# Mechanical design and 3D printing process of an exoskeleton used for elbow joint rehabilitation

**I A Tătulea[1], C N Drugă[1], I Şerban[1]**

[1]Design of Product, Mechatronics and Environment Department, Transylvania University of Brasov, Brasov, Romania

irinatatulea23@yahoo.com

**Abstract**. This paper presents the design and 3D printing process of the components which form an exoskeleton robot used in elbow joint rehabilitation. In the first part of the paper are presented a series of exoskeleton models used to rehabilitate the upper limb (4 DOF and 7 DOF). The second part is entirely dedicated to the mechanical design process of the components which form the device. In the last part of the paper are presented a series of aspects related to the physical achievement of the device using rapid prototyping technology (3D printers, filaments of material, execution time, assembly of components etc.). In this case was chosen the natural PVA filament from Ultimaker that dissolves in water. The dissolving process of the support material was analysed over a 24 hours period, in which the pieces were immersed in an aquarium. This paper represents a part of a much wider project of designing, creating and testing a bio mechatronic device used in rehabilitation of elbow joint.

## 1. Introduction

Exoskeleton robots for upper limb have been used for various purposes, such as assisting joint movements, rehabilitating and treating joint dysfunctions, muscle strength augmentation, and haptic interface. In the case of therapy and rehabilitation of joint dysfunctions, most of these devices have less than seven degrees of freedom (7 DOF) of active joints [1].

The main features of 4DOF exoskeleton robot are the following: developed by the University of Saga; segments of application: shoulder, elbow and forearm; the degrees of freedom of the active joints: 4 DOF; type of actuators: actuators type I, powered by DC servo motors; power transmission methods: cable and gear drives; purpose of the application: power assist device.

The main components of the 4 DOF exoskeleton are: a shoulder motion support part, an elbow motion support part, a forearm motion support part, a wrist force sensor, and a mobile wheel chair. The mobile wheel chair itself has 2 DOF, which provide independent movement for physically weak persons. The device has the role to assist the following movements: horizontal flexion-extension of the shoulder, vertical flexion-extension of the shoulder, flexion-extension of the elbow and supination-pronation movement of the forearm.

The main advantage of the robot is the ability to adjust the distance between the arm holder and the centre of rotation of the shoulder joint of the robot, in accordance with the shoulder motion, in order to cancel out the ill effects caused by the position difference between the centre of rotation of the robot shoulder and the human shoulder. The control method of the robot is based on EMG signals generated by human muscles [1].

The main features of 7DOF exoskeleton robot are the following: developed by the University of Washington; segments of application: shoulder, elbow, forearm and wrist; the degrees of freedom of the active joints: 7 DOF; type of actuators: actuators type I, powered by brushed motors; power transmission methods: cable drives; purpose of the application: rehabilitation device for upper limb, virtual reality simulation, power assist device (active assist and passive assist) [1, 2].

7 DOF exoskeleton robot (CADEN-7) generates the following movements: flexion-extension of the shoulder, abduction-adduction of the shoulder, internal-external rotation of the shoulder, flexion-extension of the elbow, supination-pronation movement of the forearm, flexion-extension of the wrist. In addition to this movements, the robot generates the radial-ulnar deviation [1]. The mechanism is controlled by a PID controller (proportional–integral–derivative controller) and EMG sensors [2].

## 2. Mechanical design process

For designing and 3D printing of an exoskeleton used for elbow joint rehabilitation it was required to go through the following steps: effectuating the anthropometric measurements of the upper limb circumferences; performing the mechanical design process; choosing the manufacturing technology (3D printing, CNC etc.) and the materials that will be used; choosing the actuation technology: electric actuation (stepper motors, DC motors, CC motors, servo motors etc.), pneumatic actuation (pneumatic cylinder, pneumatic muscles etc.), hydraulic actuation etc.; choosing the mechanical fasteners (self-tapping screws, nuts etc.); making the gripping wristbands of the exoskeleton on the upper limb segments (upper arm and forearm); sizing the CAD model of the exoskeleton; validation of mechanical design dimensions; performing the technological process that has been chosen (3D printing); assembling component parts; making the command and control circuit of the stepper motor; programming the stepper motor– source code; testing the final device.

### *2.1. Effectuating the anthropometric measurements of the upper limb circumferences*

To establish the suitable designing dimensions have been effectuated a number of 5 anthropometric measurements of the upper limb for a number of 20 person (10 women and 10 men), with ages between 22 and 27 years. It was taken into account the measurements of the following anatomical areas, shown in figure 1, as it follows: wrist circumference, noted with C1; forearm circumference, noted C2; the distal zone of the upper arm circumference, noted with C3; the length of the forearm segment, situated between the wrist joint and elbow joint, noted with L1; the length of the upper arm segment, situated between elbow joint and shoulder joint, noted with L2.

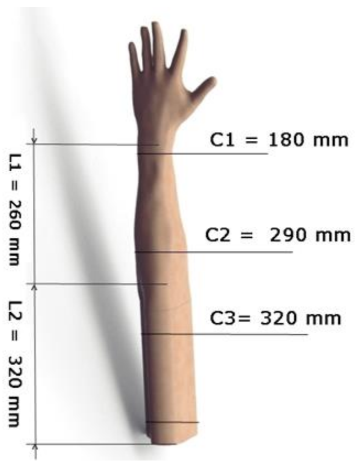



**Figure 1.** Anthropometric dimensions adopted

*2.2. Performing the mechanical design process*

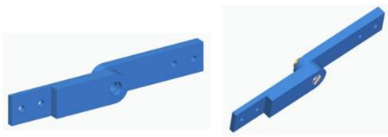
The CAD model of the exoskeleton robot has been designed using the Solid Edge Academic Edition - Siemens PLM Software. The final model is made up of 24 pieces of which only 7 of these were obtained using 3D printing technology. The components of the CAD model are the following: cuffs for supporting the forearm C1-C2, shown in figure 3.a; cuff for supporting the upper arm C3, shown in figure 3.b; passive joints assembly; the holder; active joint; the bolted joint; three gripping wristbands; thirteen gripping screws; NEMA 17 stepper motor, shown in figure 4.a.

Designing process involves the succession of 7 main design stages. The cuff for supporting the wrist (C1) was designed with a radius of 29 mm and a wall thickness of 5 mm. Its width was generated using the Extrude command at a value of 25 mm. The cuff for supporting the forearm (C2) was designed with a radius of 46,5 mm and a wall thickness of 5 mm. Its width was generated using the Extrude command at a value of 30 mm. The distance between the cuffs (C1 and C2) is 160 mm. The cuff for supporting the upper arm (C3) was designed with a radius of 51 mm and a wall thickness of 5 mm. Its width was generated using the Extrude command at a value of 30 mm.

a) b)

**Figure 2.** The CAD model for: a) Cuffs for supporting the forearm C1-C2; and b) Cuff for supporting the upper arm C3

The joining elements creates a mechanical link between the cuffs. These joints have a length roughly around 84,5 mm respectively 82 mm and a maximum width of 10 mm. The central hole, shown in figure 3, represents the place where the bolted joint will be assembled. It has a outer diameter of 9,5 mm and a inner diameter of 7,5 mm.



a) b)

**Figure 3.** The CAD model for: a) Passive joints; b) Mechanical link between the passive joints created by positioning the bolted joint through the existing holes

The bolted joint, shown in figure 4, represents the essential element which creates mobility of the passive subassembly within the biomechanical system. The outer diameter has a value of 6,6 mm and the inner diameter a value of 4,8 mm. The total length of the bolted joint is around 13 mm.

a) b)

**Figure 4.** The CAD model of the bolted joint; a) Sideway view; a) Bolted joint assembly;

The assembly process of all the components presented previously has been performed by using the ISO Metric Assembly module of the Solid Edge Academic Edition – Siemens PLM Software. The render image has been achieved using Key Shot for Solid Edge software. The final CAD model of exoskeleton robot is shown in figure 5.

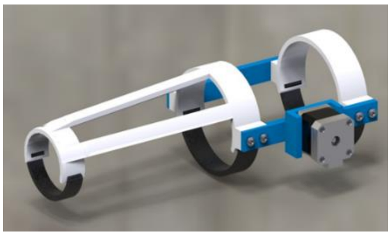


**Figure 5.** The final CAD model of exoskeleton robot

In the assembly were used a number of eight 4,2x13 self-tapping screws. These were used to perform the assembly between the joining elements and cuffs for supporting the upper arm (C3) and forearm (C1-C2). Four M3X10 screws have been used to mount the stepper motor housing. To perform the joint was used one 4,8x13 self-tapping screw.

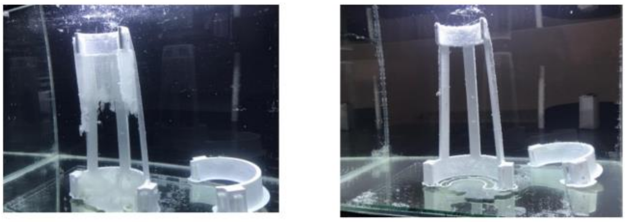
To actuate the exoskeleton robot was chosen to be used a NEMA 17 stepper motor, shown in figure 6.a, which has the role of creating simulation of the gradual flexion-extension movement in the elbow joint. Technical characteristics of the stepper motor can be found in reference [3]. It is commanded and powered by means of TB 6600 stepper motor driver, shown in figure 6.b. This is a professional two-phase stepper motor driver. It supports speed and direction control. Technical characteristics of the stepper motor can be found in reference [4].

a) b)

**Figure 6.** a) NEMA 17 stepper motor; b) TB6600 stepper motor driver [3, 4]

## 3. 3D printing process

The 3D printing process of the final product (bio mechatronic exoskeleton for rehabilitation of elbow joint), was performed by using two models of 3D Ultimaker printers: Ultimaker 3 and Ultimaker 3 Extended. As work material, was chosen the CPE (copolyester) filament from Ultimaker, due to its remarkable mechanical, thermal and electrical properties. Mechanical, thermal and electrical properties of this material can be found in the reference [5]. The execution time of parts totalized a number of 35 hours of 3D printing out of which 22 hours have been allocated for printing the cuffs for supporting the forearm C1-C2. Due to the complex geometric configuration of the printing parts, it was required to use a support material. In this case was chosen the natural PVA filament from Ultimaker that dissolves in water. The dissolving process of the support material, shown in figure 7, took 24 hours. The pieces were placed inside of a transparent aquarium full of water so as to the dissolving process of the support material to be easily monitored. To generate the G-code was used Ultimaker Cura software. The final product achieved by means of rapid prototyping technology is shown in figure 8.



a) b)

**Figure 7.** Dissolving process of the support material: a) After 12 hours; b) After 24 hours

a) b)

**Figure 8.** Attaching the bio mechatronic exoskeleton for rehabilitation of elbow joint on the user's arm: a) In a flexion position; b) In extension position

## 4. Conclusions

Although the constructive solution chosen for this project is not very complex, the exoskeleton robot achieved by means of rapid prototyping technology presents a series of advantages: it’s easy to put into operation and to be used, the amplitude and frequency of movements can be easily modified from the software, the cost price is low, can be used for didactic purposes in the Medical Engineering Laboratory for a number of specialized disciplines, maintenance is easy to carry out etc.

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