Bioinspired Mechanical Design of an Upper Limb Exoskeleton for Rehabilitation and Motor Control Assessment

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Abstract—Robotic rehabilitation is a field that experienced a rapid expansion in the last decades due to two main reasons. First, due to the growth of population with rehabilitation needs such as stroke survivors, and two, due to the technological advances allowing the implementation of robotic devices in the clinical practice. These robotic rehabilitation devices can be broadly classified in two groups: the end-effector robots and the exoskeletons. Regarding the latter, it is important to note that the coupling with the human body demands a high safety factor. If the exoskeleton tries to impose kinematic or dynamic configurations that are not compatible with the human body, it may cause injury to the user. This issue is more critical in motor rehabilitation as the patients could show muscle weakness. In this context, this manuscript presents a bioinspired upper limb robotic exoskeleton, aiming to optimize the dynamic compatibility with the human arm. With this approach, it is expected that safety is intrinsic to the exoskeleton mechanism.

I. INTRODUCTION

In the recent years the number of people suffering from motor disabilities has increased due to several factors, such as the ageing population. The Cerebral Vascular Accidents (CVAs), often called “strokes”, are considered the main cause of motor disability in the population of developed countries. Only in United States of America and Europe the incidence of CVA is about 180 and 120 occurrences for each 100 thousand habitants, respectively [1]. In Brazil, recent studies from IBGE (Brazilian Institute of Geographic and Statistics), showed that CVA is responsible for 8% of the admissions with 19% of the total costs from public hospitals [2].

Another frequent motor disability is due to Spinal Cord Injury. It is estimated that in Brazil, the population with Spinal Cord Injury (SCI) can reach the number of 130 thousand of people and this number increases of 11 thousand every year. The majority of these people are between 16 and 30 years old [3].

It must also be noted the Cerebral Palsy (CP) that is a congenital brain injury with non-progressive disorder of posture and movement. It may cause neuromuscular disorders such as spasticity and changes in muscle tone and stiffness. In the U. S., the incidence of CP has varied between 1.5 and 5.9 per thousand of live births. In Brazil, it is estimated that in 1000 born children, 5 to 7 has CP [4]. This condition affects the patient for life.

The techniques used for the rehabilitation of patients with neuromotor disabilities, specially in the case of CVA recovery, are based on repetitive mechanical exercises [5], [6]. Such exercises can be performed passively or actively by the patient. In the passive exercises, the therapist moves the affected limb in order to perform certain movements with little active motor intervention of the patient. In the active exercises, the patient starts the motion and, if necessary, the therapist helps the patient to complete the task [5]. Whereas the rehabilitation progress is directly related to quality and intensive training, the use of robotic exoskeletons on this kind of therapy provides good results for cases of CVA recovery [7], [8]. This is due to the fact that exoskeletons (i) allows repetitive and accurate movements execution and (ii) measures the forces involved in the therapeutic exercises.

In this context, robotic rehabilitation emerges as a multidisciplinary field that aims at developing platforms that operates in parallel to human limbs, enabling the application of specific therapy to patients with neuromotor disabilities. There are many proposed rehabilitation exoskeletons in literature, for both upper limb [9], [10], [11] and lower limb [12], [13]. There are two basic approaches concerning robotic rehabilitation: end-effector therapy, like MIT-Manus robot [14] and exoskeleton therapy, like L-Exo [15] and Armin [16] and motor control [17].

Because of the strong coupling between human limb and exoskeleton, special attention should be given to user safety. In order to have the exoskeleton cooperating efficiently with users and to avoid any conflict between human and machine movements, different control strategies have been proposed, such as impedance control, [18], [19] or fictitious gain [20]. However, it is expected that if the exoskeleton kinematic and dynamic behavior resembles that of the human, the interaction will be achieved more effectively. This is expected to increase rehabilitation exoskeletons reliability.

Based on previous works applying bioinspired approaches to develop exoskeleton systems, such as the NEUROExos actuator [21], we propose a bioinspired mechanical design to achieve kinematic and dynamic compatibility between biological and artificial systems. This paper presents the construction of a bioinspired exoskeleton that provides elbow flexion-extension as proof of concept of this approach.

In Section II a review of the biological actuation solution is presented as a previous step of the design presented in Section III. In Section IV the preliminary results are presented and discussed in the following section (Section V). The final sections, VI and VII deal, respectively, with the Future Work and Conclusions.
II. BIOINSPIRED APPROACH

In order to apply this bioinspired approach, the geometric principles of muscle force transmission will be reviewed before analyzing the advantages of this biomimetic approach.

A. Muscle Review

The muscle configuration is an important factor that defines the generation of human motion. First of all, it must be noted that muscle motion occurs only in contraction. Therefore, the movement in one direction, caused by a muscle contraction, must be compensated with an opposing contraction. This is why in each joint there are agonist-antagonist pairs of muscles. While one muscle flexes the joint, as the biceps brachii flexes the elbow, the antagonist extends it, as the triceps brachii would extend the elbow [22].

It is also well-known the maximal active muscle tension is a non-linear function of the length. However, the passive length-tension relation is linear and is simulated as a spring. The muscle also shows a velocity-tension relation during contraction, as velocity increases the tension decreases and there is an optimal muscle velocity contraction in terms of power generation [22].

Muscles generate rotational motion around a joint by active contraction, therefore the location of muscle attachments to the bone are very important to determine the joint dynamics. If the muscle has its proximal origin far from the joint but inserted close to the joint, thus having short moment arms, this implies that the contraction would cause a fast joint rotation with a low torque and it is called a spurt muscle. If, on the contrary, the origin is close to the joint but the insertion far from it, the muscle is a shunt one and it can produce larger moments at the expense of a slower rotation [22].

![Fig. 1. Schematic configuration of the elbow flexor. The graphs (right) were generated with a constant muscle tension of 1 N, for the complete range of motion of the elbow. The parameters a (a=0.2925) and b (b=0.0675) are, respectively, the distances from the elbow joint to the muscle proximal and distal insertion points [23]. The muscle length is \( \lambda_m \) and \( r \) is the muscle moment arm.](image)

B. Bioinspired Model

Any exoskeleton will operate in parallel to the human members. Invariably, acting in parallel means some level of conflict. These two complex systems find different solutions to perform the same task. Moreover, the intrinsic redundancy of the human arm – modeled as a linkage system with seven degrees of freedom in a three-dimensional space [24]. If there are points of attachments among them, one solution will interfere with the other. In this way, it is possible to see the human-exoskeleton ensemble as a parallel system. In order to avoid a dangerous lock-in kinematic configuration, it is necessary that the two solutions are mutually consistent. In other words, they must have a cooperative behavior. There are, in this case, two options: (i) the human limb adapts to the robot by a controller (the nervous system), or (ii) the robot adapts to the human limb.

It has been chosen in this work to focus on the latter options rather than the first one. One way to accomplish this is using a robot with an arbitrary dynamics and develop a specific controller that generates the desired behavior. This approach places more effort in the controller than in the mechanical design. However, it is possible to increase the mechanical complexity in order to simplify the controller. In fact, an exoskeleton with arbitrary kinematic design will not necessarily behave like a human elbow in response to a step excitation input. Thus, it will be the responsibility of the controller to implement a human-like behavior on the exoskeleton. On other hand, if the exoskeleton mechanical design is oriented to achieve the human elbow kinematics, then a simple step excitation in the controller will be sufficient to generate an elbow-like behaviour. This is the simplification expected for the controller with this bioinspired approach.

Therefore, this approach aims at designing a robot with human-like kinematics and dynamics in order to reduce controller effort and computational cost while improving human-user interaction and safety.

For this bioinspired approach implementation, it has been chosen the elbow joint and its major muscles, i.e. biceps brachii and triceps brachii. Although the elbow is not a pure hinge joint [25], it can be modelled as a 1 DoF revolution joint. Therefore, the bioinspired model it is a 2D system. As explained in II-A, the pair agonist-antagonist is needed to provide rotation of joint in both flexion and extension directions. Yet, in order to minimize the exoskeleton weight, it has been chosen to use a motion driver capable to performance both flexion and extension movements.

III. EXOSKELETON DESIGN

A. Conceptual Design

The proposed upper limb exoskeleton is modeled as a planar mechanism, as shown in figure 2. The rotational joint motion in the elbow is applied by the muscle shortening. Analogously, in the exoskeleton, that uses conventional DC motors, a screw changes the length of the bar and provides the rotational motion. The screw is represented by its bearings and motor. The bars \( OP \) and \( OQ \) represent the exoskeleton forearm and arm, respectively. The distance \( b \) is fixed and represents the insertion point of the artificial muscle in the robot forearm. The rigid bar \( e \) represents the robotic muscle and the distance \( c + L_f \) represents the
insertion point in the exoskeleton arm. As commercial off-the-shelf components have been used, motion system became too heavy to mimic the muscle and its length variation. To deal with this, we selected the muscle length to be fixed and the muscle insertion in arm to be variable.

Thus, as the motor rotates the screw, it moves the nut and varies the insertion point of the bar. This change is due to the \( e \) bar stiffness and it drives the flexion-extension elbow movement.

For the mathematical modeling, it is assumed that the mechanism is a triangle in which the side \( c + L_f \) is variable and it causes the angle \( \theta \) variation. Using the law of cosines and solving for \( L_f \), it is possible to obtain the expression that relates the variation of \( L_f \) as function of \( \theta \) (equation 1).

\[
L_f = b \cdot \cos(\theta) + \sqrt{e^2 - b^2 \cdot \sin^2(\theta)} - c
\]  

(1)

Analyzing equation 1 it can be seen that when \( b \to 0 \), \( c + L_f \to e \). Besides that, when \( \theta \) ranges from \( 0^\circ \) to \( 180^\circ \), \( L_f \in [0, 2b] \). As \( b \to 0 \), then \( L_f \to 0 \) and therefore \( c \to e \). This configuration is illustrated in figure 3. This means that it is possible to obtain a wide range angle of flexion-extension with a small variation in muscle length. This represents a high mechanical gain with a low volume cost. A similar result is found in the study of human anatomy (spurt muscle), indicating a good proximity between artificial and biological models (see also figure 1).

Equation 2 is obtained by torque balance with respect to elbow (\( E_o \)).

\[
F^y_e = -\frac{P \cdot (L + b)}{b}
\]

(2)

It is possible to observe that when \( b \to 0 \), \( F^y_e \to \infty \). In other words, the required muscle force for a small \( b \) will be too high to be bore by any embedded mechanical actuator. Therefore, to obtain a drive system with high mechanical gain and low volume, it should be able to bear high loads. As the drive system has a low volume, it becomes feasible from a geometrical point of view to distribute the load between different drive systems operating in parallel.

B. Exoskeleton Design

Figure 5 shows the CAD project of the exoskeleton developed. The recirculating ball screw emulates the length variation of the muscle by modifying the insertion point in the robotic arm. It also acts as a mechanical gear with a reduction depending on the screw step.

Static analysis of mechanism also show certain similarities with the human actuation system. The figure 4 illustrates a simplified analysis of an exoskeleton static condition. \( P \) represents the load on the robot effector while the force \( F^y_e \) is the vertical component of the artificial muscle force responsible for the torque generated on the robotic elbow.

The bar that connects the nut from the screw to the robotic forearm is rigid, so it can transmit both flexion and extension movements. This makes the use of agonist/antagonist pairs unnecessary, resulting in a lighter exoskeleton. The absence of this pair simplifies the exoskeleton design and reduces its mass, but decreases the exoskeleton flexibility related to the control of joint stiffness. The importance of this issue is
illustrated in the table I that shows the maximum elbow joint torques obtained from an isokinetic study [26].

<table>
<thead>
<tr>
<th></th>
<th>Flexion</th>
<th>Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female Average</td>
<td>31.9</td>
<td>25.0</td>
</tr>
<tr>
<td>Male Average</td>
<td>79.5</td>
<td>60.5</td>
</tr>
<tr>
<td>Overall Average</td>
<td>55.7</td>
<td>42.8</td>
</tr>
</tbody>
</table>

IV. RESULTS

An elbow exoskeleton was built with one actuated degree of freedom, the elbow flexion-extension. The robotic elbow joint is actuated by a conventional DC brushed motor moving a bar mimicking a muscle. As it was not possible to control directly the bar length, a linear screw, coupled with a motor reduction spindle, moved the artificial muscle attached to the upper arm, providing the angular movement. The figure 6 illustrates the prototype built.

The goal of this prototype was to evaluate the advantages of this bioinspired design approach. More specifically, the actuation coupling is inspired in the muscle action transforming the linear motion from muscle contraction into joint flexion. It must be noted that, instead of following the bioinspired approach to implement the joint extension and implement an antagonist muscle, the same actuator system can be reversed to obtain joint extension.

The exoskeleton structure was built in aluminum in order to reduce the weight. It was chosen a 83 watt DC brushed motor (Faulhaber 357G012CR). Although it was kept in mind that the exoskeleton mass should be reduced, several parts, such as the bearings and the spindle were not optimized in this part of the project. As they are off-the-shelf components, commonly used in manufacturing CNC machines, their mechanical resistance is much larger than the load applied in the exoskeleton, thus increasing significantly the total mass of the system. Table II presents all the technical data relative to the exoskeleton built.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Torque</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 W</td>
<td>14 a 54 Nm</td>
<td>112 a 38 °/s</td>
</tr>
<tr>
<td>Mean Torque</td>
<td>45 Nm</td>
<td>48 °/s</td>
<td></td>
</tr>
<tr>
<td>Mean Speed</td>
<td>38,7 W</td>
<td>2,895 kg</td>
<td></td>
</tr>
</tbody>
</table>

From the mathematical modeling of the powertrain system, it was possible to obtain the torque curve related to the elbow joint angle during the flexion-extension movement. Figure 8 illustrates the torque curve obtained.

Fig. 7. Exoskeleton torque curve related to the elbow relative angle (in degrees).

There are experimental studies showing the isometric force of elbow flexors muscle versus elbow relative angle during an exercise of flexion-extension. This curve has approximately a parabolic shape, as shown on figure 8. Consequently, the torque-angle curve in human elbow has the same parabolic shape.

It is important to notice some aspects of the mechanical interface between the user arm and the exoskeleton. The braces that attach the exoskeleton to the arm should not be totally rigid nor have a small contact area. In order to achieve a good compromise between mass and rigidity the brace supports were custom-made of carbon fiber and EVA foam was fixed inside of the brace to provide more comfort to the user. The figure 6 illustrates the brace built.

V. DISCUSSION

As it is shown on figure 7, the angle-torque curve of the exoskeleton has a parabolic shape, due to the mechanism
geometry. The experimental torque curve of the human elbow has a similar parabolic shape, as shown on figure 8. Nevertheless, the geometrical parameters of the exoskeleton could be refined further to improve the matching with the human angle-torque curve. This means that it is possible to implement a simple position control on the exoskeleton actuator and the resulting torque applied on exoskeleton elbow joint will have the same parabolic shape as seen in human articulations. Therefore, it is expected that both artificial and natural systems have similar kinematic behavior. This would be helpful to avoid conflicts between them and make easier to use the exoskeleton during the execution of basic tasks. Another benefit of the proposed design is that a simpler control loop could be implemented, reducing the computational cost and relaxing the requirements of the processor. Nevertheless, it is still possible to apply any other control strategy to implement some desired torque curve. Finally, it must be highlighted that the torque and velocity properties of the exoskeleton prototype are compatible with the values found in the human elbow joint. Therefore, using a bioinspired approach, it was possible to design and build a mechanism showing an elbow-like kinematic behavior.

VI. FUTURE WORK

In the coming months it is planned to implement control architectures with different levels of complexity and assess the training time required to use the exoskeleton. Tests will be carried out to establish the real isometric torque curve of the robotic device. Furthermore, it is also intended to evaluate how the human motor control adapts to the exoskeleton by measuring signals of electromyography (EMG) during tests with healthy subjects. It is expected that this work provides ideas for new exoskeleton design strategies in order to make these devices more adapted to humans.

VII. CONCLUSION

In this article, the bioinspired project of a robotic exoskeleton for the human elbow joint was presented. In order to achieve this goal, the macroscopic muscle functionality and the musculo-skeletal geometry of the joint were adapted by a linear actuator. As both robotic and human systems curves have a similar parabolic shape the driving system based on the ball screw reduction is a biomimetic idea that mimics the behavior of some arm muscles, such as the the biceps brachii and brachioradialis.

The exoskeleton based on bioinspired design showed a behavior that resemble some of the human motor properties, such as the angle-torque curve presented in figure 7. It is currently under evaluation if the user learns to control this device faster and in a more precise way with this design approach.

Finally, during the exoskeleton design, it was realized that it is far from easy to obtain an artificial system equivalent to the biological system in terms of torque and mass because the design has to be adapted to the available technology.

VIII. ACKNOWLEDGMENTS

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REFERENCES


