

STRAIN TESTS DURING THE DEVELOPMENT OF AN ARTIFICAL TENDON TO BE USED AS A TENSION SPRING IN PROSTHETIC DEVICES

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Abstract: *Advances in biomechanisms have leaded researchers to the development of mechanical structures similar to natural ones. New robots can simulate with perfection some human movements and sometimes with more accuracy. New prosthetic devices can also imitate the human movements. With the use of specific leg prosthesis some athletes can run faster than normal people. Some hand prostheses can perform complex tasks such as: hold a key, hold a glass or a ball, and even more important, it can also increase the user's self esteem. The use of elastic tendons instead of tension springs in prosthetics devices was based on a biomimetic approach. This paper describes the concept behind the development of an elastic tendon and presents a mathematical model of it. The elastic tendon can be used as a connector between the motor (muscle) and the movable parts (bones) or it can be used to stabilize joints like the human tendon. The mechanical behaviour is similar to a non linear tension spring and its resilience can be adjusted according the project.*
Keywords – Biomimetic, matematical model, elastic tendon, non linear model

1.INTRODUCTION

In robotics, the human body has been a great source of inspiration for the development of new technology (Dario et al., 2002). The hands are one of the most advanced parts in the human body, when analyzed in regard of the complexity of the human movement control. In hand prosthesis, the mechanisms must be like the human hand: small, simple, light weighted, present a low energy consume and high torque (Cura et al., 2003).

In regard to that, new improvements have been developed in mechanical, electrical, and computational areas to be used during the development of a hand prosthesis. This can be observed in the new mechanisms and sensors that are being used to move and to control these new prostheses (Dario et al., 2005; Carrozza et al., 2005).These improvements allow an apparent intelligence to the hand prosthesis, during grasp movements. It can adapt to an object with complex geometry without a human action or feedback.

This kind of movement is only possible because of underactuated mechanisms. This mechanism is present in the most advanced prosthesis that have been developed (Carozza et al., 2001; Dario et al., 2002; Light and Chappell, 2001; Kyberd et al., 2001).

With them it is possible to generate in the hand prosthesis the same movements of the human finger without many actuators.

In some cases the use of springs, to generate this movement, is not possible. It is necessary a more malleable mechanism. The connection between the spring and the cable is commonly a point of precipitate break in the system.

The elastic tendon has being developed based on these underactuated mechanisms. The elastic tendon is a cable with elastic proprieties in specific areas. This tendon works as a tension spring. Because of its geometry, like a cable, it can be adapted to a small mechanism as a transmission system. Due the size, the weight and the method used to shape the elastic tendon, a tension spring with a specific elastic constant can be used to replace it.

This work presents the strain tests on an elastic tendon to define its characteristics, and to be the basis for the mathematical model in the future.

2.METHODOLOGY

A new transmission mechanism to be used in prosthesis and orthosis is presented in this paper. This mechanism can be used for the development of a more adapted and similar prosthetic device to the human hand. It is called “elastic tendon” because it presents the elastic behaviour of a spring and is also a transmission mechanism like a tendon. Its elaboration has being based on the development of a pneumatic artificial muscle (Chou and Hannaford, 1996; Nagem et al., 2002).
This tendon presents an external braid, like a cable, that involves an elastomeric component (Figure 1). Region A can be built in any size to adapt to the mechanism where it will be fixed. Region B is planned according to the elastic properties of the project’s mechanism.

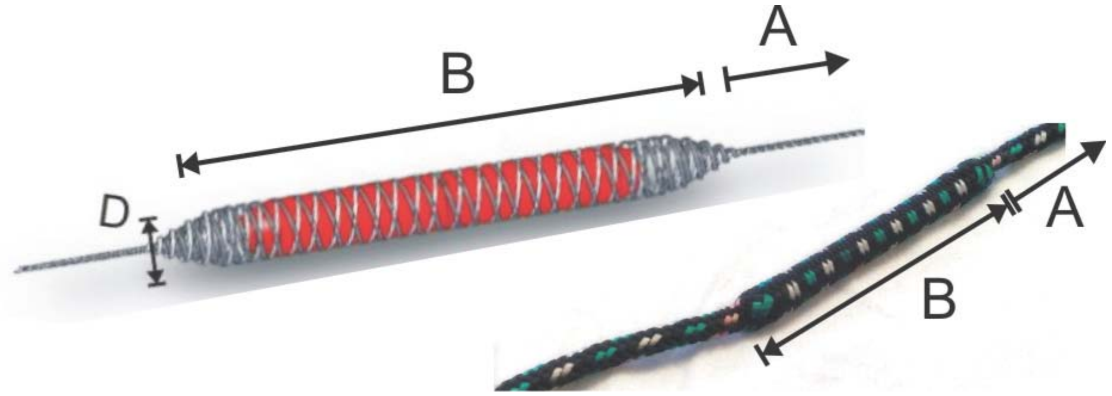

Figure 1 – Elastic tendon.

Many tension tests were performed with different elastic tendons to determinate its behaviour. These tests were executed in two parts. The first one was performed at the Mechanical Engineering Department of Dundee University, Scotland, the second one at the Laboratory of Engineering of Polymers and Composites, UFMG.

1ª Stage of the tests

At this part of the tests one kind of elastic tendon with 2.5mm of diameter was evaluated. These tests consider 4 different sizes for the tendons and 4 different speeds for the tests in each tendon. They were used to define the pattern for the tests in the next phase. On this phase an INSTRON 4202, with a load cell of 1kN were used.

Before each test the size of the elastomeric region and the diameters were measured. The tendon was fixed to the machine with a 10cm distance between the grips. Three tests were performed on each tendon to adjust the braid at the elastomeric region, each one with 100 cycles. The tests were executed with a speed of 500, 250 and 125mm/min, with a maxim force of 35 N. After each test the tendon was readjusted to the machine.

After that a series of tests on each tendon were performed, each test with 50 or 100 cycles. The speed was defined as 62,5, 125, 250, 500mm/min and a maximal force of 5, 10, 20, 30N.

2ª Stage of the tests

The second part of the tests was performed at UFMG, in the Laboratory of Polymer Engineering and Composites. For these tests the EMIC® model DL 3000 was used, for tension tests with a load cell of 200N.

The tendons were built with an elastomeric part with 2, 4, 6, 8, 10cm. The diameter was measured and the angle of the braid over the elastic region was determined. Three tests were performed on each tendon to adjust the braid at the elastomeric region, each one with 30 cycles at 250mm/min with a 40N of maximal force. After the braid adjustment, the tendon was fixed at the machine to start the tests. A test of 10 cycles at 250mm/min was performed with a 30N of maximal force. The tendon was fixed at the grips with 2cm from the elastic region.

With this data it was possible to determinate the tendons behaviour to be used in a future model.

3.RESULTS

In the first part of the tests, accomplished at Dundee University, an elastic tendon with 2.5mm and 4 different lengths of the elastic region was used at 3 speeds. Table 1 shows the information about the tendons used in the tests.

Table 1- Characteristics of the tendons of the tests performed at Dundee University.

Classification	Diameter (mm)	External Braid Thickness (mm)	Tendons Lenght on the Measuring Instrument (mm)
D01	2,50±0,05	17,30±0,05	100±0,005
D02	2,50±0,05	23,10±0,05	100±0,005
D03	2,50±0,05	24,20,±0,05	100±0,005
D04	2,50±0,05	100±0,005	100±0,005

Figures 2 to 5 show the curves that represent 90% of the maximal strain for a force of 1 N in each cycle of tests performed at Dundee University.

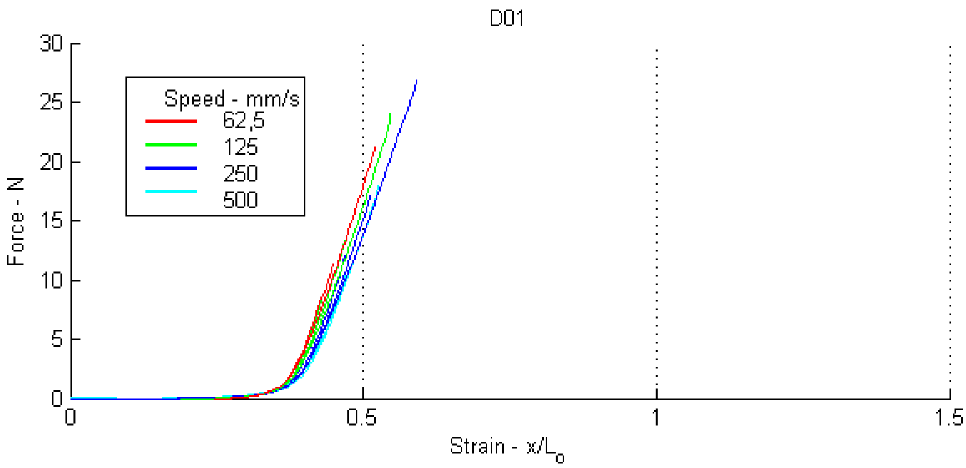

Figure 2- Presents the average of all curves Force x Elongation for the tests performed with D01 tendons.

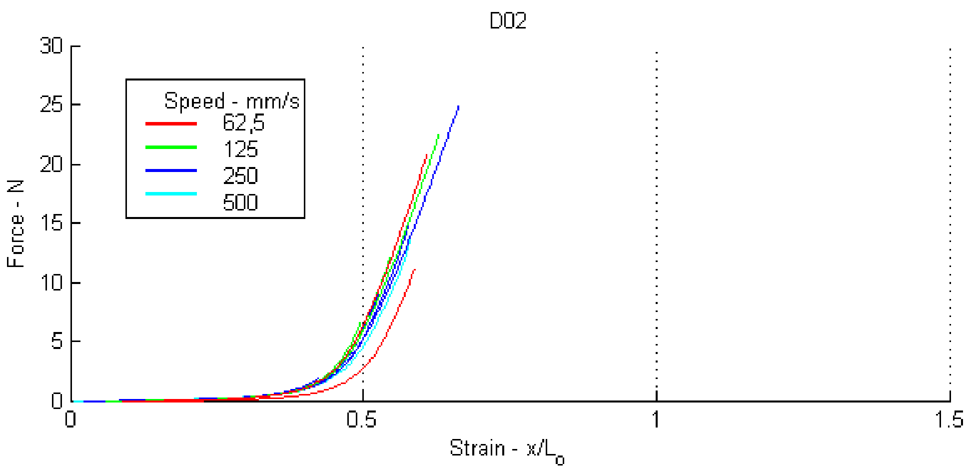

Figure 3- Presents the average of all curves Force x Elongation for the tests performed with D02 tendons.

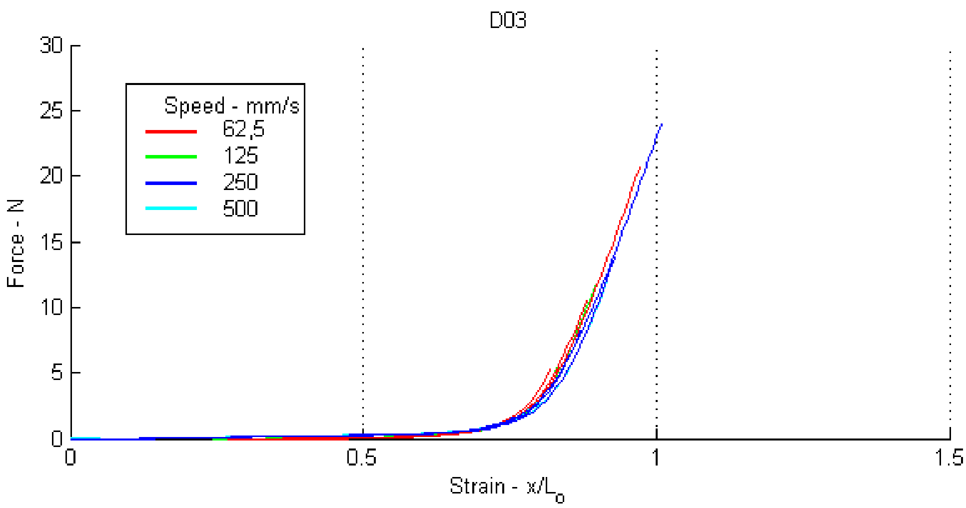

Figure 4- Presents the average of all curves Force x Elongation for the tests performed with D03 tendons.

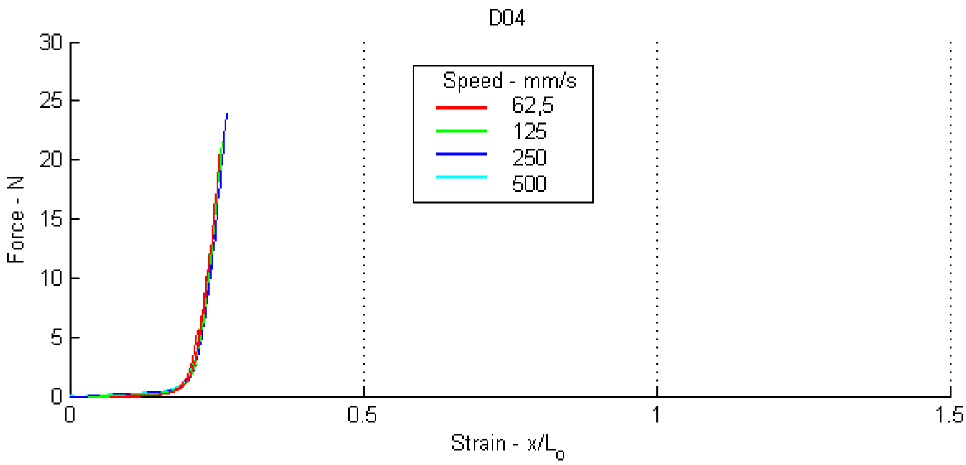

Figure 5- Presents the average of all curves Force x Elongation for the tests performed with D04 tendons.

Table 2- Characteristics of the tests performed at UFMG.

Classification	Total Diameter (mm)	External braid thickness (mm)	Braid's angle.	Length of elastic region (mm)
UF01-1	5,47±0,26	1,04±0,06	58º38'±4º05'	21,53±0,77
UF01-2				36,37±0,70
UF01-3				61,13±0,83
UF01-4				78,33±1,85
UF01-5				100,42±1,48
UF02-1	5,83±0,57	1,12±0,06	57º45'±4º10'	16,80±0,13
UF02-2				29,70±1,40
UF02-3				60,34±1,29
UF02-4				79,80±1,16
UF02-5				99,42±1,23
UF03-1	6,17±0,49	1,11±0,09	54º02'±4º43'	22,31±0,69
UF03-2				38,97±1,57
UF03-3				60,31±1,77
UF03-4				76,60±1,37
UF03-5				99,88±1,02

The average of the correlation coefficients between the curves of the same tendon is 0.99 and the standard deviation is less than 0.2 N for tests with the same tendon. It is possible to conclude that the relation between force and displacement is not related with the speed of the displacement, but is only a function of the size of the elastomer and the constructive characteristics of the braid. After the tests it was observed that the curve that represents the 90% of the maximal strain it is set between the 28th and 29th cycle on most cases (average of 28.24). This means that it is possible to perform a test with a smaller number of cycles; therefore in the next stage of tests only 30 cycles were performed.

The 2º part of the tests was performed using 3 kinds of elastic tendon with, these tendons were named and their properties can be seen in Table 2. They were tested at 250mm/min in a test with 30 cycles.

Figure 6 to 8 show the average of Force x Stress curves for the tests in UFMG. It is noticeable that the curves are not similar with other materials that present the same Strain x Stress curve for all shapes.
In the elastic tendon this is not true, as can be seen the shape of the material, the diameter and the braid's angle change the behaviour of the material.

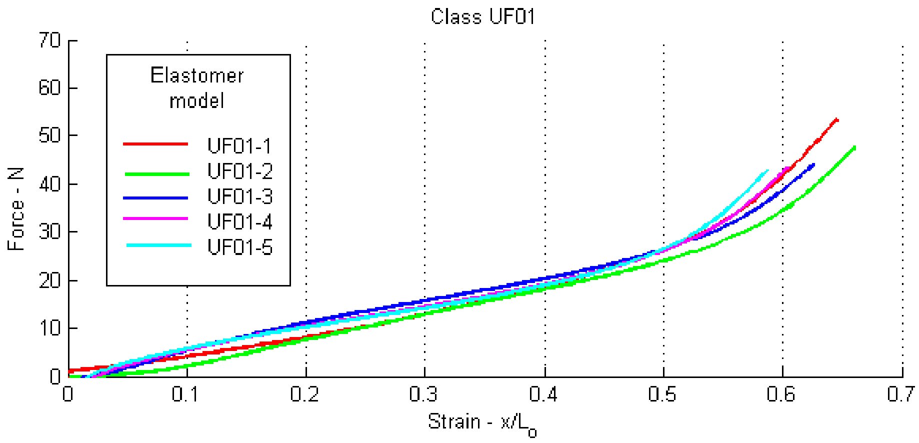

Figure 6 – Average Force x Stress curves for UF01 tendons.

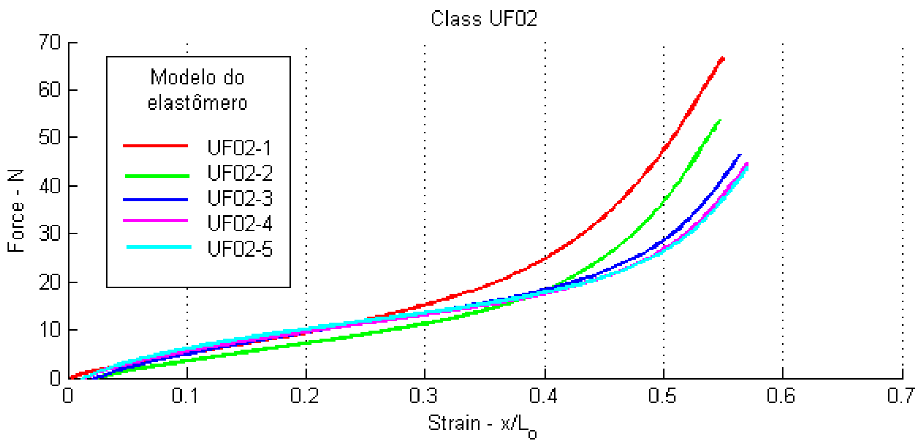

Figure 7 – Average Force x Stress curves for UF02 tendons.

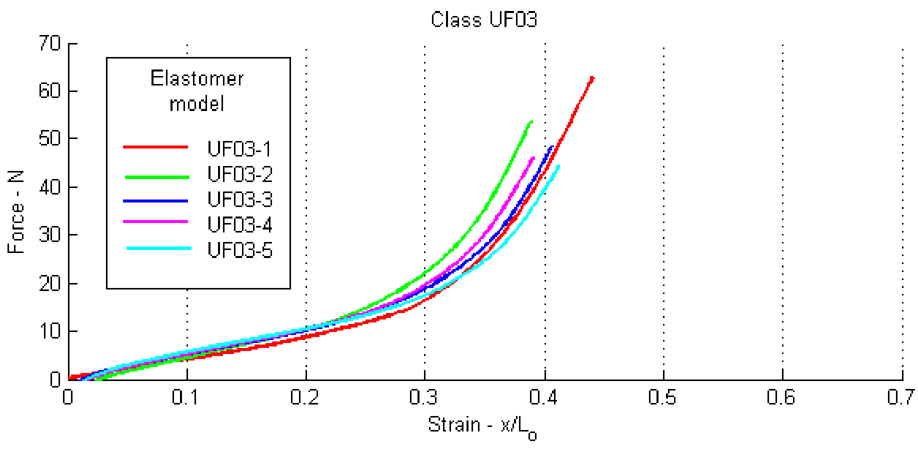

Figure 8 – Average Force x Stress curves for UF03 tendons.

With this curve, it is possible to presume that the force applied to the external braid, to stretch it, propagates to the elastomer at least 2 ways.

During this movement, the braid compresses the elastomer in one direction and stretches it in another direction. The elastomer changes its shape, gaining a shorter diameter and a larger length.

Equation 1 and figure 4 show the energy, represented by *W*, in the elastic tendon during its tension test.

$$W_{Elastomer\ Compression} + W_{Elastomer\ stretch} = W_{Elastic\ Tendon} \tag{1}$$

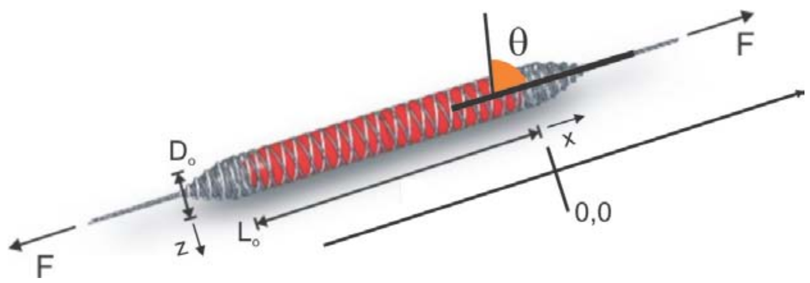

Figure 9– Elastic tendon with variables displayed.

The equation 1 can be rewritten as:

$$dW_{Elastomer\ Compression} + dW_{Elastomer\ stretch} = dW_{Elastic\ Tendon} \tag{2}$$

Using Figure 9 and equation 2 it is possible to write the equations 3 to 7 bellow:

$$dW_{Compression} = f_{Compression}(z)dz \rightarrow f_1(z)dz \tag{3}$$

$$dW_{Stretch} = f_{Stretch}(x)dx \rightarrow f_2(x)dx \tag{4}$$

$$dW_{Total} = f_{Total}(x)dx \rightarrow f_3(x)dx \tag{5}$$

dw_i is defined as the work spent to cause a small variation of force and size on each component, elastomer and tendon. *f(x)* or *f(z)* is the variation of force applied to the elastomer or to the tendon to change its shape in Δx or Δy.

$$f_3(x)\Delta x = f_2(x)dx + f_1(z)dz \tag{6}$$

$$f_3(x) = f_2(x) + f_1(z)\frac{dz}{dx} \tag{7}$$

This model was implemented based on the development presented by Chou and Hannaford (1996) for McKibben's artificial muscle, where the external cables' lengths remain constant during the tendon's movement. The elastomer's length and diameter are represented by *L* and *D*, external cable's length by *b*, the braid's angle by θ, and *n* represents the number of turns of the cables over the elastomer. These variables define equations 8 to 13.

$$L = b\cos(\theta) \tag{8}$$

$$dL = x = -bsen(\theta)d\theta \tag{9}$$

$$D = bsen(\theta)/n\pi \tag{10}$$

$$dD = z = b\cos(\theta)d\theta / n\pi \tag{11}$$

$$d^2L = dx = -b\cos(\theta)d\theta^2 \tag{12}$$

$$d^2D = dz = -\frac{b}{\pi n}sen(\theta)d\theta^2 \tag{13}$$

Substituting equation 15 in 17, we obtain equation 20:

$$z = \frac{b}{n\pi}\cos(\theta)\frac{x}{-bsen(\theta)} \rightarrow -\frac{x}{n\pi\tan(\theta)} \tag{14}$$

The negative sign shows that z is in the opposite direction of of x; therefore z is compressive and x represents a tension.
Using equations 18 and 19, we obtain equation 21:

$$\frac{dz}{dx} = \frac{-\frac{b}{n\pi}sen(\theta)d\theta^2}{-\mathrm{b}\cos(\theta)d\theta^2} \rightarrow \frac{\tan(\theta)}{n\pi} \tag{15}$$

Other factor that should be considered is that compression displacement described by *z* refers to the stretching of the tendon and not of the interior elastomer region. This internal structure is, simultaneously, under longitudinal traction and lateral compression. The internal structure presents a behavior in which it

reduces its width if placed under traction; the relation between width reduction and traction is expressed by Poisson coefficient *v*.
This way, length reduction of the entire component due to traction is represented by the following equation:

$$\frac{L_o}{\Delta L}\frac{\Delta D_v}{D_0} = \nu \rightarrow \Delta D_v = \frac{\nu D_o \Delta L}{L_o} \qquad (16)$$

Real reduction of the elastic region is now represented not by *z*, but by:

$$z_{\mathrm{E}lastic} = z - \Delta D_v \qquad (17)$$

Therefore equation 13 may be rewritten:

$$f_3(x) = f_2(x) + f_1\left(\frac{x}{n\pi\tan(\theta)} - \frac{\nu D_o x}{L_o}\right)\frac{\tan(\theta)}{n\pi} \qquad (18)$$

It is therefore possible to obtain a model that represents the behavior of f_3 in function of displacement *x*, the constructive characteristics of the tendon and the traction/compression curve of the elastomer.

4.CONCLUSION

With the tendon's Stress x Strain curves it was possible to determine the necessary parameters for a future completed mathematical model of the tendon. It was noticed that the speed of the stretch does not affect the tendons behaviour. The stretch applied to the external braid is used to compress the elastomer and to stretch it in different directions.
The mathematical model defined in equation 18 shows the basis of a model that will describe the tendon's behaviour based only in the stretch measured on the tendon.

5.ACKNOWLEDGEMENTS

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