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"MOVEMENT-MIRRORING" ARM EXOSKELETON IN REHABILITATION

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Aim. The aim of this article is to develop the prototype of arm exoskeleton for the treatment of upper limb movement activity after intracerebral hemorrhage or heart attack. **Materials and methods.** "Movement-mirroring" function was introduced with the help of the manipulating device consisting of the device for wireless data transfer, Arduino controller, exoskeleton servomotors, 3 accelerometers GY-85 and software, which detects angles. **Results.** We developed the prototype of the rehabilitation device, which was tested by 6 volunteers. Arduino controller allowed us to reduce the time needed for servomotor response up to 400 msec. **Conclusion.** If only one arm is affected as a result of hemiparesis or hemiplegia, then the rehabilitation therapy can be conducted in accordance with the program stated or by copying the movements of a healthy limb by means of 'movement-mirroring' function.
Keywords: *exoskeleton, movement, rehabilitation.*

1. Introduction

In modern medical practice the recovery of impaired limb function is often performed with the help of CPM machines (Continuous Passive Motion) – power-driven devices that allow the selection of angle of the limb flexion-extension in isotonic and isometric modes with controlled speed and range of motion [13, 17, 22]. Robot-assisted mechanical treatment reduces the time needed for recovery of the range of motion in isolated joint, tissue regeneration, and edema alleviation. Such treatment also decreases the incidence of adhesions and joint contractures [1, 8, 15, 21, 23, 26, 27]. Another benefit of CPM therapy is that the patient may start exercising as early as in 24 hours after brain hemorrhage episode, which prevents complications associated with prolonged immobility, such as contractures and muscle atrophy, thrombosis and thromboembolism etc. [24, 25, 26].

In order to improve the effectiveness of post-hemorrhage rehabilitation process, the principle of mirror therapy is used: the patient sits at the table with his arms stretched along the table; on the table there is a mirror placed in such a way that the patient can see the reflection of his/her intact arm meanwhile his/her affected arm is behind the mirror [4, 12, 19]. The patient tries to rise up both arms, but, due to brain damage, the affected arm does not move at all, or its movement is restricted. However, thanks to the mirror, the patient is unable to see it and believes his/her affected arm to be intact and move freely. Thus, damaged regions of the motor cortex are stimulated to find new neural connections, which accelerates the recovery process [3, 9].

The modern technique of mirror therapy is the following: the manipulating device put on the intact arm transfers the signal to servos of exoskeleton that copies the movements of the manipulating device. The manipulating device allows the therapist or the patient him/herself to conduct rehabilitative treatment remotely or at home [10, 11].

The aim of our research was to design a prototype robot-assisted "movement-mirroring" machine with manipulating device that is put on the intact arm and "reflects" its movements on the exoskeleton servos to recover motor function of the affected upper limb.

2. Materials and methods

When we started working on the prototype of the robot-assisted system we had to fulfil several related tasks and analyse the ways of rehabilitation [2, 6]. We intended to minimize the range of potential problems for the patient, so we chose to make the device compact (5 kg max, working dimensions limited to 70×30×20 cm max), affordable (1000 € max), and available.

It is known that the sooner rehabilitation starts, the more effective the recovery process is. The device should resemble regular household items, be smooth to the touch, be visually acceptable, and not provoke mental discomfort associated with movements of the motors. The length of device should be approximately equal to the average arm length of an adult. The general layout of the device is shown in Fig. 1.

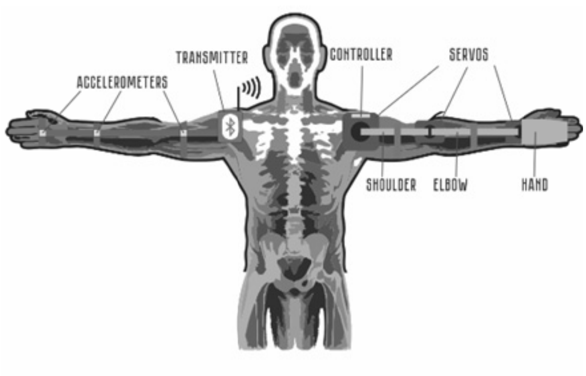

Fig. 1. General layout of "movement-mirroring" arm exoskeleton

2.1. General Layout and Principles

Servos were attached to the rectangular acrylic glass (plexiglass) plate 70 cm long and 25 cm wide. For softness the plate was covered with polyester wadding and fabric.

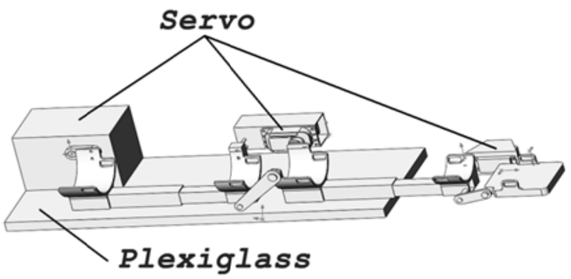

Fig. 2. Exoskeleton sketch

Servos were chosen for their ability to hold the weight at the preset angle [14]. For rehabilitation of three joints at once (elbow, shoulder, and wrist joints) we chose the following servos: Torxis i00800 High Torque Servo responsible for shoulder joint actions; Xq-S5650 servo responsible for elbow joint actions; and Savox sv1272sg servo responsible for wrist joint actions. We used SolidWorks software to create a 3D model of the arm exoskeleton where Torxis servo was located on the acrylic glass plate and supports the skeleton frame of elbow and wrist joints together with servos (Fig. 2).

Ideally, mirror therapy technique requires that the intact and affected arms should move exactly in the same manner. As the servos able to hold the weight exactly in the pre-set position were chosen for the affected arm, it was rational to use accelerometers for the intact arm because they were able to locate the exact position at the given moment of time. We used 3 self-calibrating chips GY-85 to locate the positions of shoulder, elbow, and wrist joints.

The controller responsible for functioning of exoskeleton servos was ARDUINO UNO R2. The exoskeleton was powered with Inwin 300w power supply without overload protection. To create operating voltage for elbow and wrist joints we used down-converter for ARDUINO DC-DC using LM2596S microcircuit with input voltage of 12 V and output voltage of 7.2 V for each servo. The aluminium radiator was used to reject the heat which could be produced at on-load position holding. Bluetooth receiver connected to adapter was chosen from Arduino developer set (HC-04).

2.2. Procedure

We conducted a series of experiments to assess the exoskeleton performance. Healthy volunteers were seated with their relaxed left arm in the exoskeleton meanwhile the laboratory technician was standing 1 meter apart and controlling the exoskeleton using the manipulating device (Fig. 3).

Test protocol included 10 slow repetitions of vertical movements: in shoulder joint with 0...90° amplitude (30-second pause), in elbow joint with 0...120° amplitude (30-second pause), in wrist joint –30...+30° (30-second pause). The next test involved 10 repetitions of the following succession of movements: shoulder joint raise by 60...70°, elbow joint bending by 70...90° and wrist joint bending by 20...30° (60-second pause). The experiments involved 6 volunteers in total; average experiment session time was 8 minutes.

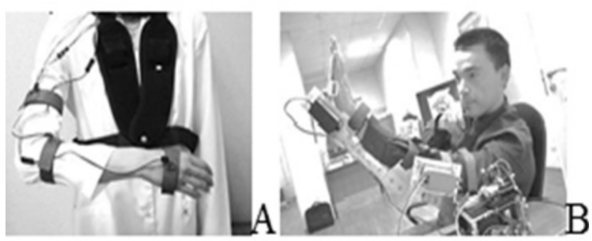

Fig. 3. The experiment procedure

3. Results

3.1. Servo Feedback Adjustment

The construction features of the chosen servos do not include feedback, i.e. the controller does not receive the information that the servo has shifted to the required angle. Potentiometers of the servo were soldered with wires further connected to the controller for the current angle positioning. After doing this we were able to know the moment when the arm movement would be painful for the potential patient. For example, Fig. 4 presents the angle position chart for exoskeleton elbow frame. The controller sent the signal to the servo to shift the elbow frame by an angle of 50 degrees in 6 seconds. Having received the signal the servo started uniform velocity motion by the set angle. From 3.5 sec it may be seen that the speed started to drop, and the controller decided to stop the elbow frame motion.

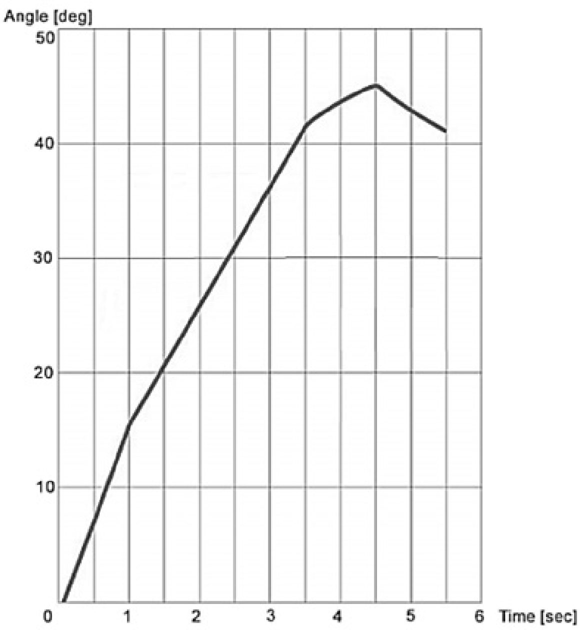

Fig. 4. Principle of servo functioning with adjusted feedback (servo stop at non-uniform motion)

3.2. Accelerometer GY-85 angle detection

To transfer output data of the accelerometer to degrees we used Open Source library Razor AHRS. We assembled the test stand (Fig. 5) including ARDUINO UNO R3 controller, 9V battery, accelerometer GY-85 and Xq-S5650 servo to test functioning and signal lag between accelerometer and servo.

Synchronization of vertical movements of accelerometer and servo was one of the main tasks for "movement mirroring" implementation. When accelerometer moves vertically servo should shift by the needed degree. To check it we disassembled the servo, soldered the wires to the potentiometer and connected them to Arduino controller. Fig. 6 presents the plot of angle shift versus time for accelerometer and servo. Maximum signal lag time between them was 400 ms, maximum error was 2.6 deg. and occurred during rapid displacement of the accelerometer.

The next step was to construct the manipulating device prototype (Fig. 7) including CubieBoard controller, APC M10BK-EC.10000mAh battery, three accelerometers GY-85 attached on the belts and controller-powered, and USB-Bluetooth transmitter.

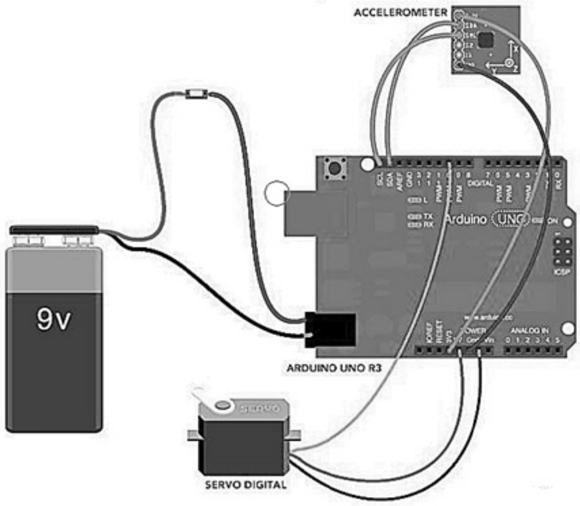

Fig. 5. Test stand for accelerometer positioning in degrees

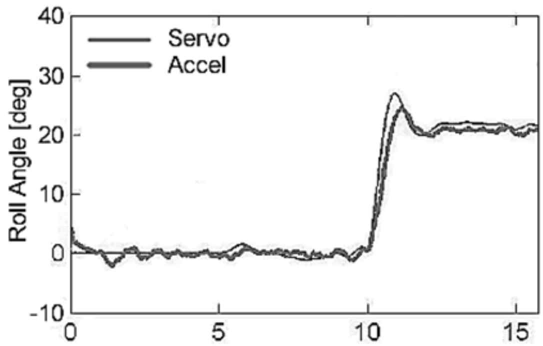

Fig. 6. Lag in signal transmission between accelerometer and servo potentiometer

Then we assembled the exoskeleton consisting of servos, frame with arm supporting clamps and locks (Fig. 8). The frame is made of two square aluminium pipes 40×40 and 35×35 mm in diameter for adjustment of shoulder and forearm length. For arm position support in the exoskeleton we made 4 semi-circular clamps of ABS plastic using 3D printer. ARDUINO UNO R3 controller is located on Torxis i00800 servo. Servo power management boards were attached on each side of the construction for space saving purpose. Input voltage is 12 V for Torxis servo (shoulder joint), and 7.2 V for Xq-S5650 (elbow joint) and K-Power DMM300 (wrist joint) servos.

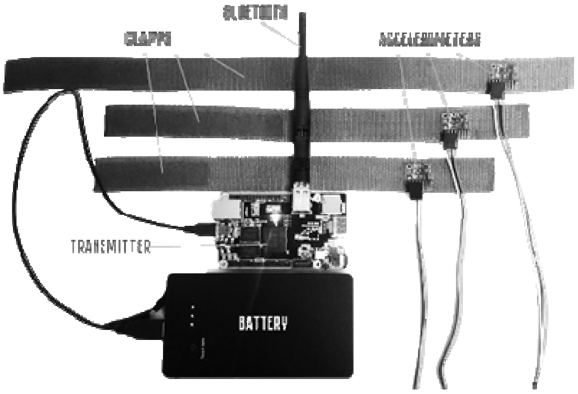

Fig. 7. Manipulating device prototype

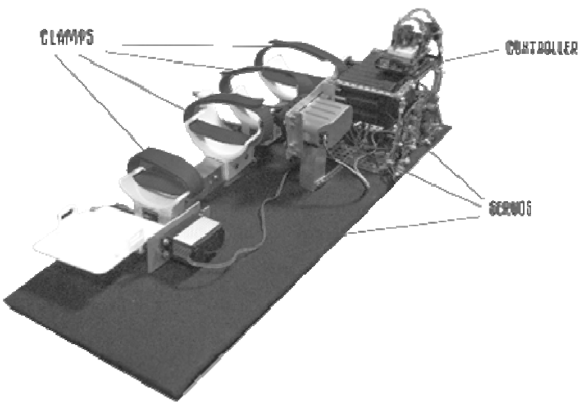

Fig. 8. “Movement-mirroring” arm exoskeleton prototype

4. Discussion

4.1. Performance evaluation

We evaluated the robot-assisted system performance using the following criteria:

Lag in signal transmission from accelerometers to servos;

As seen from Table 1, average lag time in the working prototype, in contrast with the test item, is over its former maximum values. However, we believe such lag to be insufficient as there are no visual differences in movements of the manipulating device and the accelerometer.

Table 1

Signal delay time

№	Servo	Lag, ms
1	Shoulder	490.5 ± 32.1
2	Elbow	410.2 ± 46.8
3	Wrist	450.8 ± 27.3

Voltage consumption for different arm weights.

As seen from Table 2, the voltage converter using ARDUINO DC-DC LM2596S microcircuit is not suitable for our task and, thus, should be replaced with the more effective one [5, 20].

Table 2

Voltage consumption

№	Arm weight, kg	Output voltage in LM2596S, V
1	4.1	5.9
2	2.7	7.0
3	4.3	5.6
4	3.3	6.5
5	3.1	6.8
6	3.7	6.2

Besides, the drawback discovered in the construction is the apparent vibration that starts at increasing load in elbow joint. However, the mechanical stability of the whole system will be improved if the exoskeleton construction includes stabilizing elements.

4.2. Limitations and further research

One of the main objectives of our research was to create the device that would be financially affordable for most of patients. Thus, the choice of materials and elements for the designed unit was limited.

The experiments were conducted on healthy volunteers in accordance with the approval granted by the Ethical Committee of the University (№39, 04.05.2016). Further research will involve the experiments using the model simulating a patient with hemiplegia.

The series of tests for assessment of electrical safety of the device is being conducted now.

“Movement-mirroring” arm exoskeleton prototype for rehabilitation of patients with disordered motor functions (for example, after brain haemorrhage) has proved its good performance. Construction elements are affordable and readily available. We believe that structural rework of exoskeleton will start the new trend in robot-assisted rehabilitation, available for in-home use in particular.

In future, in addition to construction defect eliminating, we are planning to add the remote control function using the remote control unit or via the Internet, so that the data could be analysed and transmitted to the treating doctor.

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ПРИМЕНЕНИЕ ЭКЗОСКЕЛЕТА РУКИ С ФУНКЦИЕЙ «ЗЕРКАЛЬНОГО ДВИЖЕНИЯ» В РЕАБИЛИТАЦИОННЫХ ЦЕЛЯХ

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Цель. Разработать прототип экзоскелета руки, предназначенного для лечения проблем движения верхней конечности после кровоизлияния в мозг или инфаркта. **Материалы и методы.** Функция «зеркального движения» реализована с использованием манипуляционного устройства, включающего в себя три акселерометра GY-85, программное обеспечение, которое отслеживает углы перемещения, устройства для беспроводной передачи данных, контроллер Arduino и сервомоторы экзоскелета. **Результаты**. В ходе этого исследования был разработан прототип реабилитационного устройства. Устройство было протестировано на 6 добровольцах. Использование Arduino позволило сократить время отклика сервомоторов до 400 мс. **Выводы**. Если поражена только одна рука, в случае гемипареза / гемиплегии, то восстановительная терапия может проводиться в соответствии с указанной программой или путем копирования движений здоровой конечности путем «зеркального движения».

Ключевые слова: *экзоскелет, движение, реабилитация.*

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