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Shoulder-elbow exoskeleton as rehabilitation exerciser

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Abstract. This paper presents a 2 degree of freedom exoskeleton designed for the rehabilitation of the shoulder and elbow movement in the sagittal plane; a semi-portable design strategy was chosen, which enables an easy attachment to a standard medical chair as well as the patient upper limb. A dedicated driver enables the control from a graphical user interface, which also provides the option of customized rehabilitation exercises. The potential of future improvements is assessed, and recommendations of research direction are made in order to broaden the usability of the proposed device.

1. Introduction

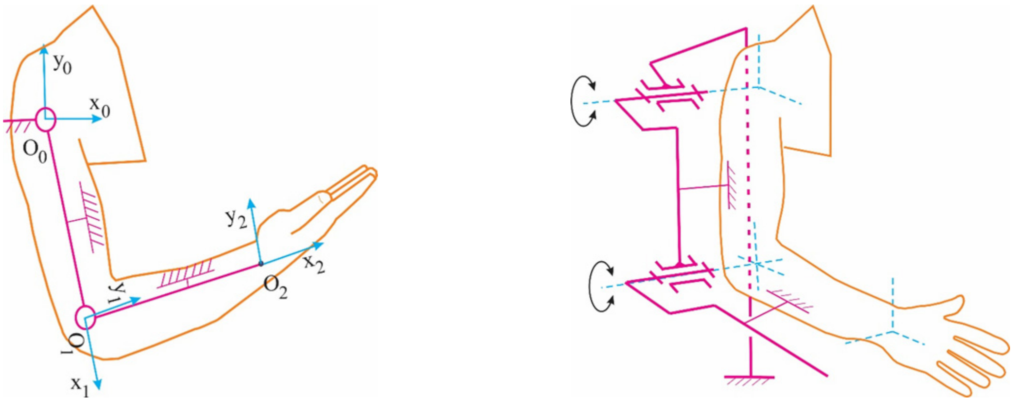
The momentum gained by rehabilitation engineering was possible due to many technological advances that allowed more complex algorithms to be run by more compact hardware, accompanied by a greater market penetration due to reduced costs. On the other hand, better life condition is usually coupled with a reduction of birth rate and an increase of life expectancy [1] that leads to the phenomena of aging population: it is estimated that by the year 2047, there will be more elder people than children in the world [2]. Such a coupling between demand and supply makes the interest into the design of rehabilitation equipment important and necessary; it is evident that the improvement in the quality of life that the research in this area provides, it is not limited only to existing patients, but also gives the opportunity of better understatement of disability and the proper means to handle it that might help to deter it in the first place by responsible ergonomic design.

Rehabilitation engineering encompass a wide range of branches – assistive robotics, rehabilitation equipment, environment adaptation, to name just a few – and intertwines many disciplines, primary from medical and engineering sciences. This interdisciplinary approach brings together specialists with very different educational background, which is both advantageous as well as a challenge: it is unquestionable that combining the experience of various experts poses as a big advantage, but there is a communication barrier laid down by the jargon that has to be surmounted, and this is often a challenge.

The present paper aims to describe the design process of a semi-portable shoulder-elbow exoskeleton suited primarily for passive exercises; it is a member of a larger family of rehabilitation exoskeletons, differentiated among themselves by the number of degree of freedom and the combination thereof, all sharing a modular strategy that allows easy recombination. This particular exoskeleton is meant to be attached to the backrest of a standard hospital wheelchair, but it may be easy reconfigured to have a wider attachment capability. The devised user-friendly graphical interface aids a physiotherapist customise exercises for the upper limb tailored to a patient's specific need, and gives a feedback of the exoskeleton state.

2. Theoretical model of the shoulder-elbow exoskeleton

The upper limb orientation is the subject of seven anatomical movements (flexion-extension, inner-outer rotation and abduction-adduction of the arm, flexion-extension and pronation-supination of the forearm, and abduction-adduction and flexion-extension of the hand) [3]; previous work [4] was done in order to systematise different structures of exoskeletons.



(a) (b)

Figure 1. Shoulder-elbow exoskeleton mechanism: (a) side view; (b) isometric view.

For the purpose of the exoskeleton that constitutes the object of this paper, only two anatomical movements were considered: the shoulder and the elbow in the sagittal plane. Figure 1 pictures the exoskeleton mechanism as it is attached to the upper limb. The distance between the two joints varies between individuals, 85% of male and female Caucasians older than 20 years falling into the 291…428 mm interval [5]. Biomechanical constraints were regarded by the design of the angular amplitudes of the joints, which are as follows: -90°…+60° in respect to the transverse plane for elbow, and -20°…+95° in respect to the frontal plane for shoulder [6].

2.1. Kinematic analysis

In order to assess the direct kinematic analysis, the Denavit and Hartenberg (D-H) convention was used as described in [7] with the D-H parameters presented in table 1 (refer also to figure 2 on next page). The angles θ_1, θ_2 are known, therefore the position of $O_{2,0}$ and orientation $R_{2,0}(\theta_1,\theta_2)$ of a point associated to the hand are determined in relation to the shoulder joint, which is considered as being connected to the chassis. The length of the linkages are notated l_1 for the element that joins the shoulder and the elbow, respectively l_2 for the element bound to the forearm. The results were as follows:

$$\begin{cases} x_2 = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ y_2 = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{cases} \tag{1}$$

$$R_{2,0} = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \end{bmatrix} \tag{2}$$

Table 1. Denavit and Hartenberg parameters.

Joint	θ_i	α_i	a_i	d_i	**Variable**
1 (shoulder)	θ_1	$\alpha_1 = 0^\circ$	l_1	0	θ_1
2 (elbow)	θ_2	$\alpha_2 = 0^\circ$	l_2	0	θ_2

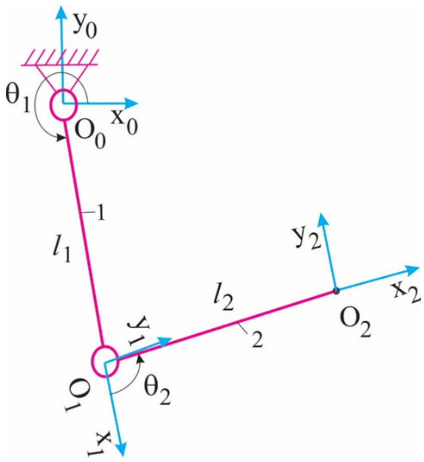


Figure 2. The two degree of freedom two bar-linkage mechanism and the D-H parameters.

For the indirect kinematics analysis, very important for the effective numerical control of the shoulder-elbow exoskeleton, the geometric method was considered more appropriate, by applying the cosine theorem in the $O_0O_1O_2$ triangle (refer to figure 3); the results for the angles θ_1 and θ_2 are the following equations:

$$\theta_1 = 2\pi - (\alpha + \beta) = 2\pi - \left(\arctan \frac{y_2}{x_2} + \arctan \frac{l_2 \sin\theta_2}{l_1 + l_2 \cos\theta_2} \right) \tag{3}$$

$$\theta_2 = \arctan \left[\frac{\pm \sqrt{1 - \left(\frac{x_2^2 + y_2^2 - l_1^2 - l_2^2}{2 l_1 l_2} \right)^2}}{\frac{x_2^2 + y_2^2 - l_1^2 - l_2^2}{2 l_1 l_2}} \right] \tag{4}$$

Following from the fact that equation (3) and (4) accept two solutions, it is worth mentioning that the point O_2 might be brought to a particular position in space with two distinct configuration of the mechanism, but only one is biomechanically feasible, as seen in figure 3.

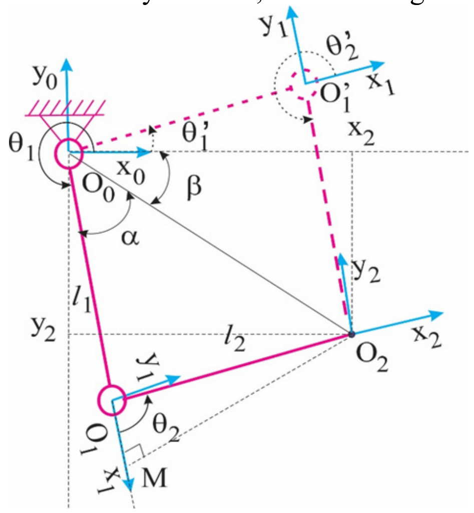


Figure 3. Possible solutions to the inverse kinematic analysis of the exoskeleton mechanism.

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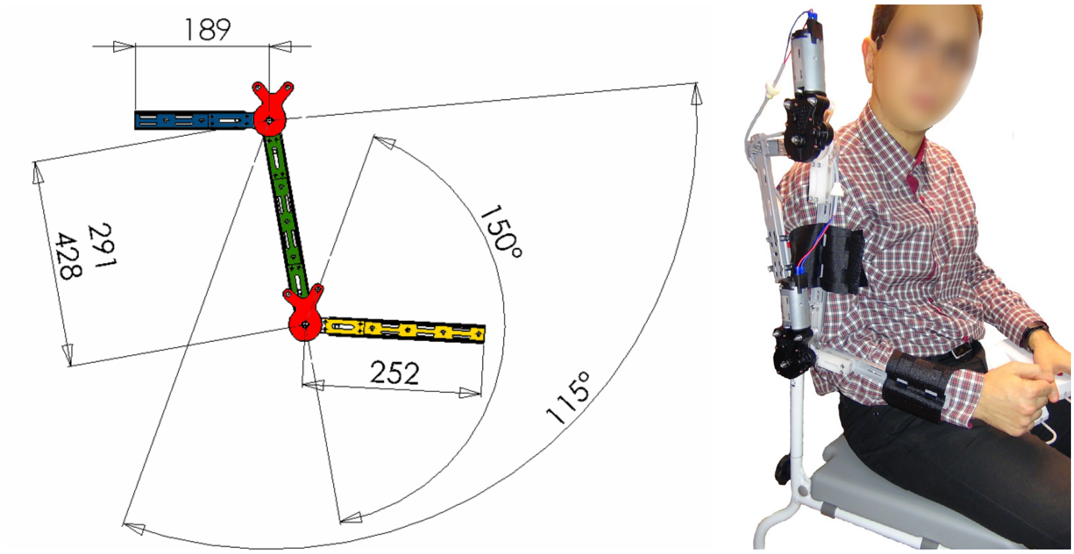
2.2. Design and construction details of the shoulder-elbow exoskeleton

The 3D model was designed in Dessault Systemes SolidWorks 2010 software, which was further used for computer numerical controlled machining on an ISEL CPM 2018 4-axis mill (although, only 3 axis were needed). The joints were made out of a combination of polymethyl methacrylate (PMMA) and polytetrafluoroethylene (PTFE), that in a finite element analysis of internal stresses (not pictured) proved to be effective, and the linkages out of aluminium, this combination yielding the best compromise between sturdiness and reduced weight. The exoskeleton is actuated by two 12 V DC motors, capable of delivering 20 Nm of torque, controlled by a dedicated driver – further details will be discussed later in this paper.



(a) (b)

Figure 4. Design and construction details of the shoulder-elbow exoskeleton.

The element A in figure 4a is attached to the backrest of a wheelchair primary used for the transport of a patient; in order to prevent unwanted movement, its wheels are equipped with brakes that have to be engaged during an exercise. The element B is attached to the arm (refer also to figure 4b) and is adjustable in order to accommodate the patient limb length. The element C is attached to the patient forearm, its length being fixed and chosen as such as to provide sufficient leverage for passive limb movement. J_1 and J_2 are the motors mounting plates.

3. Control system of the shoulder-elbow exoskeleton and operation

In order to control the exoskeleton, a custom driver was built around four IR2112 chip MOSFET driver from International Rectifier; according to the motor data sheet, it draws 34 A of current at maximum torque. Also, both the speed and the sign of the rotation has to be controlled, therefore, for each motor a full H-bridge was constructed using four N-MOSFETs. For the correct operation of the high-side MOSFETs, the well-known floating ground method was employed, in order to ensure the required switch-on voltage.

For the control of each H-bridge n, the custom driver takes two variables, s_n for sign, which can be either low or high and dictates the clockwise/contraclockwise rotation of the motor, and p_n for pulse width modulation (PWM), which control the speed. Using the notation M for the correspondent input to the IR2112 chip, A and B for the two legs of the H-bridge and HI and LO for the input that drives the high-side MOSFET, respectively the low-side MOSFET of the bridge leg, the following Boolean expressions are used:

$$M^{n}_{HI,A} = \neg s_n \wedge p_n \tag{5}$$

$$M^{n}_{LO,A} = \neg(\neg s_n \wedge p_n) \tag{6}$$

$$M^{n}_{HI,B} = s_n \wedge p_n \tag{7}$$

$$M^{n}_{LO,B} = \neg(s_n \wedge p_n) \tag{8}$$

The previously described logic was implemented in hardware using a 74HC04N hex-inverter chip in combination with a 74HC00N quad-NAND gates chip, both from Texas Instruments. This custom driver receives the signals mentioned before from the communication module (refer to figure 5), which, for this prototype, is an Arduino UNO board; it is planned in the future to be replaced by a dedicated communication module. The communication module receives feedback from the exoskeleton for the relative angular position and the limit of the movement amplitude; these are implemented using limiting switches which triggers the interrupt service routine on the board, which in turn calibrate the signal from the resistive goniometers and an absolute angular position is computed (this is done only once in the calibration step). The communication module is in permanent connection with the computer, so that a physiotherapist can monitor through the graphical user interface the rehabilitation exercise.

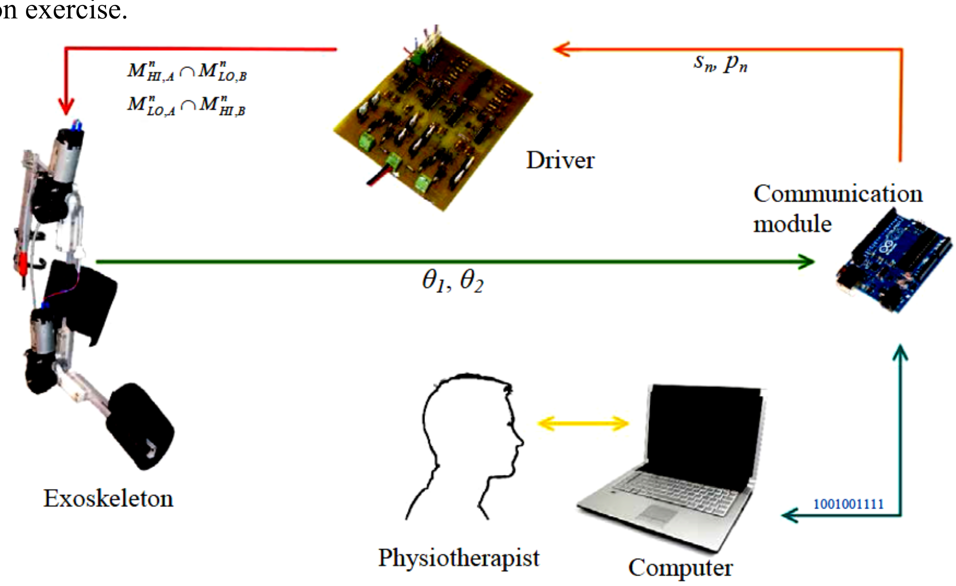


Figure 5. Control architecture of the shoulder-elbow exoskeleton.

The resistive goniometer consist of a potentiometer which act as a voltage divider; this voltage is fed into an 10-bit analog-to-digital converter, which gives a resolution of roughly 20 arcminutes; the accuracy might be improved with a dedicated rotary encoder.

The graphical user interface was designed using MATLAB R2014a; this choice was determined by the fact that future developments are easier to integrate using the powerful simulation environment that this software provides – more on this subject will be discussed in section 4 of this paper. Figure 6 pictures the graphical interface and its components: before the beginning of every exercise, the serial communication has to be started by pressing the connect button; afterwards, the physiotherapist has the option to begin a prerecorded exercise, or to control the exoskeleton directly, by manually moving the correspondent sliders – left/right controls the counterclockwise/clockwise rotation, and the distance from the slider center proportionally to the speed in that direction. The feedback panel shows the position and the computed speed and acceleration (the computation is done by the computer, in order to keep the communication module as idle as possible).

The communication module monitors permanently the angular position, and it automatically stops the correspondent joint of the exoskeleton, as needed; this is especially useful in manual mode control, as the physiotherapist can concentrate on the exercise parameters; nonetheless, there is a conveniently placed "Stop" button; in the worst-case scenario, the joint press the limiting switches, which triggers in turn the interrupt service routine that stops the movement and recalibrate the signal, as necessary.

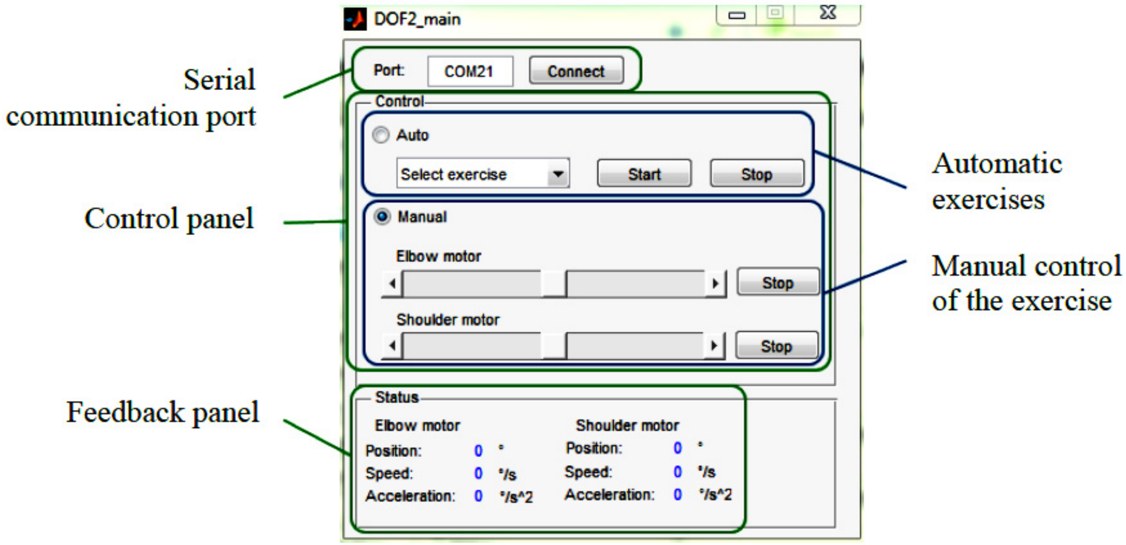


Figure 6. Graphical user interface of the shoulder-elbow exoskeleton

4. Conclusions and further improvements

The presented prototype of a shoulder-elbow exoskeleton is very useful for passive rehabilitation exercises; its minimalist design keeps the weight reduced, and the modular design provide an easier pathway to further development.

As far as further development is considered, two new sections into the graphical user interface are planned to be added in the near future: a semi-automatic panel that provides easy minimum and maximum angle as well as speed configuration for a simple back-and-forth exercise, and a brain-computer interface connection. The latter planed addition was the main reason of using MATLAB as a development environment.

Another planned further development is the integration of a functional electrical stimulator, which can be proven especially useful for patients that undergo rehabilitation after cerebrovascular accident.

5. References

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