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A new bio-inspired joint with variable stiffness

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Abstract. This paper addresses stiffness modulation and antagonistic actuation in light-weight tendon-driven bio-inspired manipulators suitable for safe interactions. Designing manipulators with variable stiffness is of great interest in human-robot collaboration tasks. Remote actuation with tendons allows inertia reduction and, if the tendons are properly routed, makes it possible to tune joint stiffness. The way in which the tendons are connected to the bodies for their actuation requires attention. Pulleys are often used to ensure a constant lever arm. However this approach does not allow antagonistic forces to change the joint stiffness. The condition for allowing an increase in stiffness via an increase in antagonistic forces is established. Then this condition is used to propose a new bio-inspired variable-stiffness joint.

Keywords: antagonist actuation, stiffness, tendon driven manipulator, pulley

1 Introduction

The scope of this work is the design of bio-inspired collaborative robots suitable for safe interactions, i.e. allowing joint stiffness modulation. Biological organs constitute interesting models of inspiration for the roboticist. Indeed, they propose frugal solutions both in matter and energy. To mimick the joint between two animal vertebrae, the simplest mechanism is a revolute joint but, if the center of rotation is not fixed like in the knee joint [1], an anti-parallelogram mechanism would be more appropriate. Biological joints are actuated by antagonistic muscles. Most of the time, two antagonistic muscles work in opposite ways: when one contracts, the other relaxes, so that energy consumption is minimized [2]. However, simultaneous activation of antagonistic muscles may occur for a short time. This so-called *coactivation* principle aims to increase the stiffness of the joint [2]. Moreover, energy consumption should be minimized and one should be able to increase joint stiffness when needed. Variable stiffness actuators (VSA) have been developed to allow for joint stiffness modulation in applications involving interactions, such as in robots and biped [3]. Stiffness modulation in VSA can be achieved through software or hardware. Several different hardware implementations of VSA have been proposed with appropriate spring arrangement and properties [4-6] or by changing transmission angle with cams [7]. Other

solutions use antagonistic cable actuation together with springs [8]. In such solutions, several pulleys are needed and stiffness modulation uses rather complex solutions.

In this paper, a simple solution is proposed to allow for stiffness modulation in tendon-actuated joints. This solution uses a elliptical pulley. This rest of this paper is organized in two parts. Section 2 studies and compares coactivation of antagonistic forces in a circular pulley and in a X-joints. The proposed solution, called E-pulley, is proposed in section 3. Section 4 concludes this paper.

2 Joints actuated by antagonist tendons

In biological systems, the joints are often modeled with revolute joints actuated by antagonistic tendons and/or muscles [9]. However, it was shown recently that stiffness decreases when antagonistic tendon forces increase in simple revolute joints [10]. When designing tendon-driven joints, the attachment points of the tendons must be defined carefully to avoid singularities when the tendon line crosses the joint. Accordingly, tendons can be attached via pulleys. Not only this solution avoids singularities but it also produces a constant lever arm and it mimics bones swelling at their extremities [11].

Some biological joints such as the knee joint [1] or intervertebrae joints in the bird neck [12] can be modeled by crossed four-bar joints or *X-joints*. On the other hand, we observed that the knee and ankle joints can be modelled as pulleys, with antagonistic muscles being used to modulate stiffness. Measurements on the bones suggest that the pulleys may not be circular. In the work presented here, we compare the coactivation of X-joint solutions with circular and elliptical pulleys, which could be found in the osteo-muscular system of birds.

We first compare the two joints actuated with antagonistic tendons shown in Fig. 1: the P-module (for pulley) on the left and the X-module (for anti-parallelogram joint) on the right. The P-module (resp. the X-module) is defined by parameter R (resp. b and L). The moving link is attached to the pulley or to the upper bar of the anti-parallelogram.

2.1 Joint stiffness

Let U be the potential energy of a module: $U = U_g + U_k + F_1 l_1 + F_2 l_2$, where U_g (resp. U_k) is the contribution of gravity (resp. of the springs if any), l_1 , l_2 are the cable lengths and F_1 , F_2 are the forces applied by the cables (see Fig. 1). The equilibrium condition of a module is $\frac{dU}{d\alpha} = 0$, that is:

$$G + \frac{dl_1}{d\alpha} F_1 + \frac{dl_2}{d\alpha} F_2 = 0 \quad (1)$$

where $G = \frac{dU_g}{d\alpha} + \frac{dU_k}{d\alpha}$. From fig. 1, it is apparent that $\frac{dl_1}{d\alpha} \leq 0$ and $\frac{dl_2}{d\alpha} \geq 0$ around $\alpha = 0$ (this will be detailed later). The equilibrium solution with minimal forces s.t. $0 \leq F_{min} \leq F_i \leq F_{max}$ is therefore obtained when one of the forces is at F_{min} . For simplicity, we take $F_{min} = 0$.

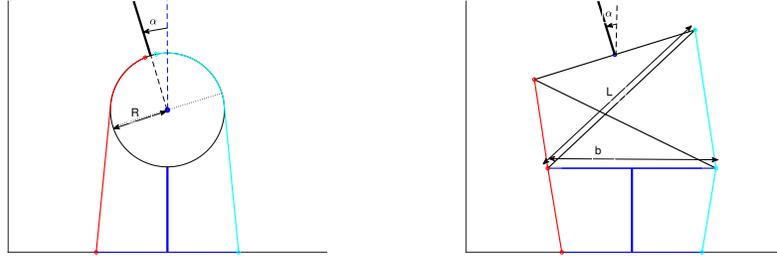


Fig. 1. Two possible ways to build a rotating joint actuated by antagonistic tendons: a P-module (left) and a X-module (right)

Suppose that we want to reach a desired configuration α^d such that $G(\alpha^d) < 0$. Then, the minimum force solution denoted by F^* is:

$$F_2^* = -\frac{G(\alpha^d)}{\frac{dl_2}{d\alpha}}, \quad F_1^* = 0 \quad (2)$$

Other solutions, which would involve coactivation, can be defined in terms of F_2 as follows:

$$F_2 = -\frac{G(\alpha^d) + \frac{dl_1}{d\alpha} F_1}{\frac{dl_2}{d\alpha}} = F_2^* - \frac{\frac{dl_1}{d\alpha}}{\frac{dl_2}{d\alpha}} F_1 \quad (3)$$

The joint stiffness, for given cable forces F_1, F_2 is defined by :

$$K = \frac{d^2U}{d\alpha^2} = \frac{dG}{d\alpha} + \frac{d^2l_1}{d\alpha^2} F_1 + \frac{d^2l_2}{d\alpha^2} F_2 \quad (4)$$

For the equilibrium with minimal forces, the stiffness is :

$$K^* = \frac{dG(\alpha^d)}{d\alpha} - \frac{\frac{d^2l_2}{d\alpha^2} G(\alpha^d)}{\frac{dl_2}{d\alpha}} \quad (5)$$

The impact of a non-zero force F_1 on the system stiffness is written using equation (4):

$$K = K^* + D_1 F_1 \quad (6)$$

with

$$D_1 = \left(\frac{\frac{d^2l_1}{d\alpha^2} \frac{dl_2}{d\alpha} - \frac{d^2l_2}{d\alpha^2} \frac{dl_1}{d\alpha}}{\frac{dl_2}{d\alpha}} \right) \quad (7)$$

To be able to change the joint stiffness by the antagonistic forces, when must have $D_1 \neq 0$. Finding a behavior similar to that observed in biological systems

implies that $D_1 > 0$ for values of α s.t. $G(\alpha^d) < 0$. Let C be the numerator of D_1 . Since $\frac{dl_2}{d\alpha} > 0$, this condition can be written:

$$C = \frac{d^2 l_1}{d\alpha^2} \frac{dl_2}{d\alpha} - \frac{d^2 l_2}{d\alpha^2} \frac{dl_1}{d\alpha} > 0 \quad (8)$$

A similar condition can be written for values of α s.t. $G(\alpha^d) > 0$. It can be shown that this leads to the same conditions (8).

2.2 Joint stiffness modulation for the P-module

For the P-module shown in Fig. 1, when the output rotates of an angle $\delta\alpha$, the length variation of the left tendon is obviously the length of an arc of circle of angle $\delta\alpha$, namely, $R\delta\alpha$. Note that the point of contact of the cable around the pulley does not move since it is defined by the point where the tendon is tangent to the pulley. The length variation of the left tendon is: $R\delta\alpha$.

Accordingly :

$$\frac{dl_1}{d\alpha} = R, \quad \frac{dl_2}{d\alpha} = -R, \quad \frac{d^2 l_1}{d\alpha^2} = \frac{d^2 l_2}{d\alpha^2} = 0, \quad C = 0 \quad (9)$$

This shows that stiffness modulation is not possible with a P-module and additional devices must be used, see [7] for example.

2.3 Joint stiffness modulation for the X-module

The cable lengths l_1, l_2 are:

$$l_1 = l_{10} + l - b \sin\left(\frac{\alpha}{2}\right), \quad l_2 = l_{20} + l + b \sin\left(\frac{\alpha}{2}\right) \quad (10)$$

where l_{10}, l_{20} are constant values, and l is the distance between the midpoints of bottom and top bars [12]:

$$l = \sqrt{L^2 - b^2 \cos^2\left(\frac{\alpha}{2}\right)} \quad (11)$$

Upon successive differentiations, we obtain:

$$\frac{dl_1}{d\alpha} = \frac{b^2 \cos\left(\frac{\alpha}{2}\right) \sin\left(\frac{\alpha}{2}\right)}{2\sqrt{L^2 - b^2 \cos^2\left(\frac{\alpha}{2}\right)}} - \frac{b}{2} \cos\left(\frac{\alpha}{2}\right) \quad (12)$$

$$\frac{dl_2}{d\alpha} = \frac{b^2 \cos\left(\frac{\alpha}{2}\right) \sin\left(\frac{\alpha}{2}\right)}{2\sqrt{L^2 - b^2 \cos^2\left(\frac{\alpha}{2}\right)}} + \frac{b}{2} \cos\left(\frac{\alpha}{2}\right) \quad (13)$$

$$\frac{d^2 l_1}{d\alpha^2} = \frac{b^2 (L^2 \cos(\alpha) - b^2 \cos^4\left(\frac{\alpha}{2}\right))}{4(L^2 - b^2 \cos^2\left(\frac{\alpha}{2}\right))^{3/2}} + \frac{b}{4} \sin\left(\frac{\alpha}{2}\right) \quad (14)$$

$$\frac{d^2 l_2}{d\alpha^2} = \frac{b^2(L^2 \cos(\alpha) - b^2 \cos^4(\frac{\alpha}{2}))}{4(L^2 - b^2 \cos^2(\frac{\alpha}{2}))^{3/2}} - \frac{b}{4} \sin(\frac{\alpha}{2}) \quad (15)$$

Thus :

$$C = \frac{b^3(L^2 - b^2) \cos^3(\frac{\alpha}{2})}{4(L^2 - b^2 \cos^2(\frac{\alpha}{2}))^{3/2}} \quad (16)$$

Since $\cos(\frac{\alpha}{2}) > 0$ within the joint limits and since $L > b$, C is always positive.

3 A novel module : the E-module

From the previous study, we observe that an increase in stiffness by forces coactivation requires that the cable length expression be non-linear in α and this condition is not satisfied with a classical pulley. We now show that it can be the case if the pulley is elliptical. For more simplicity, we are interested in a symmetrical joint with a rotation center fixed at the center of the ellipse. We call this joint and its antagonistic actuation a E-module (for ellipse). Figure 2 shows an example with $a = 0.045$ m, $b = 0.06$ m, base point at $A = (0.02, -0.1)$ m for the right tendon and a symmetric base point for the left tendon.

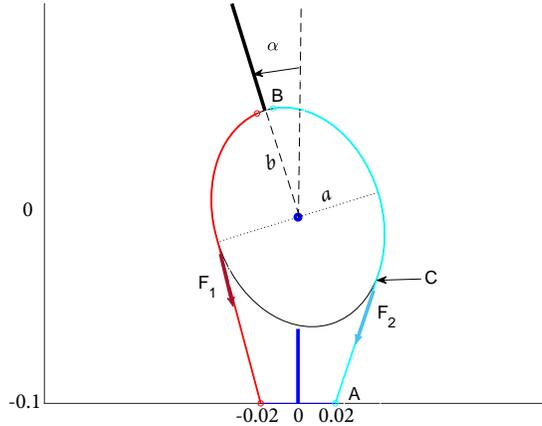


Fig. 2. A E-module is a rotating joint actuated by antagonistic tendons attached to an elliptical pulley.

Each tendon is attached to the ellipse at a certain point (indicated as B for the right tendon) and passes through a certain base point (A for right tendon). We now need to express the tendon lengths as functions of α . To this goal, we calculate the coordinates of the point of tangency between the ellipse and the tendon (at point C for the blue tendon) as a function of α . For the ellipse, no

closed form expression of the arc length CB exists, we thus proceed by numerical integration.

Let us consider the E-module of Fig. 2. The plots of the tendon lengths l_1 and l_2 (resp. of their derivatives $\frac{dl_1}{d\alpha}$, $\frac{dl_2}{d\alpha}$, $\frac{d^2l_1}{d\alpha^2}$, $\frac{d^2l_2}{d\alpha^2}$) are shown in Fig. 3, top left (resp. top right and bottom left). The coefficient C is calculated using Eq. (8) and its plot is shown in Fig. 3, bottom right. It turns out that C is positive in the range $-0.70 \text{ rad} < \alpha < 0.70 \text{ rad}$. This means that coactivation is possible within this range. We call this range *coactivation range*.

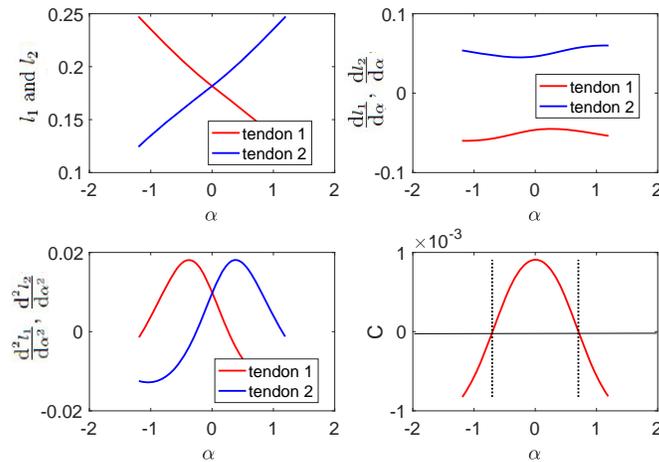


Fig. 3. Plot of tendon length (top left) and of their successive derivatives (top right, bottom left). Bottom right: plot of coefficient C showing the coactivation range.

3.1 Design parameters of the E-module

We first study the effect of the ellipse shape on the coactivation range. We fix b and the attachment points of the tendons as in Fig. 2 and we investigate several values of a , namely, $a = 0.03 \text{ m}$, $a = 0.045 \text{ m}$ (as in Fig. 2), $a = 0.06 \text{ m}$ (i.e. a circle) and $a = 0.075 \text{ m}$. For each case, C is plotted against α in Fig. 4. When $a = 0.03 \text{ m}$ and $a = 0.045 \text{ m}$, coactivation around $\alpha = 0$ is possible and the coactivation range is similar for these two values. However, coactivation is not possible when $a = 0.075$. This means that the orientation of the ellipse axes plays a central role: the long axis must be vertical at $\alpha = 0$ to have coactivation. However, the length of the semi-axis has little influence on the coactivation range. We also notice the special case $a = b$ (circle) for which $C = 0$, as expected.

A second study is the effect of the direction of the antagonistic tendons. Considering the symmetric E-module of Fig. 2, the lateral distance of point

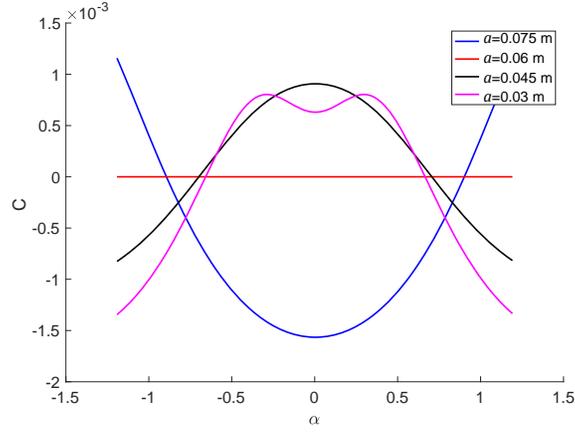


Fig. 4. Influence of the ellipse shape on coactivation range for an E-module.

A x_A is varied from 0 to 0.08 m, and the corresponding variation of $C(\alpha)$ is plotted in Fig. 5. It appears that for coactivation to exist, x_A must be lower than a certain value. In fact, we have observed that this value is the length of the horizontal semi-axis but this result needs to be proved. In other words, the limit is when the two tendons are vertical at $\alpha = 0$. Besides, decreasing x_A does not change the range of coactivation. In conclusion, the choice of the tendon base points also affects coactivation.

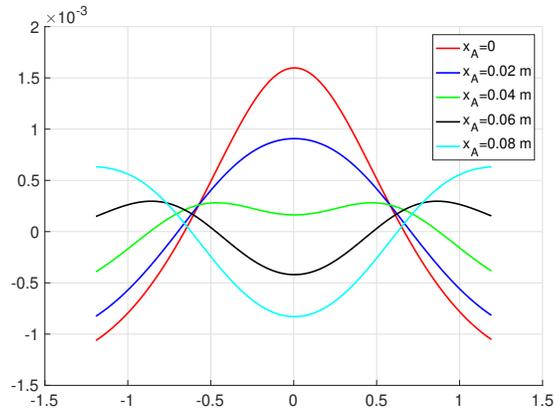


Fig. 5. Influence of the location of tendon base points on coactivation for an E-module.

4 Conclusion

The ability to modulate joint stiffness is an important property in collaborative robotics. To move safely with low energy consumption, it is desirable to provide low stiffness. In contrast, it can be necessary to increase stiffness by coactivation when needed, such as, e.g., during process tasks. In this study, we have proposed a new way to design a rotating joint with variable stiffness via the E-module. This new design can have applications in the design of variable stiffness SEA joints in robotics and for studying biological joints. Interesting avenues of study include studying non-symmetrical pulleys, eccentric or moving rotation axis.

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