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STRAIGHT FIBRES PNEUMATIC MUSCLE: AN ACTUATOR WITH HIGH TRACTION FORCE

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ABSTRACT

This work deals with the design and development of a novel kind of flexible pneumatic actuator, called *straight fibres pneumatic muscle*. The paper describes a prototype that has been realised and characterised experimentally. In addition, a mathematical model, able to evaluate the static performance, has been derived. The model takes into account the overall geometry and the mechanical characteristics of both the flexible material and the fibres. The results have been validated by experimental tests.

The straight fibres muscle gives very interesting results as regards the pulling force, even if compared with traditional muscle actuators with the same size.

KEYWORDS: Pneumatic muscle actuator, Flexible actuator, Fluid power actuator.

1 INTRODUCTION

In some applications of non conventional robotics it may be necessary to use actuation devices with particular characteristics, usually not provided by conventional actuators like fluid power cylinders or electrical motors.

In general, an ideal actuator should be compact, reliable, non-pollutant, cheap, durable, able to generate a high force with respect to its volume and weight. In addition to these generic characteristics, the actuators should give particular performances according to their use.

For instance, actuators to be used in biomechanical applications for assisting disabled people must have psychologically acceptable shape and size, and should have preferably a non-rigid structure. The motion of geometrically defined structures, aimed at assisting disabled people, or used as active tutor, can be advantageously driven by actuators giving high pulling forces with respect to their mass and volume, having a soft and flexible structure that adapts itself to the structure geometry.

In aerospace applications, the actuators should be particularly light and able to work in vacuum, even subjected to high changes of temperature, without mechanical parts in relative sliding motion, so as to avoid the use of lubricant and dynamic seals.

The natural muscles may be an ideal model for developing actuators for special applications [1]. In fact they show very good characteristics, like a high power-to-weight ratio (from 40 to 225 W/kg, up to 1 kW/kg in particular cases), a value of force per cross-sectional area varying from 15 to 40 N/cm², an average contraction velocity of 500% s⁻¹, good position controllability, high efficiency; moreover, they obviously are not pollutant. Among actuators approaching these characteristics, different types of flexible actuators have been studied by numerous authors, and the Flexible Pneumatic Actuators (FPA) turned out to be particularly interesting. They are made up of a deformable chamber, usually of an elastomeric material, able to dilate under the effect of the internal pressure; by adopting proper constraints, it is possible to control the deformation in the most convenient way.

Among the various typologies of FPA, the McKibben muscle, conceived in 1950 and used for actuating an arm devoted to biomechanical tasks, found a remarkable success. Several works have been conducted in order to identify and simulate the behaviour of this muscle [2], [3], [4]. The McKibben muscle has been adopted both in aerospace [5] and biomechanical applications [6], [7], [8].

Researches aimed at optimising the McKibben muscle highlighted how its performances are greatly influenced by the cross section and the mechanical characteristics of the stretchy chamber, as well as from the winding angle of the constraining weave [9].

This work deals with the development of a new kind of muscle actuator, named straight fibres muscle, whose force performance has been optimised.

The structure of a prototype is described, the static mechanical characteristic obtained experimentally is reported.

Then a mathematical model of the actuator is defined, able to foresee its performance as a function of the geometrical parameters and the material characteristics. The model has been validated on the basis of experimental tests.

Finally, the model has been used to carry out an analysis of the influence of geometry and material properties on the actuator's performances.

2 THE PROTOTYPE

The fig.1 shows a picture of the prototype of straight fibres muscle.

The muscle is made up of a stretchy chamber, of elastomeric material, stiffened in the longitudinal direction by very strong fibres, attached to the end-caps.

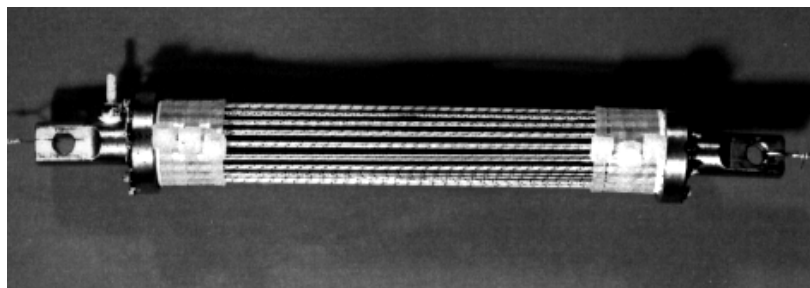


Figure 1: prototype of muscle actuator

By increasing the internal pressure, the actuator takes the shape of a barrel (see fig.2) and, since the length of the fibres remains practically constant, the two end-caps approach and the actuator shortens.

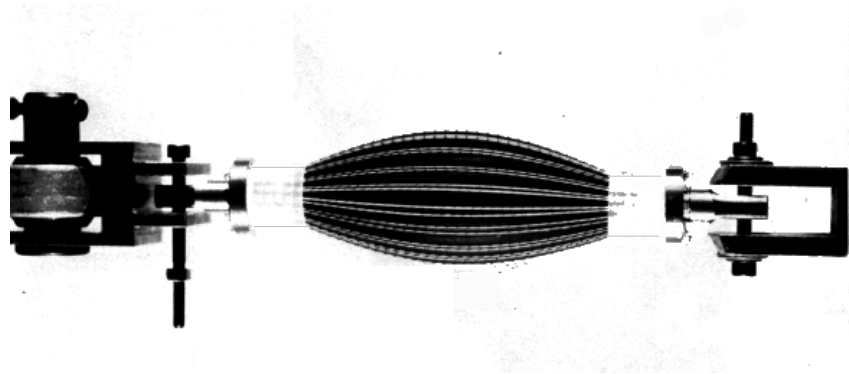


Figure 2: the prototype in load condition

The fig. 3 shows a scheme of the actuator, both in undeformed (dashed line) and deformed condition (continuous line). The muscle realised is made up of a stretchy chamber, of initial length $l_0=100$ mm and initial radius $r_i=6$ mm, attached to two end-caps of radius $r_o=7$ mm. The total length, including the end-caps, is equal to 190 mm; the mass is of 185 grams.

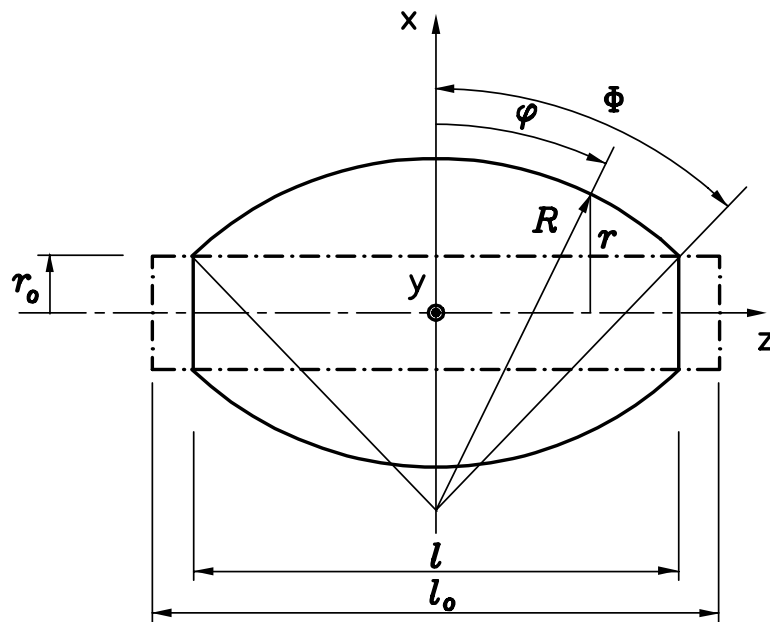


Figure 3: geometry of the muscle actuator

The muscle, subjected to a traction force, reaches in equilibrium condition a new length l depending on the values of the supply pressure and the applied force. Vice versa, once a given length is imposed to the actuator, it exerts a pulling force depending again on the internal pressure, and on the imposed length.

Fig.4 shows a typical experimental characteristic of the actuator, i.e. the pulling force as a function of the contraction ratio, for different supply pressures. The contraction ratio is defined as:

$$\Delta l\% = \frac{l_o - l}{l_o} \cdot 100$$

where l_o is the initial length of the actuator and l is its actual length.

As highlighted by fig.4, at the same supply pressure, the pulling force F of the actuator decreases as the contraction ratio $\Delta l\%$ increases.

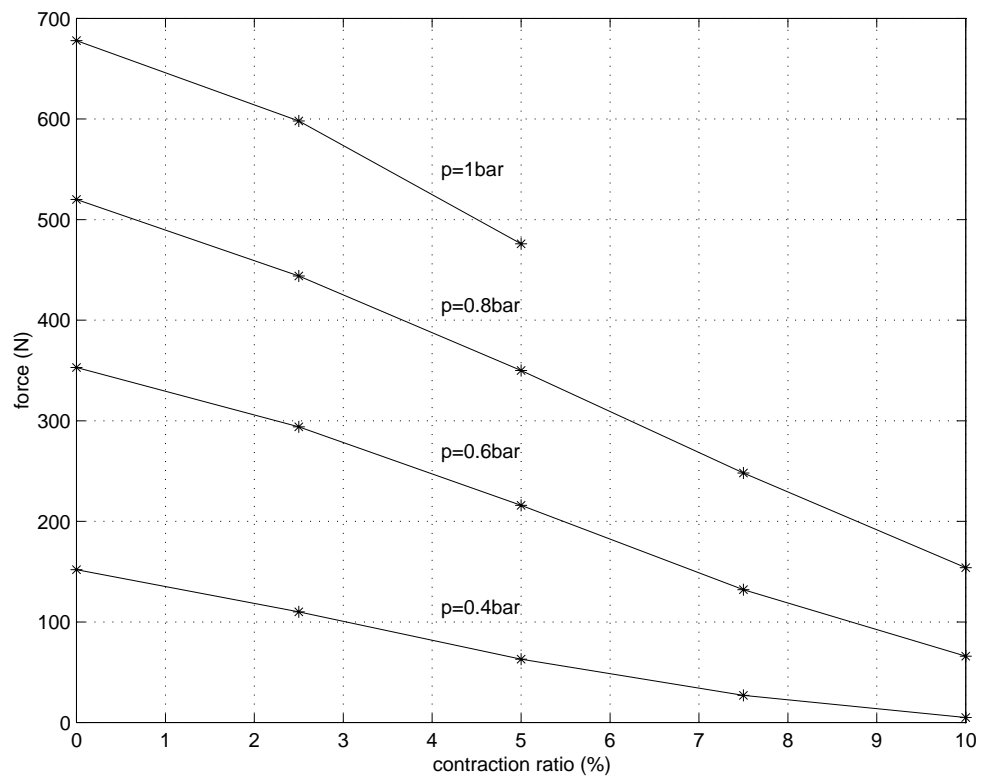


Figure 4: pulling force versus the contraction ratio

3 MATHEMATICAL MODEL

To foresee the performance of the muscle actuator, i.e. the pulling force as a function of the supply pressure and the contraction ratio, and to evaluate the influence of the geometrical parameters and the properties of the materials, a mathematical model of the straight fibres muscle has been developed.

The condition corresponding to actuator completely extended, with no external load and no supply pressure, has been defined as initial.

The muscle has been considered as a tube of elastomeric material, with Young's modulus E , initial length l_0 , initial radius r_i and thickness s , attached to two end-caps of radius r_0 , and stiffened in the longitudinal direction by N strings with Young's modulus E_f , cross section A_f and initial length l_0 .

The fig.3 shows, with dashed line, the lateral view of the geometric scheme of the actuator in initial condition. The reference frame x-y-z has been assumed with the origin placed in the middle of the actuator and the z-axis coinciding with the actuator axis.

Once given values of length l and pressure p have been imposed, the actuator exerts a pulling force F . In fig.3 the continuous line indicates the shape of the actuator when a length l is imposed. It has been hypothesised that the cross section of the actuator wall along the symmetry axis takes the shape of an arc, with curvature radius R . The angle subtending this arc is indicated as 2ϕ .

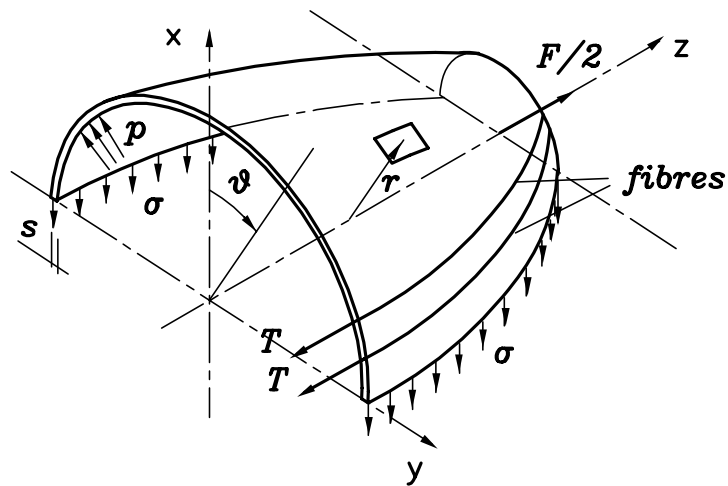


Figure 5: 3-D scheme of 1/4 deformed actuator

The fig.5 shows the 3-D scheme of a quarter of the actuator in the deformed condition, with the indication of the stresses acting on the membrane.

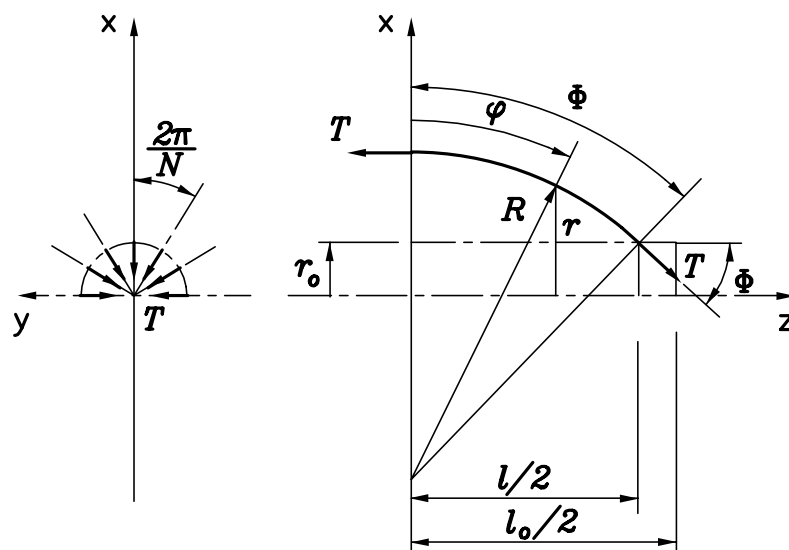


Figure 6: force equilibrium of the fibre

The forces acting on x-direction are: the projections of the internal pressure forces, the projections of the tensions in the fibres and the resultant of the stress σ in the membrane. In particular, called T the tension in each of the N fibres, the resultant of the tensions in x-direction is given by the sum of the projections of T in this direction, as highlighted in fig.6.

Then, with reference to the figures 3, 5 and 6, the force equilibrium of 1/4 actuator in x-direction can be written as:

$$\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_0^{\phi} p \cos \vartheta \cos \varphi r R d\vartheta d\varphi - T \operatorname{sen} \phi \cdot \left(\sum_{n=-N/4}^{+N/4} \cos \left(\frac{2\pi}{N} n \right) \right) - 2ERs \int_0^{\phi} \frac{r_o + R(\cos \varphi - \cos \phi) - r_i}{r_i} d\varphi = 0 \quad (1)$$

Similarly, the forces acting in z-direction are: the pulling force F of the muscle, the projections of the internal pressure forces and the projections of the tensions in the fibres. The equilibrium in z-direction is expressed by the following equation:

$$\frac{F}{2} + \frac{p\pi r_o^2}{2} + \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_0^{\phi} p \operatorname{sen} \varphi r R d\vartheta d\varphi - \frac{NT}{2} = 0 \quad (2)$$

By substituting in (1) and (2) the expression of the radius r of the generic cross-section:

$$r = r_o + R(\cos \varphi - \cos \phi) \quad (3)$$

and integrating, one obtains the following equilibrium equations:

$$\frac{2ER^2s}{r_i} (\operatorname{sen} \phi - \phi \cos \phi) + El_f s \frac{r_o - r_i}{r_i} + T \operatorname{sen} \phi \cdot \left(\sum_{n=-N/4}^{+N/4} \cos \left(\frac{2\pi}{N} n \right) \right) - p \left(\phi R^2 + 2Rr_o \operatorname{sen} \phi - \frac{R^2}{2} \operatorname{sen} 2\phi \right) = 0 \quad (4)$$

$$F + p\pi(r_o + R(1 - \cos \phi))^2 - NT = 0 \quad (5)$$

The characteristic equation of the fibre is:

$$l_o \left(1 + \frac{T}{E_f A_f} \right) - l_f = 0 \quad (6)$$

Finally, for the geometrical congruence of the muscle, it can be written:

$$R\phi - \frac{l_f}{2} = 0 \quad (7)$$

and:

$$R \text{ sen } \phi - \frac{l}{2} = 0 \quad (8)$$

The solution of the equation system given by (4), (5), (6), (7) and (8) allows to derive, for given supply pressure p and actuator length l , the pulling force F exerted.

The fig.7 shows a comparison between the results given by the mathematical model and the results measured by experimental tests.

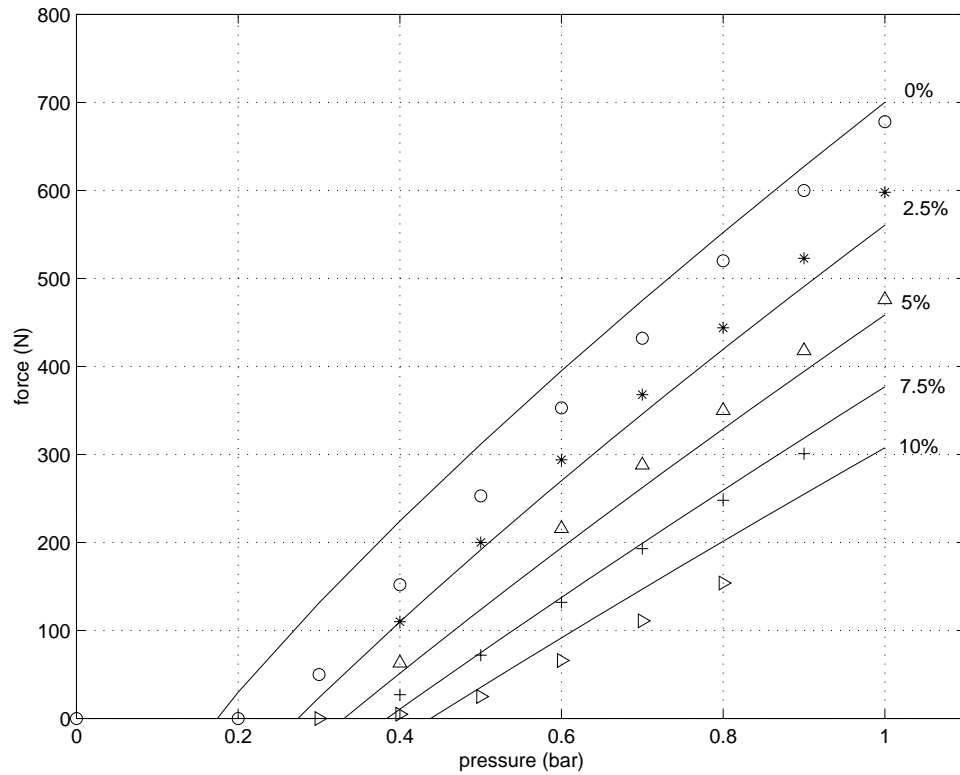


Figure 7: traction force versus the pressure: theoretical (continuous line) and experimental results at 0%, 2.5%, 5%, 7.5% and 10% contraction ratio

For a given contraction ratio, as the supply pressure increases, the pulling force of the actuator increases with a regular trend.

The model proves to be able to foresee the behaviour of the muscle in the whole working range investigated experimentally. In particular, the minimum values of supply pressure necessary to produce a pulling force of the actuator can be individuated.

Being in this way validated, the model has been used to investigate the influence of the two main geometrical parameters (the length l_0 and the radius $r_i=r_0$ in initial conditions) on the actuator's performance.

The fig.8 shows the values of the actuator's pulling force evaluated by the mathematical model, as a function of the initial length. The analysis was carried out for different supply pressures, considering an initial radius $r_i=r_0=7$ mm and a contraction ratio equal to 0%. At low supply pressure (0.2 bar) the force shows a maximum for a length of about 0.12 m, then it decreases for greater values of l_0 . In fact, for the same contraction ratio, the deformation energy of the rubber chamber increases as the initial length increases: at low working pressures, almost the whole of the fluid energy is converted in deformation work.

For greater supply pressures, increasing the initial length determines an increasing of the traction force. Anyway, in design stage the structural limits of the elastomeric material must be taken into account.

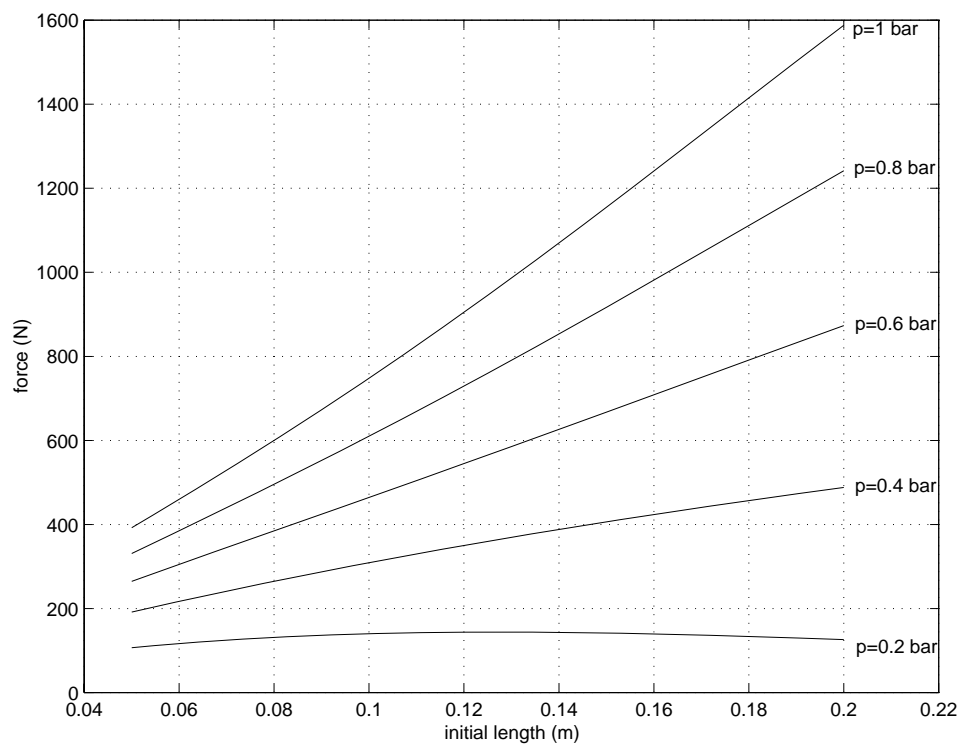


Figure 8: traction force of the muscle versus the initial length ($r_i=r_0=7$ mm, contraction ratio=0%)

In fig.9 the same kind of muscle as above ($r_i=r_0=7$ mm) was considered. Here the pulling force versus the initial length has been evaluated for a supply pressure of 1 bar and for different values of contraction ratio (0%, 5% and 10%). In addition, the model calculated at the same conditions also the maximum strain in the elastomeric material of

the membrane, i.e. the strain measured in the cross section with the maximum radius. As the initial length and the contraction ratio increase, the strain increases as well, reaching the maximum acceptable value for the material used (for the prototype realised, the material of the rubber chamber had a maximum admissible strain of 450%). Therefore, it is clear that the initial length of the muscle cannot be increased over a certain value.

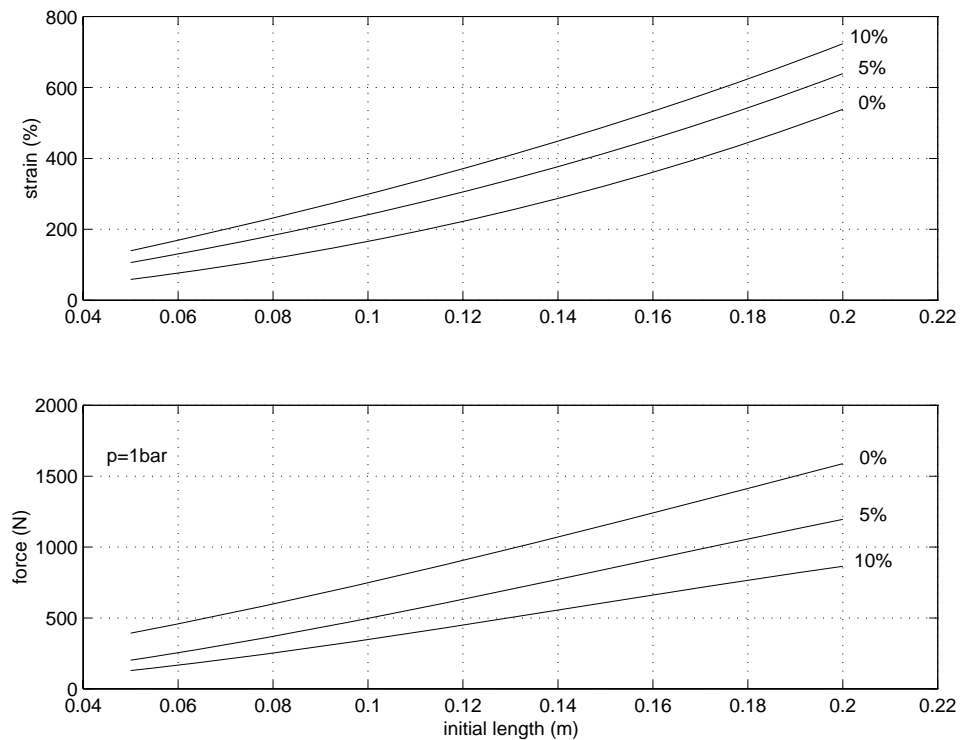


Figure 9: maximum strain in the elastomeric material and traction force of the muscle versus the initial length ($r_i=r_0=7$ mm, $p=1$ bar)

Vice versa, keeping constant the initial length of the actuator, it is possible to investigate the influence of the initial radius on the pulling force. The diagrams of fig.10 allow to discuss this effect. Here the values of the pulling force are presented as a function of the initial radius $r_i=r_0$, for a supply pressure of 1 bar, initial length l_0 of 0.1 m and for different contraction ratios (0%, 5% and 10%).

The increasing of the initial radius determines an increasing of the pressure thrust acting in radial direction on the fibres, so enhancing the contraction ability of the muscle; on the other hand, the pressure force tending to stretch the muscle in the axial direction increases as well. Therefore, for a given contraction ratio, there is a certain value of initial radius maximising the pulling force of the muscle.

The fig.10 shows also how the strain in the chamber material tends to decrease as the initial radius increases, for the same contraction ratio.

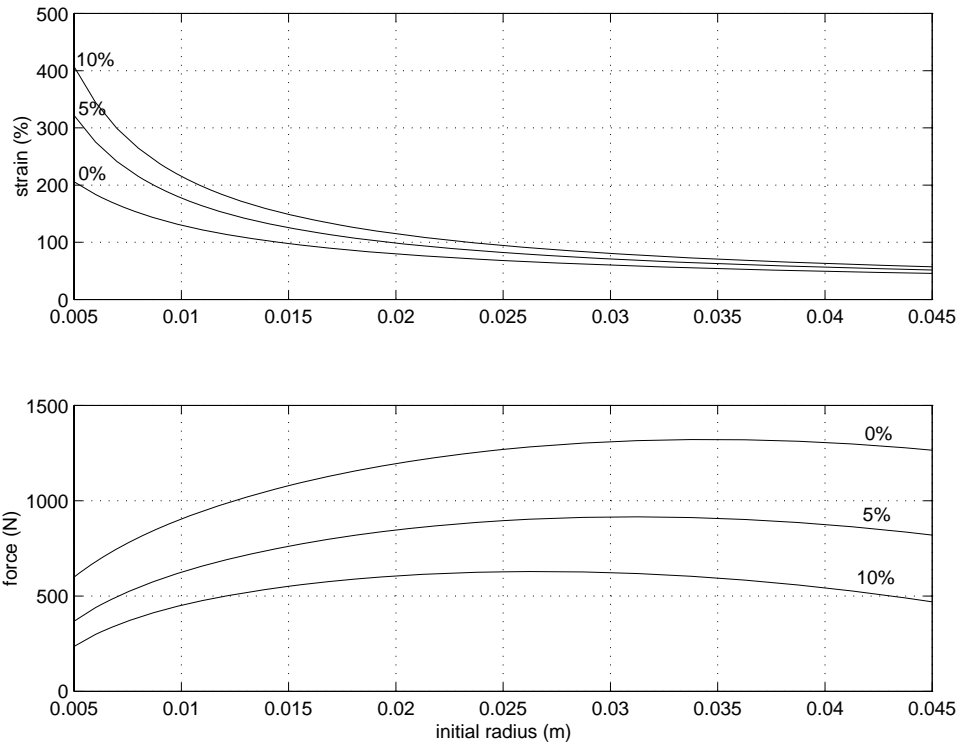


Figure 10: maximum strain in the elastomeric material and traction force of the muscle versus the initial radius ($l_0=0.1$ m, $p=1$ bar)

Finally, the fig.11 highlights the effect of the initial radius on the pulling force for contraction ratio of 0% and initial length of 0.1 m, at different supply pressures. For each curve, corresponding to a given supply pressure, it is possible to individuate a value of initial radius determining a maximum value of the pulling force.

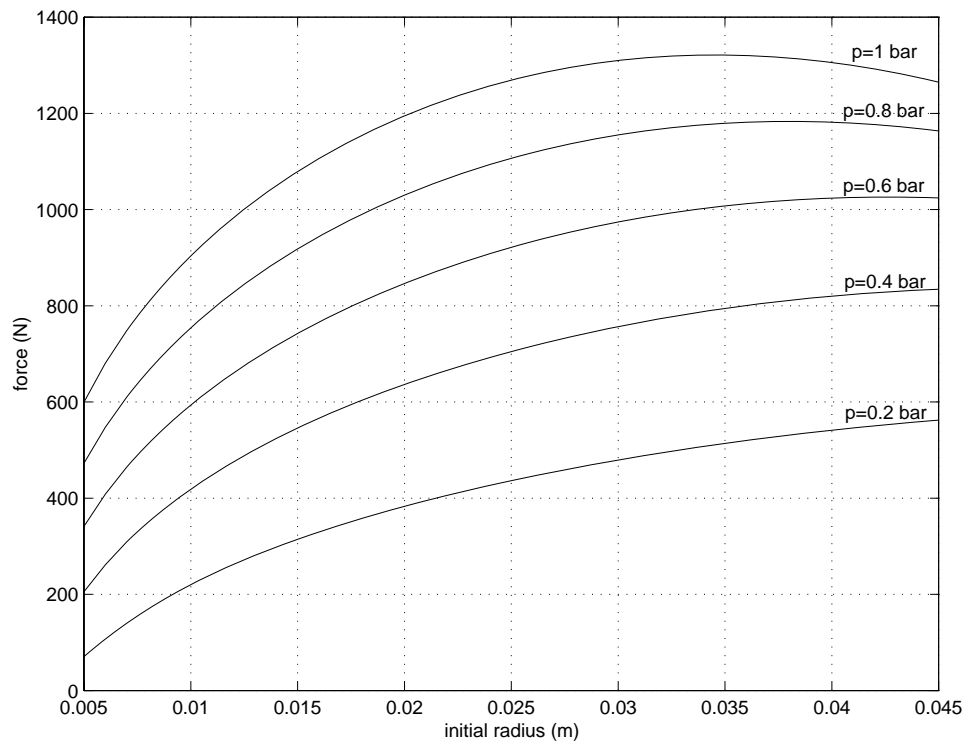


Figure 11: traction force of the muscle versus the initial radius ($l_0=0.1$ m, contraction ratio=0%)

4 CONCLUSION

A new kind of muscle actuator, with non-extensible fibres oriented in longitudinal direction, has been developed.

A prototype has been constructed and tested. It showed very interesting performances in comparison with the traditional McKibben muscle.

Furthermore, a mathematical model of the muscle has been realised and validated experimentally.

The model has been used to investigate the performance of the actuator imposing variations to the values of the main physical parameters.

It has been highlighted how the behaviour of the actuator's force as a function of the two main geometrical parameters, i.e. the initial length and radius, is strongly non-linear.

Moreover, the model showed that it may be used as a design tool in order to choose proper actuator's parameters for the performances requested: at a design stage, according to the desired performance and applications, for given materials of the deformable chamber and the fibres, it is possible, by means of the model described, to individuate optimal values for the initial length and the initial radius of the chamber.

NOMENCLATURE

A_f	Area of the fibre's cross section
E	Young's modulus of the deformable chamber
E_f	Young's modulus of the fibre
F	Pulling force of the muscle actuator
l	Actual length of the muscle
l_f	Length of one fibre
l_o	Initial length of the muscle
N	Number of the fibres
p	Supply pressure
R	Curvature radius of the deformed actuator
r	Radius of the generic cross-section
r_i	Initial radius of the chamber
r_o	Radius of the end-cap
s	Thickness of the chamber
T	Tension in one fibre

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