Design, development and control of a robotic arm

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Summary

The aim of the present project is the improvement of an upper limb orthosis, oriented at the elbow joint, developed during a master's degree. The orthosis was already able to assist in movements of flexion and extension of the arm. Our work has been focused on the implementation of the rotation of the forearm. The movements are controlled by the use of EMG signals picked up with surface electrodes at the forearm and the biceps. The signals are compared against a threshold and, if surpassed, the movements are carried out by two servomotors.

1. Introduction

An orthosis is a medical device used to modify the functional and structural characteristics of the neuromuscular and skeletal system of the patient [1]. While prothesis replace the affected body part, orthoses are used to correct the deformity or assist in the function of an already existing structure.

Orthoses can be classified according to their function in four types: supportive (they hold a position and avoid non-desired movements), dynamic or functional (they assist in the movement of a paralyzed limb), corrective (they rectify a skeletal deformity) and protective (they keep the alignment of an injured limb) [2].

The demand for orthoses designed so that they can be used without fatigue in both domestic and clinical settings is rising [3]. Among these, the ones oriented to the upper limb can have a major impact in the improvement of the quality of life [4] and economic capacity of the patients, since the upper limb is fundamental when interacting with the environment and working.

One characteristic of orthoses is that they are made in a personalized way for the user's particular anatomy and needs. 3D printing technologies have revolutionized the field of orthoses in this aspect, due to the decrease in costs derived from materials. Specially with children, whose size varies continuously as they grow up. Therefore, the use of 3D printed transitional orthoses represents a great advance [5].

This work is based on a previous orthosis developed in the master's degree in the CEU San Pablo University (Máster Universitario en Ingeniería Biomédica). The device was 3D printed and was able to assist in the flexion and extension of the arm, movements performed by the biceps braquii and the triceps brachii, respectively. The control could be exerted using proportional myoelectric control or by performing complete joint movements once a single threshold was surpassed.

The objective of our project was to modify the orthoses in order to extend the number of movements it can assist with. The movement chosen has been the rotation of the forearm, that is, its supination and pronation. The pronator teres and pronator quadratus are the muscles responsible for the pronation of the forearm by pulling on the radius. Similarly, the supinator and the biceps brachii supinate the forearm [6].

The rest of the paper is structured in the following way: in section 2, the 3D design of the device is explained; section 3 discusses the electric components and the behaviour of the orthosis; section 4 deals with the results obtained; finally, section 5 presents the main conclusions and section 6, the future work.

2. 3D design

Like the previous version of the orthosis, the new one has been designed with a CAD software (FreeCAD) and printed using a Witbox 3D printer and PLA filaments.

In Figure 1 the complete 3D model is shown, whereas Figure 2 shows a detailed view of the new rotation mechanism, which simply consisted of a straight bar with two fittings in the earlier model.

The orthosis can be divided in two main parts, A and B, corresponding to the pieces attached to the arm and the forearm, respectively, through the use of velcro straps, that can be adjusted according to the individual needs. The A piece corresponds to the arm piece of the previous model of the orthosis, whose forearm piece has been redesigned into piece B.

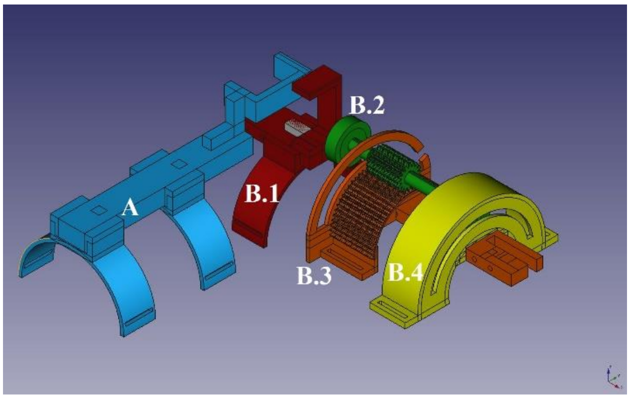

Figure 1. *3D model of the complete orthosis, divided in the following pieces: A (blue), B.1 (red), B.2 (green), B.3 (orange) and B.4 (yellow).*

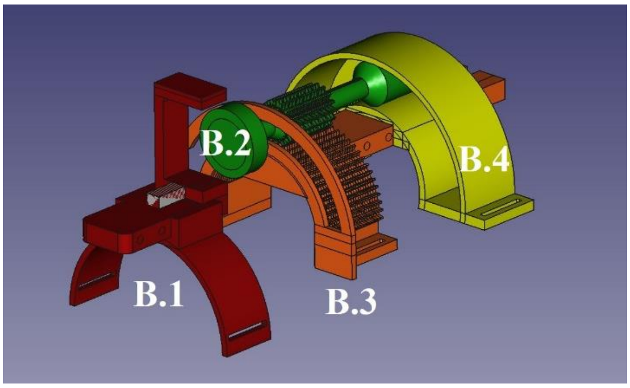

Figure 2. *Detailed view of the pronation/supination mechanism. Pieces: B.1 (red), B.2 (green), B.3 (orange) and B.4 (yellow).*

The first joint mechanism is in charge of the elbow. It performs the movements of flexion and extension of the arm. A servomotor is placed at the end of the arm piece A and its complementary part is attached to the forearm piece B.1. This way, when the signal is received, the servomotor rotates the forearm with respect to the arm. The signal used to control this movement is an EMG signal resulting from the biceps contraction. One contraction flexes the arm, and another extends it.

The second mechanism has been developed through a process of trial and error and is used to perform the pronation and supination of the forearm. The forearm piece B is divided in four different parts:

- B.1: Has the complementary piece of the elbow's servomotor and the servomotor of the forearm coupled.
- B.2: Is attached to the complementary piece of the second servomotor and transmits the rotation movement, through a cylindrical gear, to piece B.3.
- B.3: It is attached to the forearm. It has a gear complementary to the one of B.2 and an arch that surrounds it to keep the gears from distancing.
- B.4: It is coupled to the forearm and to B.3. It consists of an arch that holds B.2 aligned with B.3 as the rotation takes place. A screw also keeps the end of B.2 against B.4 through an arched opening in the latter.

The rotation of the forearm is controlled by an EMG signal coming from the contraction of the forearm muscles as the hand is closed. Similarly to the first joint mechanism, one contraction rotates the arm in one way and a second one reverts the movement. When a signal is received, the servomotor rotates its external cylinder. The movement is transmitted to the complementary part, which is attached to B.2. As B.2 starts to rotate, the movement is transmitted through the gear interaction to B.3. B.4 also rotates since it is attached to B.3. Finally, the rotation movement is transmitted to the forearm by B.3 and B.4. The arches of B.3 and B.4 hold the mechanism in place, avoiding B.2 and the B.3 from distancing due to the curvature of the forearm. The arches also limit the possible angle of rotation.

The last piece of the orthosis is a surface where the electronics are attached, also by using velcro straps. The piece is coupled to A.

3. Electronic components

The orthosis movements are controlled using EMG signals coming from the contraction of the forearm muscles and the biceps. Three main electronic components take part in this action, a diagram of which can be seen in Figure 3.

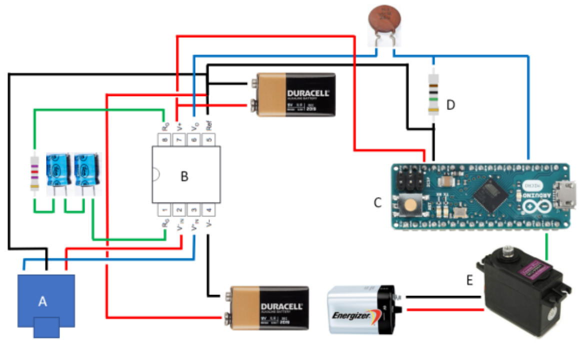

Figure 3. *Diagram of the orthosis electronic components. Composed of: A-EMG jack, B-instrumentation amplifier INA128P, C-Arduino Micro, D-gain resistor R_G, E-servomotor. Note that, for clarity purposes, only one EMG amplifier circuit and one servomotor have been represented.*

The first one is a pair of EMG amplifiers. They pick up the EMG signal using surface electrodes (two per muscle group and one for reference) whose disposition is shown in Figure 4.

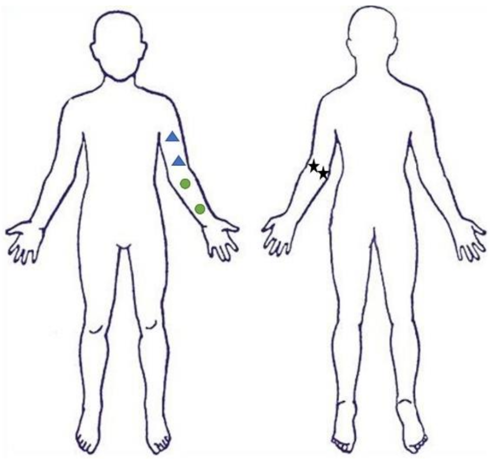

Figure 4. *Diagram representing the disposition of the surface electrodes of the arm (blue triangles) and the forearm (green circles). Each pair has a corresponding ground electrode placed on the elbow (black stars).*

The signal enters the circuit through an audio jack and is sent to an instrumentation amplifier. The signal is filtered and amplified with a gain G expressed in (1). The value of R_G has been selected according to the value of the signal recorded, so that each muscle group produced signals whose values where clearly differentiated.

$$G = \frac{5*10^4}{R_G} + 1 \qquad (1)$$

The next one is an Arduino Micro microcontroller. It is responsible for receiving the amplified EMG signals and, if they surpass a certain threshold, activating the servomotors to perform the movement.

The last component is a pair of servomotors which carry out the motions of the arm.

The forearm muscles and the biceps are functionally related, so the contraction of one also activates the other. This could cause a problem, making both servomotors work simultaneously when only one was targeted. In order to avoid this, different values of R_G have been chosen for each EMG amplifier, so that the two thresholds to surpass are clearly separated.

To check that the system works correctly, ten series of five contractions have been recorded for each muscle group, five series measuring the signal when the contraction is intended and five, when the contraction is a result of the other muscle group activation. That is, a series of intended contractions of the forearm was performed and the signals obtained from the forearm (voluntary contractions) and from the biceps (involuntary contractions) were recorded. The process was repeated but contracting the biceps voluntarily and the forearm, involuntarily. The top five measurements have been selected for each series, resulting in the top twenty-five values which represent the maximum contraction values for voluntary and involuntary contractions. The mean of these twenty-five measurements has been obtained and compared. This test was carried out by a single healthy user. The results can be seen in Table 1.

Signal	Top 25 values mean
Voluntary forearm	180.6
Involuntary forearm	63.28
Voluntary biceps	386.16
Involuntary biceps	265

Table 1. *Results from the comparison of the top mean signals obtained when a voluntary and involuntary contraction of each muscle group is recorded.*

We can see that there is a noticeable difference between the values of an active and a passive contraction of each muscle group. Since the forearm contraction is exerted by pressing the hand, the use of a force sensitive resistor located in the palm was considered. However, after seeing that the EMG signal would suffice, this possibility was dismissed.

The previous procedure has been implemented in an algorithm and is performed every time the user turns on the orthosis as a setup step. The only difference is that, instead of five series of five contractions for each type of contraction (voluntary and involuntary), only one series of five contractions is recorded. This has been done to speed up the process. This way, the threshold values are automatically adapted to the user in question and the particular disposition of the electrodes, which may change between sessions.

The flexion/extension of the arm and the pronation/supination of the forearm are performed completely once a valid signal is read. That is, the orthosis will conduct the whole movement from the starting to the end position with the need of only one contraction and will hold the final position. One contraction will result in one motion and another, in its opposed one. This is done in order to avoid having to maintain the muscle contracted throughout all the movement, allowing the patient to relax and not to fatigue when the orthosis is flexed.

4. Results

The device has been tested in three healthy male subjects (19, 22 and 53 years of age) with similar arm lengths. Each subject was required to perform four voluntary contractions of each muscle group. The three patients were able to use the orthosis correctly, interacting with the targeted servomotor without activating the other one.

Curiously, the rotation of the forearm worked better in the two younger subjects whereas the behaviour of the elbow joint did not change between participants. That is, the orthosis had some difficulty carrying out the pronation/supination of the forearm of the older subject when compared to the other two. This is due to the fact that the forearm of the older subject is considerably thicker in its section closest to the elbow than those of the younger subjects. Because of this, piece B.1 is placed higher in relation to B.3 and B.4, resulting in strain upon B.2 and affecting in the interaction of the gears. This can be solved by adjusting the height of B.3's gear and B.4 arch. Since the structure of the whole orthosis is 3D printed and must be adapted to the particular length of the upper limb of each patient, this modifications in B.3 and B.4 can easily be taken into account to avoid this issue.

5. Conclusions

The objective of the project has been fulfilled. The previous orthosis model has been improved by the addition of a completely new rotation mechanism that allows for the pronation and supination of the forearm.

The new mechanism is controlled using EMG signals and it has been tested that it can be used simultaneously with the other joint mechanism, without both signals interfering with each other. An image of the final result can be seen in Figure 5.

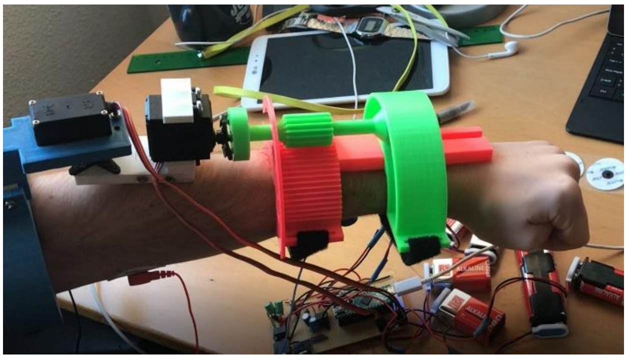

Figure 5. *Photograph of the new rotation movement taken during one of the tests*

Also, a new algorithm to obtain valid threshold values has been developed. These values, which need to be surpassed in order to carry out a movement, vary from patient to patient and between different electrode dispositions. Their automatic computation provides a fast setup process and avoids having to perform additional configuration with a computer each time the device is used.

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6. Future works

As future work, more improvements in the orthosis can be made. The fittings of piece A can be made adjustable, so they can be placed at different positions of the piece, allowing for more comfort for the patient.

It may also be interesting to replace the servomotors by conventional motors, since servomotors have a limited angle of rotation (up to 180º) and the forearm rotation could benefit of some more.

Finally, more joint mechanism can be added to extend the functionality of the orthosis. Specially interesting would be the addition of one more degree of freedom in the wrist, allowing for its flexion and extension or radial and ulnar deviation.

The 3D model, Arduino code, electronic diagrams and the rest of the materials are all available for anyone interested to access in a GitHub repository [7].

Acknowledgements

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