Towards Articulated Soft Robots for Bionic Upper Limbs

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Abstract—**Thanks to the inherent elasticity in their musculoskeletal system, vertebrate animals can modulate the impedance of their joints to enhance their interactions with the environment and to perform high dynamic tasks such as throwing, jumping, or running. Implementing these characteristics inside the prostheses seems a promising approach to improve their capacities. Up to now, there are very few devices for upper limb prostheses that have an inherent and controllable elasticity.**

In this paper, we discuss different approaches to design bionic upper limbs with a controllable elasticity, highlighting their strengths and challenges. In addition, we present a mechanical implementation of an articulated soft elbow joint that has a static behavior similar to a human joint. This joint serves as a basis to investigate the use of user-controllable elasticity in bionic upper limbs.

Index Terms—**articulated soft robots, upper limb, prostheses, variable stiffness**

Fig. 1. Each human joint is activated by at least two muscles. Human beings control their impedance through posture and co-contraction. The picture shows the musculoskeletal scheme of the elbow joint (left) and the mechanical implementation (right) of the articulated soft elbow prosthetic joint presented in this work.

I. Introduction

Taking advantage of our musculoskeletal system, we modulate the impedance of our joints to interact safely, robustly, and proficiently with the surrounding environment. Each human joint is controlled by at least two antagonistic muscles. To modulate the impedance, in particular the stiffness of our joints, we can either co-contract the pair of antagonistic muscles or we can modify the position of our limb [1]. These observations inspired the design of articulated soft robots that can thus interact more safely and robustly with their environment [2]. In the last years, Variable Impedance Actuators and the subgroups of Variable Stiffness Actuators (VSAs) received increase attention from the researchers [3]. It seems straightforward to use them as prostheses [4]. However, many challenges need to be solved before such new bionic upper limbs could be available for prosthetic users.

First challenges arise from the control of this new type of actuators that combines both motion and impedance controls. The simplest natural way to control them is to map the co-contraction of a single pair of antagonistic muscles to the impedance and the difference of their activation to the motion such as suggested in [4], [5]. However, this strategy relies on the accurate acquisition and decoding of muscle activations [5]. While improving these sensing technologies, researchers are also going one step further investigating the extraction of neural information from the muscle activity [6]. This paves the way for more complex control strategies for a multi degree-of-freedom (DoF) upper limb prostheses. Using this new data and the motor control theories combining the equilibrium point hypothesis and the motor synergies, we could develop a natural and effective way to control upper limb prostheses [7].

Besides the control strategies, the utility and effectiveness of having impedance control for upper limb prostheses are under investigation. In 2008, Sensinger *et al.* found that for precision positioning tasks users did not voluntarily modulate the impedance of the prosthetic joint if it was around a high impedance level. They concluded that having a proportional control of the impedance is not suitable for prostheses and that an alternative could be to allow the user to select a predefined impedance level [5]. More recently, Blank *et al.* stated that the preferred impedance level could be task-dependent [8]. This result is in line with at least the implementation of several and selectable impedance levels in prostheses. Combining this result with the innovations on the control previously mentioned, it seems to possible to aim to design and use a bionic upper limb with variable impedance control as human beings do.

From these aspects arise the challenges on the mechatronic design of variable impedance upper limb prostheses. One particular point with two facets motivates the following work. How to implement the compliance and the variable stiffness ability of human joints in prosthetic devices? In this work, we discuss and present one approach to this challenge applied to the design of a prosthetic elbow joint (see Fig. 1). The first section presents the selected approach and the second one describes the mechanical implementation.

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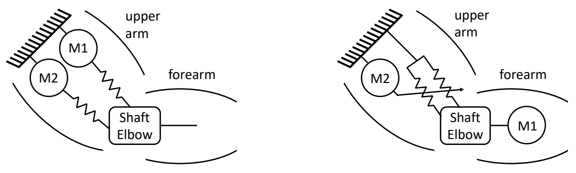

(a) (b)

Fig. 2. Possible prosthetic architectures of various VSA configurations: (a) for antagonistic configuration and (b) for the proposed distributed ESV configuration (independent configuration).

II. Mechatronic Design

A. Impedance control strategy

To have a user-controllable elasticity, a first approach is to modulate the stiffness behavior of the device only through software control [3]. This approach allows the design of lightweight devices which can emulate any desired stiffness behavior. However, the compliant behavior of such systems during impact is restricted as the controller may not be fast enough to react [9]. To tackle these limitations, VSAs are developed with an inherent compliance. The variable stiffness ability is then made through a mechanical reconfiguration of the system [3]. This strategy increases the safety and robustness with respect to stiff actuators and may have better performances in case of cyclic or explosive tasks [2].

One constraint of VSAs is that one mechanical implementation is one embedded passive behavior. An appealing goal is to match the passive behavior of a human joint. However, the mechanical complexity of the system should fit the design requirements for a prosthesis that should be ideally as compact and lightweight as possible while being able to do ADL.

B. Proposed approach

There are several types of requirements to design a variable stiffness (VS) elbow joint with human-like passive behavior. First, it should have anthropomorphic dimensions in terms of size, mass, and shape. Then, its performance should be enough to do ADL. Finally, its passive static behavior should be similar to the human one. It means that under an external load the system should behave like a human joint. Concretely, using the human muscle model in [10] and assuming that the elbow can be considered as driven by a single of antagonistic muscles, its output torque function can be approximated as

$$\tau = R(\rho_1(e^{\gamma A_1} - 1) - \rho_2(e^{\gamma A_2} - 1)), \quad (1)$$

where R represents the instantaneous lever arm, (ρ_1, ρ_2) magnitude parameters specific to each muscle, γ a form parameter common to all muscles and (A_1, A_2) the specific muscle activations (the reader is invited to refer to [10] for more details on this model).

Adjusting the stiffness of one DoF joint through a mechanical reconfiguration requires two motors. The first arrangement of these two motors is directly inspired by the musculoskeletal system. It consists of two serial arrangements of one motor and one elastic element which are placed antagonistically on each part of the joint. When the two motors move in the same direction, we can control the motion of the joint, and when they move on opposite directions, we can control its stiffness like the co-contraction of human beings. A possible architecture of this setup is shown Fig. 2a. This layout can have a compact design. Yet its shape is more complex and may have difficulties to fit in a small volume as both motors (M1 and M2) should be located on the same side of the joint. Alternative works rely on the independent setup where one motor is dedicated to the control of the motion (M1) and one is dedicated to the modulation of the stiffness (M2). When the control of the motion and the stiffness are completely decoupled in absence of any external load, this setup is called Explicit Stiffness Variation (ESV) configuration. This layout gives the possibility to distribute the actuation units around the joint. As the primary focus of our applied prototype was on the anthropomorphism and behavior of the system, we selected this approach. Its simplified architecture is shown Fig. 2b. The reader is invited to refer to [3] and [11] for extended explanations on the principle and mechanical designs of VSAs.

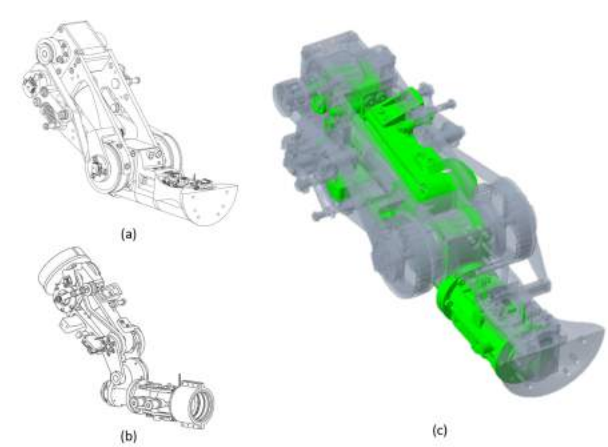

Fig. 3. Mechanical design in 3D view of (a) first version, (b) the mechanical optimization, and (c) the superposition of the two to highlight the improvements (the first version is in grey and the new version in green).

In addition, to ensure the bi-directionality of the compliance of the joint, we proposed an antagonistic arrangement of the elastic elements. And to reduce the power consumption of the device, we implemented locking devices within both actuation units. Moreover, these devices are protecting the motors during interactions with the environment as they cancel the static load [12]. Therefore, the selected approach used in the following part is based on the design of a VSA with nonreversible actuation and antagonistic elastic elements.

III. VS Elbow: Distributed Mass and Natural Behavior

Based on the approach described in the previous section, we design a variable stiffness elbow joint with anthropomorphic dimensions, a distributed mass around the joint, and a passive behavior analogous to the human elbow joint driven by a single pair of antagonistic muscles.

TABLE I
DEVICE DATASHEET OF THE FIRST PROTOTYPE

#	Description	Value
1	overall volume	500 cm3
2	overall weight	1.775 kg
7	active rotation angle	-25°to 155°
8	peak torque	15 Nm
9	maximum stiffness	390 Nm/rad
10	minimum stiffness	1.4 Nm/rad
11	maximum speed	101°/s

The first version of the system is extensively described and characterized in [13]. The main dimensions and performances of the system are given TABLE I. These data are in the range of anthropomorphic data[1] or in the order of existing devices. The reader is invited to refer to [13] for more details.

In addition, to reduce the mass and volume occupied by the mechanism, we are developing an optimized version of the system using the same principle of work described hereafter. We expect the mass of the second prototype to be 55% of the mass of the first version (so around 1 kg) and its volume to be 60 % of the previous version.

Fig. 3 shows the designs of the two versions and highlights the improvements of the mechanical optimization.

A. Principle of work

In each version, the system can be divided into two parts such as shown Fig. 2: the position unit (PU) located in the forearm (M1) and the variable stiffness unit (VSU) located in the upper arm.

The PU is composed of a nonbackdrivable motor/gears assembly. The nonbackdrivability is ensured by a worm/gear system. It can rotate around the elbow shaft and control the equilibrium position of the elbow joint.

The VSU is composed of a similar nonbackdrivable motor-gears assembly and a nonlinear elastic transmission. This elastic transmission consists in belts between two pulleys tensioned by linear traction springs. One pulley is rigidly linked to the motor M2 and the other one is the elbow shaft. To adjust the stiffness, the available length of the belt is modulated by wrapping more or less the belt around the pulley on the motor side. If the belt is straight, then the elbow is rigid. Please refer to [13] for more details on the mechanical implementation.

B. Static behavior

Based on the characterization done in [13], the output torque model of the proposed system is as

$$\tau_{out} = \lambda_1 e^{-\alpha_1 q_{M2}}(e^{\mu\delta} - 1) - \lambda_2 e^{-\alpha_2 q_{M2}}(e^{-\mu\delta} - 1), \quad (2)$$

where q_{M2} stands for the position of the stiffness motor and δ stands for the deflexion of the elbow joint with respect to its equilibrium position. λ_1, λ_2, α_1, α_2 and μ are the coefficients of the model.

[1]https://msis.jsc.nasa.gov/volume1.htm

This model is similar to the human model described in (1). The products $\lambda_i e^{-\alpha_i q_{M2}}$ are analogous to the magnitude parameters ρ_i of each muscle and μ to γ as δ can be seen as the activation of the elastic elements.

IV. CONCLUSION

In this paper, we discussed a new approach to design upper limb prosthetic joints based on articulated soft robots, and more specifically VSAs. We illustrate this approach with a variable stiffness elbow joint that has a passive static behavior similar to a human musculoskeletal model.

Taking advantage of the inherent and user-controllable elasticity, this type of joints could outperform the rigid existing prosthetic joints in highly dynamic tasks and increase their range of possible achievable tasks.

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