therapy include an interaction between the patient and the therapist in which the therapists guide the patient to perform a repetitive exercise based on a specific program arranged by them[3]. The success of such treatment depends on several factors among them including the number of repetitive exercises, the period of rehabilitation, condition of patient disability, and date since the disability[4, 5]. There are several problems associated with traditional rehabilitation such as the decrease in time of therapy as the number of patients is small compared with number of therapists, moreover, the traditional rehabilitation was lacked to an assessment of the patient's progress through their therapy and after it. Due to these limitations and other ones, the rehabilitation robotics have been presented and developed over the years[6]. The rehabilitation robotics considered as a specific branch of biomedical engineering has the role of decrease and solve the problems related to traditional rehabilitation. By development of the proposed exercises and evolution of the robotics devices, robotics rehabilitation can support several functions of the sensori motors. Rehabilitation robotics subdivided into three main types those for upper limbs, lower limbs and for full body[7-11]. Generally, robotics can be classified into an end-effector and exoskeleton. The end-effector one is easy to implement and interact with the human at one end that enables the patient to hold it with his/her hand and provided the motions at the joints but it forwards limited information about the patient's limb. On the contrary, the exoskeleton provides a quantitative assessment of the limb, moreover, the exoskeleton structure has links and joints matching that of the human anatomical one. The exoskeleton consists of electronic components, reinforced with algorithms in addition to actuators and controllers to feed the actuators with data enabling the exoskeleton works as required[12, 13]. Several studies have been interested in this field of rehabilitation aiming to overcome the problems associated with traditional rehabilitation[14-19]. There are several restrictions are related with that studies in terms of their, mode of operations, number ranges of motions, some of them have been designed with 2 DOF or 1 DOF that may causes ineffective and incomplete in rehabilitation therapy making the joint regain its activity in two or one motion rather than of all them, other studies have been interested in haptic part of device rather than concerning on the overall design and technology usage in their construction, moreover, some of them are related with hardware complexity and their stationary conditions thus making the rehabilitation therapy available only in hospital and rehabilitation centers in addition to their high cost, furthermore, they are only restricted with specific

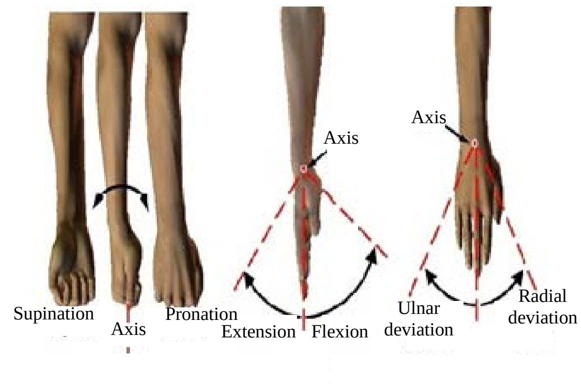

Fig. 1: Kinematics of forearm and wrist[20]

defected condition and all of these studies haven't mentioned any trails with patients who have a defected condition except[19] which has applied their device with incomplete SCI patient with 10 sessions.

The objective of this study is overcome the problems associated with the studies in this field. This study aims to design, construct and implement a wearable, low cost, 3D printed forearm-wrist robotic exoskeleton controlled using sEMG signal assisted with angle sensor by providing the exercises for rehabilitation of patients who suffer from stroke and spinal cord injury. This therapy is commonly used in restoring lost motor skills by helping the brain rebuild neural pathways lost as a result of disease or trauma such as stroke. In removing the need for a physical therapist to conduct these exercises, the patients would be able to devote more time to their therapy at a lower cost while achieving a greater level of independence in addition to home based therapy without the need for significant supervision. Thus, lead to rapidly progressing in rehabilitation process in centers and hospitals which have a large number of patients compared to the number of physiotherapist.

Anatomy and biomechanics: Two bones constitute the forearm called radius and ulna. The forearm considered as a tri-articular structure that connects the wrist and elbow joints. An interosseous membrane is a structure between radius and ulna which intercalated between (PRUJ) and (DRUJ) providing a mid-radioulnar joint (MRUJ), the pronation/supination movement of the forearm is achieved through rotating radius about the ulna as shown in Fig. 1. Several muscles are included in the posterior and anterior compartments of the forearm responsible for movements of the wrist and hand in addition to its role in movements of the elbow joint[21]. At the wrist joint, the ulna bone conveys approximately 20% of the load-bearing force and the remaining 80% is translated by the radius bone. While at the elbow joint, the humeroulnar joint carries almost 43% of the load, the 57% remaining load is transmitted by the humeroradial joint. The wrist joint is a

Fig. 2: CAD Model of the exoskeleton and its assembly

sophisticated musculoskeletal joint. Several structures are congregated to form such joint include the distal end of ulna and radius, the proximal end of metacarpal bones, the proximal and distal rows of eight bones known as carpal bones[22]. The wrist joint can move in the sagittal (flexion/extension) and frontal (adduction/abduction) planes (Fig. 1). The ligamentous and bony structure of the wrist permits it holds a load larger than 10 times the load that can keep the fingertip through the grip[23].

Design consideration: As the device based on repetitive training of patients to restore their activities and in contact with them, it must meet several requirements include: Kinematic: it must meet that of the destined joint. Safety: it must be as safe as possible. It must be reinforced with a precise controlling, mechanical stoppers an accurate components to prevent hyper movement giving an accurate measuring parameters. Comfortability: the device must be adjustable, fitting to various patients regardless of size, shape, age and volume of their lower arm. structural mechanism: the exoskeleton must not be bulky to allow the patient move freely without resistance and its structural mechanism should be meet that of the human ones. All of these requirements have been achieved in the proposed exoskeleton.

Mechanical design: Based on the biomechanical, anatomical and anthropometric parameters, the robotic exoskeleton was designed to meet the destination requirements. The robotic exoskeleton is divided into two main parts, the first part is the wrist design which is further divided into two parts, the second part is the forearm part designed provide a movement in one anatomical reference plane. All of these parts were designed using the 3D CAD software SOLIDWORKS and printed using 3D printer technology using Polylactic Acid (PLA). Figure 2 shows the CAD Model of the parts of the robotic exoskeleton and its assembly, moreover, these parts are designed in a way that compatible for all people regardless of sex, age, length and weight.

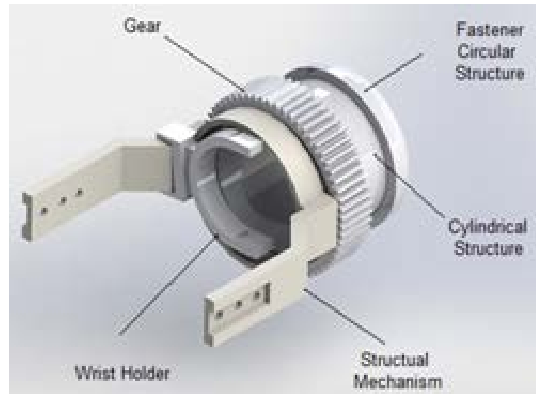

Fig. 3: Forearm design

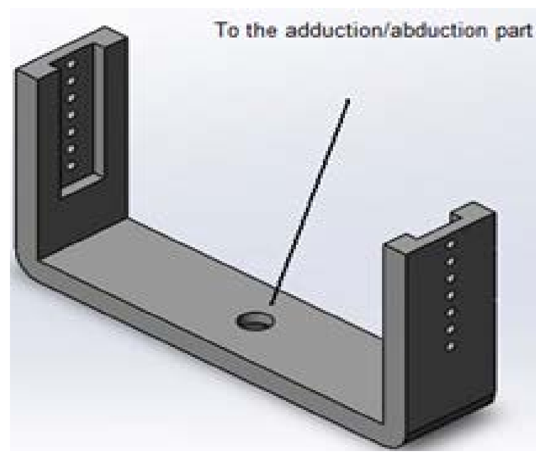

Fig. 4: Flexion/extension part

The forearm design (Fig. 3), consists of several components including cylinder structure, gears, wrist holder, fastener circular structure and the structural mechanism. The forearm design represents the pronation/supination part of the exoskeleton provides the same range of motion as that of the normal human one. The forearm part provides the pronation and supination movement through an actuation using DS3218 Digital servo motor, two gears have been used as a power transmission method allowing the translation of the movement from bevel gear to spur gear and the resulting is the rotation of the forearm mechanism.

The wrist design consists of the flexion/extension part and adduction/abduction part which are shown in Fig. 4 and 5, respectively. The flexion/extension part reflects the flexion/extension movement of the exoskeleton through the range of normal human, this movement was achieved using DS3218 Digital servo motor placed at the contact point between the

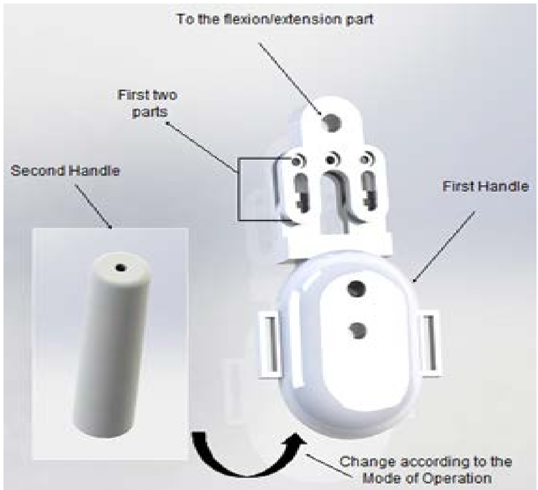

Fig. 5: Aduction/abduction part

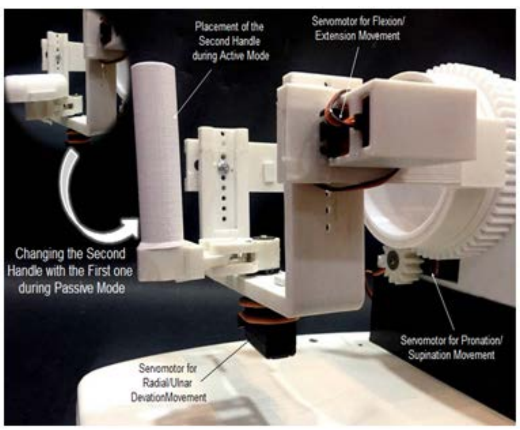

Fig. 6: Servomotors placements

flexion/extension part and the distal end of the mechanical structure of the forearm mechanism being attached screw. While the adduction/abduction part (Fig. 5) represents the distal part of the exoskeleton consists of a two mechanical structure attached to one another through springs thus provide a flexible and unconstrained motion also the distal part includes two handle mechanisms being used according to the rehabilitation progressing. The first mechanism uses during the passive mode of operation (the patient has no muscle activity) which has a strip being passed through its sides end holding the hand. The second mechanism uses during the active mode (the patient exhabits some muscle activity). The adduction/abduction part provides the adduction/ abduction movement through Tower Pro mg 995 servo motor being connected to the flexion/extension part through a screw.

Besides, a mechanical stoppers have been designed and placed at specified locations in the forearm and wrist designs to restrict the movements of the servo motors to prevent the excesses motions and match that of normal human (the ROM of flexion/extension, adduction/abduction and pronation/supination parts to 130°, 70° and 150°, respectively) thus provide more safety system. Figure 6 and 7 show the final structure of the exoskeleton compatible with the electronic circuit.

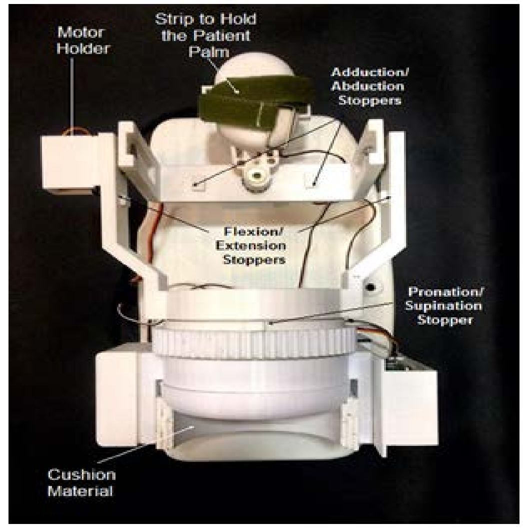

Fig. 7: Final assembly of the exoskeleton

Exoskeleton manufacturing process: All parts constructed the exoskeleton were built and configured by an additive technique which is a 3D printing. It is characterized by its naivety and customization in addition to its low cost manufacturing. By using the Fused Deposition Molding technology (FDM), the exoskeleton has been made, it is worked by providing it with a filament or metal wire being released from a coil that preparing to an extrusion nozzle. One of the characteristics that must be noted is that the printed parts being very strength along the plane of the printing as compared to that normal to it, during the printing process, each heating layer meets with the next layer and drawn together. At once the subsequent layer is printed, the former one is cooling down and harden[24].

MATERIALS AND METHODS

Electronic design: Several electronic components have been used include an EMG myoware and gyroscope sensors, pushbuttons, buzzer, microcontroller, shield V2.0 and Liquid Crystal Display (LCD). An EMG myoware sensor from Advancer Technologies has been used to measure the muscle activity non-invasively. Two EMG myoware sensors have been utilized being placed on the extensor carpi ulnaris and pronator teres (Fig. 8).

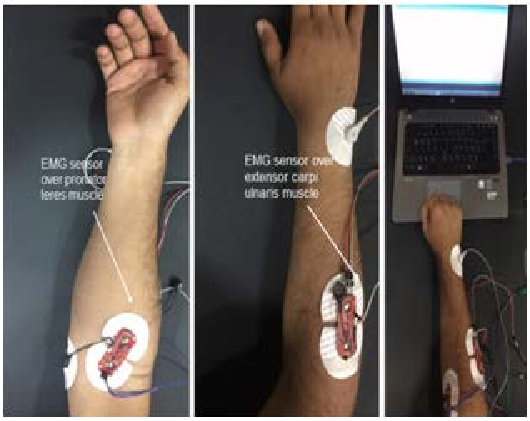

Fig. 8: Placement of EMG myoware sensor

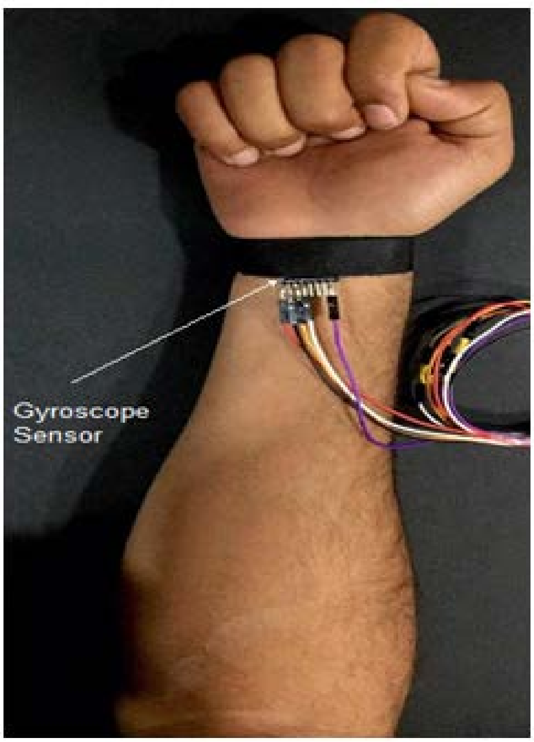

Fig. 9: Angle measurement with gyroscope sensor

Gyroscope Sensor has been used to measure the Range of Motion (ROM) and angular velocity around three axes for three proposed movements (Fig. 9). Both of the EMG sensors and gyroscope sensor have been used to provide the signal for controlling the servo motors to achieve the required movements and for evaluation of the rehabilitation progressing. Figure 8 shows the usage of a gyroscope sensor for angle measurement.

The buzzer and LCD used as an indicator for the translation between movements and cases and for displaying them in addition to the angle readings. Besides, pushbuttons that used as a switch between different operational modes and for different cases.

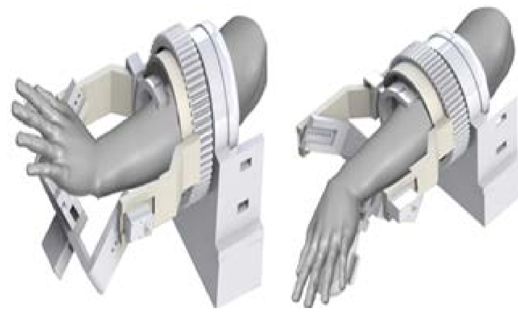

Fig. 10: Extension and flexion movement of the exoskeleton

Control system: In this system, an EMG myoware, angle sensors and switches have been utilized to control the overall system. An EMG myoware sensors extracts the muscle activity from the proposed muscles then these data were used to control the 3 DOF movements of the system's servo motors, this controlling process were done by determine the specified threshold value for both muscles. In addition, the gyroscope sensor was also used in controlling process of this system as well. The servo motors have been programmed in such a way their reflected range of motions are restricted to a specified range matching that of the normal human. In addition, to the mechanical stoppers to prevent the excessive motions reflected by these motors as mentioned in mechanical design section. The switches have been used to control the interchangeable processes between different modes of operation being choosing according to the patient's rehabilitation progressing and his/her conditions. The proposed modes of operation include passive mode and active mode (Fig. 10).

RESULTS AND DISCUSSION

The exoskeleton has been checked alone for its reflected range of motions, velocities, the motors bearing torque its prolonged working time and the battery lifetime. Then the device being tested with normal subjects with different age, sex and weight to achieve the kinematic, working, bearing, comfortability, safety and efficiency of the overall exoskeleton before tested with patients. Figure 10-15 and Table 1 show the range of motion and angular velocity analysis of the robotic exoskeleton for normal human, respectively.

After approving the required speed and ROMs of the exoskeleton, it applied with stroke and spinal cord injury patients. Table 2 shows the information of the patients.

Table 1: ROMs and velocity information of the normal human

Type of motion	Normal angle (deg)	Normal velocity (deg sec^{-1})
Pronation	80°	803.548
Supination	70°	
Flexion	75°	1970.168
Extension	70°	2175.768
Adduction	25°	27496.58
Abduction	35°	22955.46

Table 2: Patient's Information

Data	RH	MA
Age	49	52
Gender	Male	Male
Affected arm	Right	Right
Type of defect	Incomplete SCI	Stroke
Length (mm)	175	176
Weight (kg)	75	120

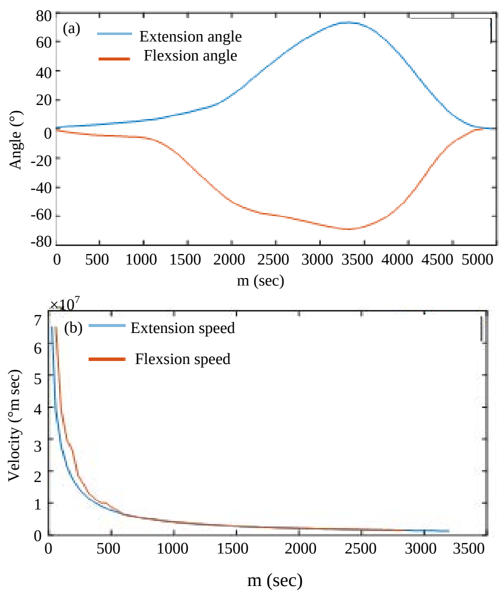

Fig. 11(a, b): ROM (left) and Velocity (right) flexion/ extension analysis of the exoskeleton

Fig. 12: Adduction and abduction movement of the exoskeleton

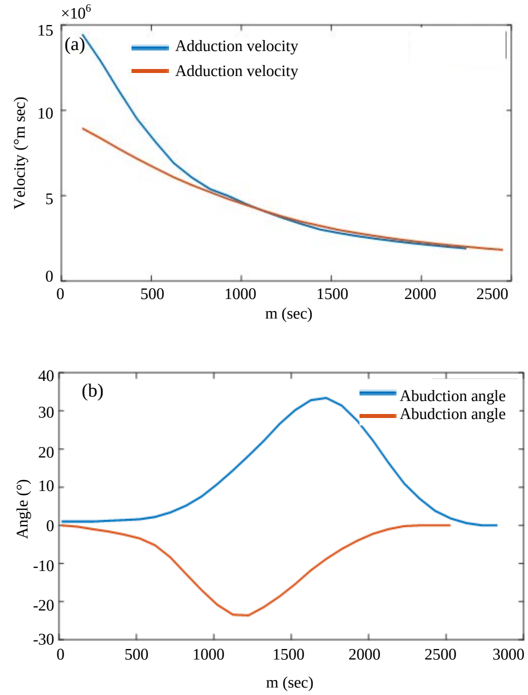

Fig. 13(a, b): ROM (left) and Velocity (right) analysis of the adduction/abduction movement of the exoskeleton

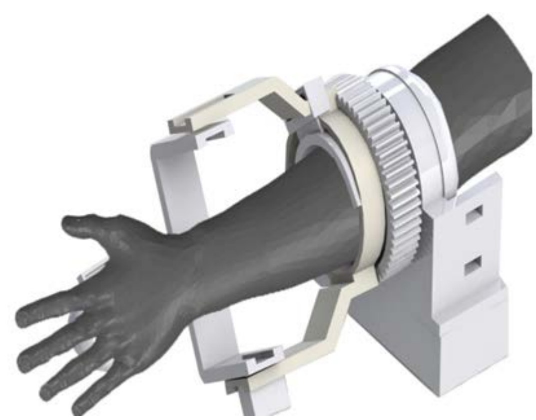

Fig. 14: Rotational movement of the exoskeleton

Figure 16-18 show the EMG activities and ROMs for wrist and forearm joints in the first session, fifth and last session for stroke patient.

The rehabilitation process begins with passive exercise (1st session), then the active exercises were started (the 5th session). Finally, the last session indicates the final progressing of physiotherapy which is more approximated to the normal human parameters. This program was applied with a stroke patient.

While with incomplete SCI patients, the rehabilitation process was started with active exercises,

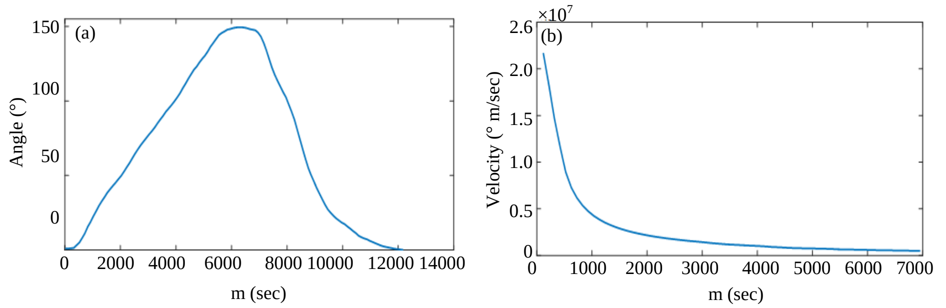

Fig. 15(a, b): ROM (left) and Velocity (right) analysis of the rotational movement of the exoskeleton

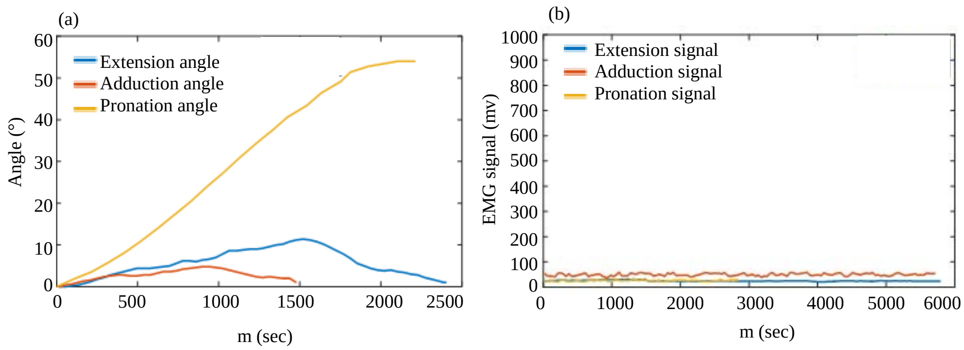

Fig. 16(a, b): ROMs (left) and muscle activities (right) of stroke patient in 1st session

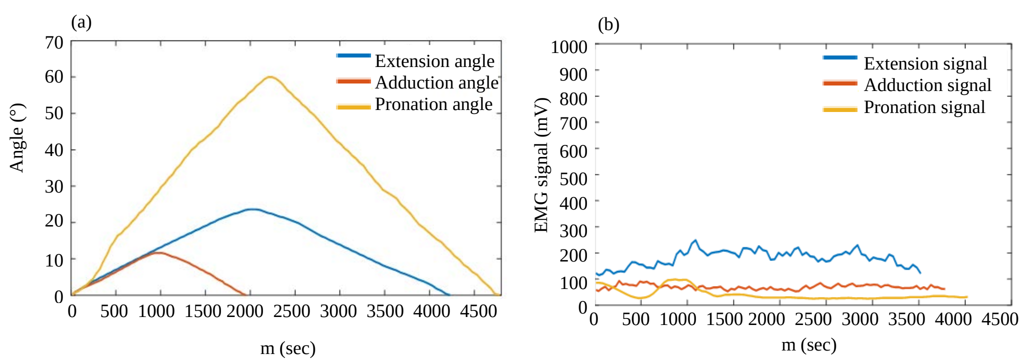

Fig. 17(a, b): ROMs (left) and muscle activities (right) of stroke patient in 5th session

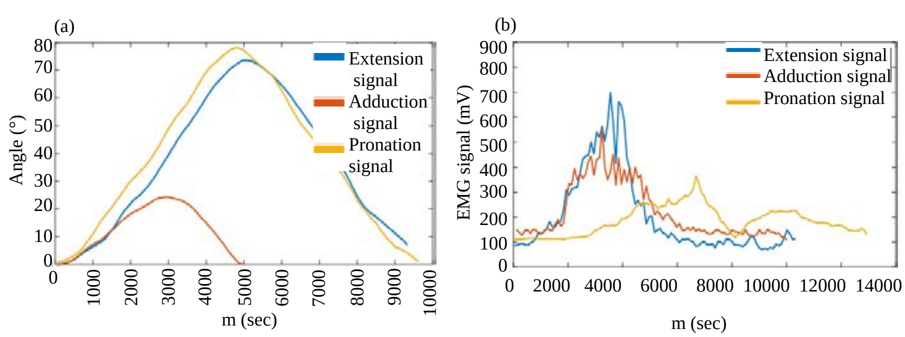

Fig. 18(a, b): ROMs (left) and muscle activities (right) of stroke patient in 15th session

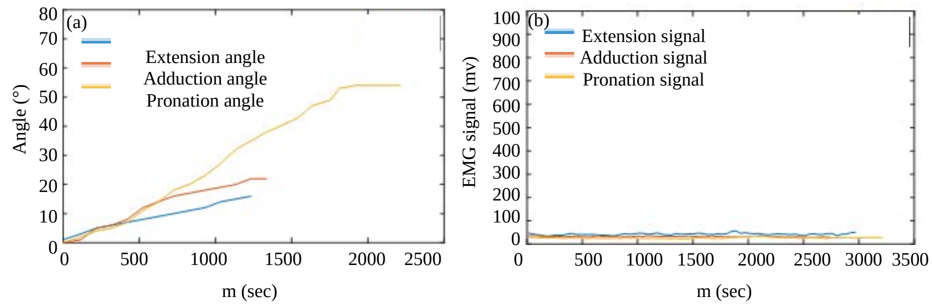

Fig. 19(a, b): ROMs (left) and muscles activities (right) of SCI patient in 1st session

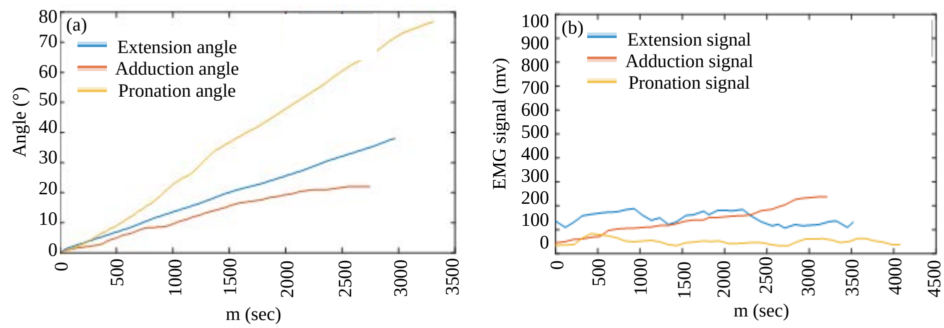

Fig. 20(a, b): ROMs (left) and muscles activities (right) of SCI patient in 5th session

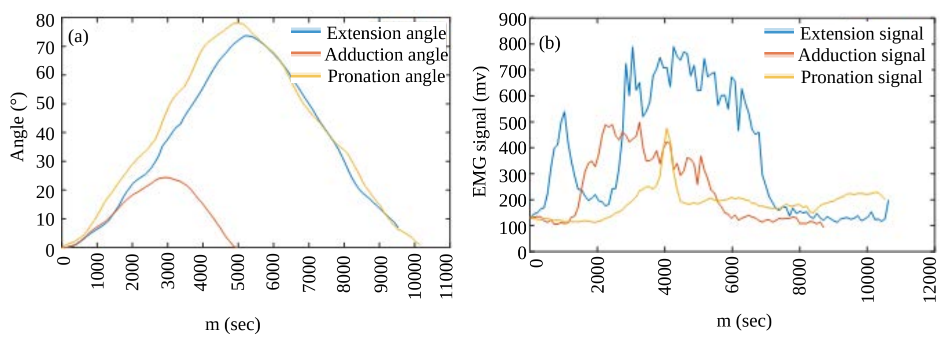

Fig. 21(a, b): ROMs (left) and muscles activities (right) of SCI patient in 12th session

then the progressing in rehabilitation was noted throughout sessions until the final progressing was achieved with restoring the muscular activities and ROMs as nearly for normal subjects as possible. Figure 19-21 presents the progressing 9 in EMG signal and ROMs information though the proposed session.

CONCLUSION

Impairment of motor function of the upper limb is a series problem due to their effectiveness in inhibiting the activities of daily living. The rehabilitation program in this study was started with passive and active exercises for stroke patients and active exercise for SCI patients. It can be concluded that the use of EMG signal and gyroscope sensors is of utmost importance for the evaluation of the rehabilitation process and controlling strategies of the exoskeleton. The EMG and gyroscope sensors wasn't used during passive exercises as the patient reach or exhibit a muscular activity and ROMs progressing, the rehabilitation process translated to active exercises. It was found that the EMG signal and ROMs for three DOF were in an enhancement with using the exoskeleton as a rehabilitation device, thus, it can be concluded that the exoskeleton is available to replace the work of the physiotherapist with low price, a short time and large enhancement of the rehabilitation progress for restoring the activities of daily living as nearly for normal subjects as possible.

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