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Paper:

Flexible Pneumatic Actuators: A Comparison between The McKibben and the Straight Fibres Muscles

Carlo Ferraresi*, **Walter Franco*** **and Andrea Manuello Bertetto****

*Department of Mechanics, Politecnico di Torino
Corso Duca degli Abruzzi, 24 - 10129 Torino - Italy
Phone +39 011 5646943, Fax +39 011 5646999
E-mail ferraresi@polito.it
** Department of Mechanical Engineering,
University of Cagliari
Piazza d'Armi, 09123 Cagliari-Italy
Phone +39-070-6755716, Fax +39-011-6755717
E-mail manuello@zot.unica.it
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The prototypes of a McKibben actuator and a straight fibre muscle are presented. Their experimental characteristics are shown. For both kind of typology a mathematical model, able to evaluate the traction force as a function of the contraction ratio and the supply pressure, has been developed, taking into account the geometrical dimensions of the muscles and the mechanical characteristics of the materials. The models have been validated experimentally. Finally, by means of such models, a comparison between the behaviour and performance of the two kinds of actuator has been carried out.

Keywords: McKibben muscle, Straight fibres muscle, Pneumatic muscle actuator, Flexible actuator

1. Introduction

In certain Robotic applications it is necessary to adopt actuators with non common peculiarities, often provided by the Flexible Pneumatic Actuators (FPA). Among the FPAs, the muscle actuators turn out particularly interesting, showing advantages such as low weight, high force/mass ratio, high efficiency, lack of sliding parts and therefore of wear, no need of lubrication, no emission of polluting substances, the possibility of working with cheap and non polluting fluids (air, water), the possibility of working in extreme environments (absence of atmosphere, heavy temperature gradients, high magnetic fields, vibration noise).

Therefore, structures for biomechanical and aerospace use may be effectively driven by such actuators.

Among the muscle actuators, the McKibben muscle earned a big success, as testified by numerous papers on identification and modelling of its mechanical behaviour.[11,12,3] Besides, the McKibben muscle has been proposed in several applications of both biomechanical and aerospace kind.[7,8,15,2,10,13]

Besides the McKibben muscle, a new typology of actuator has been recently proposed: the straight fibre muscle,[9,4,1,6] able to provide, at same working condition, very high traction forces.

The variety of the muscles' typologies, on one hand widens the possibility of employment of such actuators, on the other requires, at the design stage, the availability of criteria for the choice of the most suitable kind for the specific application.

Since the mechanical behaviour of the muscle actuators is highly non-linear and derives from geometrical parameters (length, radius and thickness of the deformable cilindrical chamber), structural characteristics (mechanical characteristic of materials), and operating conditions (supply pressure and contraction ratio imposed), such behaviour can be simulated only by the development of non-linear models.

In this work, the prototypes of a McKibben and a straight fibre muscle have been realised.

Subsequently, the non-linear models of both actuator typologies have been developed. Several authors[3,14] derived the basic equations of the model using the virtual work principle, therefore corrected by empirical coefficients. In our work the mathematical models have been written by means of the structural equilibrium and congruity equations, taking into account the physical properties of the main elements of the muscles. In this way the models can effectively used as muscle design tools.

The models have been validated experimentally.

Finally, by the simulation, a comparison has been carried out, in order to highlight the peculiar characteristics of both kind of actuators.

2. Pneumatic Muscles

The pneumatic muscle actuators are made of three main elements (**Fig.1(a)**): the internal cilindrical chamber of elastomeric material, the not lengthening fibres and the heads. The fibres are disposed on the surface of the deformable chamber and linked to the heads, which in turn allow the supplying and the sealing of the working fluid inside the chamber, and allow the external connections of the actuator.

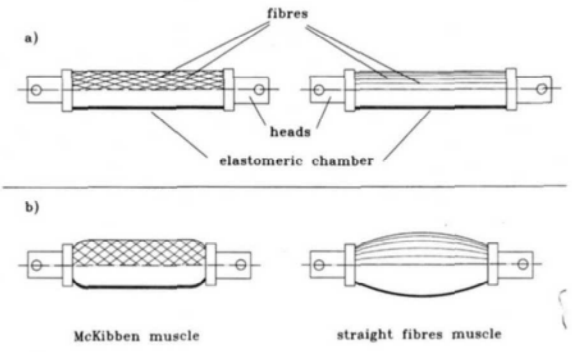

Fig. 1. Pneumatic muscle actuators. a) undeformed conditions. b) deformed conditions

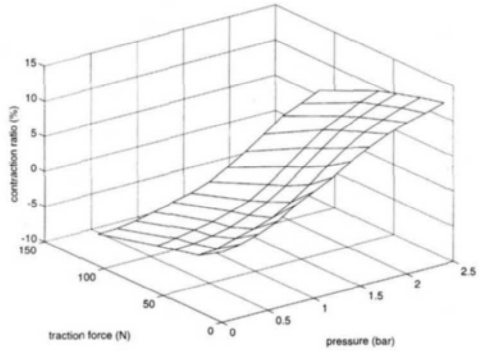

Fig. 3. Experimental contraction ratio of a McKibben muscle as a function of the traction force and the supply pressure.

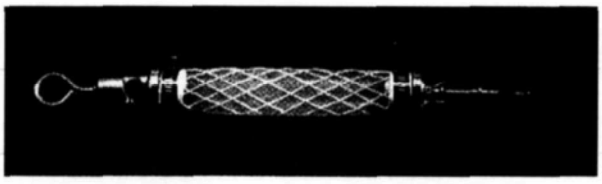

Fig. 2. Prototype of McKibben muscle.

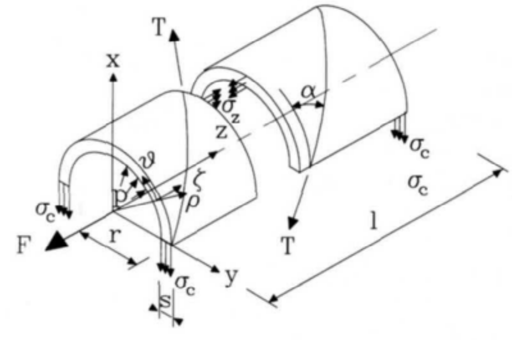

Fig. 4. McKibben muscle geometry.

When supplying the actuator at a certain pressure, the chamber tends to expand (**Fig.1(b)**). In such a way, once a definite load has been imposed, the muscle, because of the not lengthening fibres, becomes shorter and reaches a new equilibrium configuration; vice versa, once a given length is imposed, the muscle exerts a definite traction force.

If the fibres are wound on the deformable chamber with a certain angle different from 90 deg, the actuator is called McKibben muscle1.[1,12,5] If the fibres, on the contrary, are disposed parallel to the actuator axis, it is called straight fibres muscle.[9,4,1,6]

Although the structures of the two typologies of actuator are substantially similar, the mode of operating and the performance, at the same conditions, are very different. **Figure 1(b)** shows, for a generic contraction, the deformed shape of both the McKibben and the straight fibres muscle. It is evident that the shortening of the McKibben muscle is due to a dilatation of the deformable chamber that keeps almost constant along the actuator axis. In the case of the straight fibre muscle, on the contrary, the shortening is due to a cask-like deformation of the elastomeric chamber.

In order to evaluate correctly, at the design stage, the most suitable typology of actuator for the specific application, a non-linear modelling of both kind of muscles has been here developed.

The models, presented in this work, have been subsequently validated experimentally and used for a comparison of the two actuators.

2.1. The McKibben Muscles

A prototype of McKibben muscle has been realised (**Fig.2**). The deformable chamber, of silicon rubber, is 0.1m long, has an internal radius of 8mm and a thickness of 2mm. The not lengthening fibres, nylon made, are wound on the rubber chamber with an angle of 64 deg.

The prototype has been experimentally characterised. The actuator was linked to the structure of a test bench. Known and calibrated load was hanged to the actuator free end. By a pressure regulator the supply pressure was set; its value was measured by a strain gage pressure gauge (Celesco, PLC-50-G2; range 0÷3.4 bar; accuracy 0.5% F.S.). The actuator free end displacement was measured by a potentiometer displacement transducer (Celesco, DV301; range 0÷50mm; accuracy 0.25% F.S). Each measure was carried out 5 times, and then the mean value was calculated.

Figure 3 shows the actuator contraction ratio, defined as the shortening of the actuator related to the initial length, as a function of the traction force and the supply pressure. As typical, the traction force increases, for a definite contraction ratio, as the pressure increases, and decreases, for a definite supply pressure, as the contraction ratio increases, reaching eventually a null value for a certain contraction.

The McKibben muscle has been modelled as an isotropic homogeneous tube with Young modulus E (**Fig.4**). At the initial conditions, i.e. with supply pressure p and traction force F equal to zero, the chamber has a length l_o, internal radius r_o, thickness s and is wound n times by a fibre of length l_f and angle α_0.

A Cartesian frame of reference x, y, z is defined; the z direction coincides with the symmetry actuator axis. Another frame of reference ρ, θ, ζ is defined as local; in this frame of reference the ζ direction is parallel to the

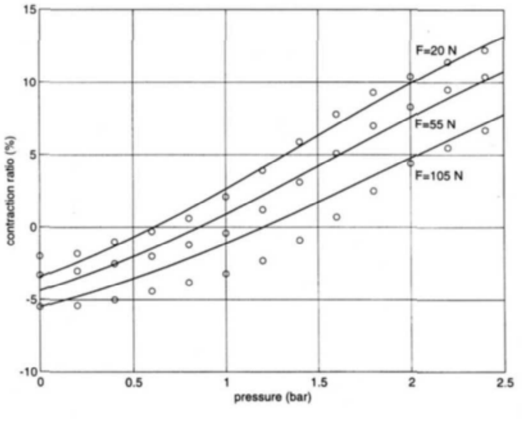

Fig. 5. Comparison between theoretical (continuous line) and experimental characteristic of McKibben muscle

symmetry axis, the ρ axis is radial, and the θ axis is tangential.

Supposing thin the tube wall and constant its thickness, increasing the supply pressure, for a given supply pressure p, the equilibrium along the directions x and z are:

$$prl = \sigma_c sl + nT\cos\alpha \quad (1)$$

$$F + \pi r^2 p = \sigma_z A + T\sin\alpha \quad (2)$$

The constitutive material equations, in circumferential and axial direction, supposing an infinite Poisson's ratio, are:

$$r = r_o\left(1 + \frac{\sigma_c}{E}\right) \quad (3)$$

$$l = l_o\left(1 + \frac{\sigma_z}{E}\right) \quad (4)$$

Finally imposing the geometrical congruity between the not extensible fibre and the flexible tube, it is possible to write:

$$(2\pi r)^2 + \left(\frac{l}{n}\right)^2 = \left(\frac{l_f}{n}\right)^2 \quad (5)$$

Since the inclination angle α between the tangent to the wire and the circumferential direction is:

$$\alpha = \mathrm{arctg}\frac{l}{2\pi rn} \quad (6)$$

it is possible to write the following equation:

$$F = \frac{p}{4\pi n^2}(3l^2 - l_f^2) - Esl^2\left(\frac{1}{n\sqrt{l_f^2 - l^2}} - \frac{1}{2\pi n^2 r_o}\right)$$

$$+ EA\left(\frac{l}{l_o} - 1\right) \quad (7)$$

Defined the geometry and the material of the muscle, the dimensional and structural parameters are known. The Eq.(7) gives the force value F provided by the actuator when supplied by a pressure p and having a length l.

The experimental validation of the model, i.e. the comparison between the theoretical and experimental contraction as a function of the supply pressure, for given loads of 20N, 55N and 105N, is shown in **Fig.5**. The model proves to be able to simulate with good accuracy the mechanical performance of the McKibben muscle. The discrepancies for low values of pressure or high values of load are due to construction imperfections, that could not be modelled.

Fig. 6. Prototype of straight fibres muscle

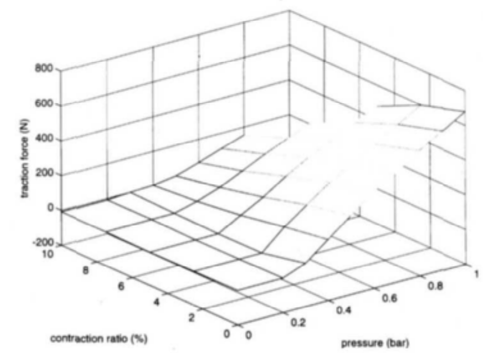

Fig. 7. Experimental traction force of a straight fibres muscle as a function of the contraction ratio and the supply pressure

2.2. The Straight Fibres Muscle

The **Fig.6** is a photograph of a prototype of straight fibres muscle realised. It is made up of an elastomeric chamber of initial length equal to 0.1m, internal radius of 7mm and thickness of 1mm. The 40 not lengthening fibres, disposed parallel to the actuator axis, are made of nylon.

The prototype has been characterised experimentally. The experimental tests conducted on the straight fibres muscle consisted of the measure of the traction force of the actuator, by means of a load cell (Bourdon-Sedeme XC 100; range 0÷1000N; accuracy 0.049% F.S.), versus an imposed supply pressure and length.

The **Fig.7** shows the traction force of the actuator as a function of the supply pressure and the contraction ratio

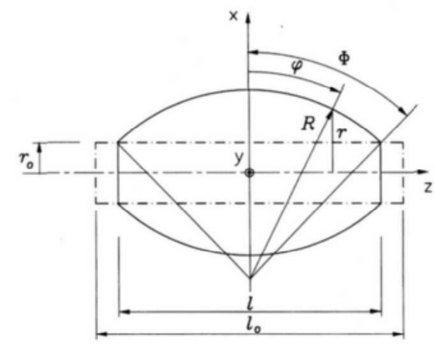

Fig. 8. Straight fibres muscle geometry

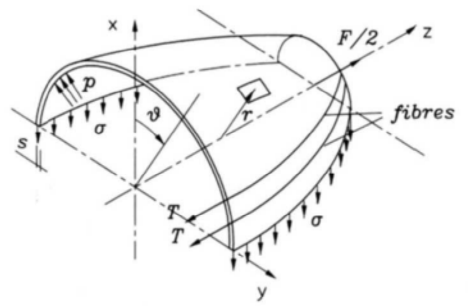

Fig. 9. 3-D scheme of deformed straight fibres muscle

imposed. Qualitatively, the muscle shows a mechanical behaviour similar to the McKibben muscle. A direct comparison between the two prototypes is not possible, since the dimensions are different, but it is possible to see that, at same supply pressure and same contraction ratio, the traction force of the straight fibre muscle is remarkably higher.

The straight fibres muscle has been modelled as a tube of homogeneous and isotropic material **(Figs.8** and **9)** having Young modulus E, initial length l_o, initial radius r_i and thickness s, linked to the heads of radius r_o and strengthened axially by N fibres having cross section A_f, initial length l_0 and Young modulus E_f.

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. Supposing that the cross section of the deformed chamber assumes the shape of a circular arc with radius R, as indicated by continuous line in Fig.8, the force equilibrium of 1/4 actuator in x-direction can be written as:

$$\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_0^{\phi} p\cos\theta\cos\varphi rR\,d\theta\,d\varphi - T\sin\phi \cdot \left(\sum_{i=-N/4}^{+N/4} \cos\left(2\frac{\pi}{N}i\right)\right) - $$
$$-2ERs\int_0^{\phi} \frac{r_o + R(\cos\varphi - \cos\phi) - r_i}{r_i}\,d\varphi = 0 \quad (8)$$

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

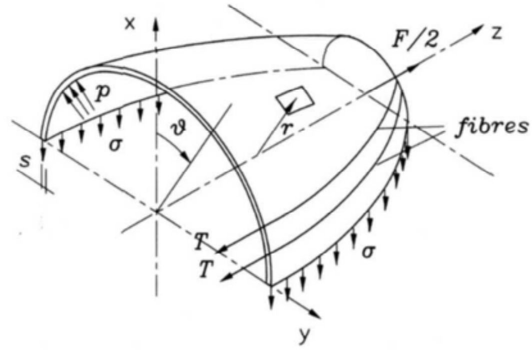

Fig. 10. Comparison between theoretical (continuous line) and experimental characteristic of straight fibres muscle

fibres. The equilibrium in z-direction is expressed by the following equation:

$$\frac{F}{2} + \frac{p\pi r_o^2}{2} + \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_0^{\phi} p\sin\varphi rR\,d\upsilon\,d\varphi - \frac{NT}{2} = 0 \quad (9)$$

By substituting in (8) and (9) the expression of the radius r of the generic cross-section:

$$r = r_o + R(\cos\varphi - \cos\phi) \quad (10)$$

and integrating, one obtains the following equilibrium equations:

$$\frac{2ER^2s}{r_i}(\sin\phi - \phi\cos\phi) + El_f s\frac{r_o - r_i}{r_i} + T\sin\phi \cdot \left(\sum_{i=-N/4}^{+N/4} \cos\left(2\frac{\pi}{N}i\right)\right) -$$
$$-p\left(\phi R^2 + 2Rr_o\sin\phi - \frac{R^2}{2}\sin 2\phi\right) = 0 \quad (11)$$

$$F + p\pi(r_o + R(1 - \cos\phi))^2 - NT = 0 \quad (12)$$

The characteristic equation of the fibre is:

$$l_o\left(1 + \frac{T}{E_f A_f}\right) - l_f = 0 \quad (13)$$

Finally, for the geometrical congruence of the muscle, one can write:

$$R\phi - \frac{l_f}{2} = 0 \quad (14)$$

$$R\sin\phi - \frac{l}{2} = 0 \quad (15)$$

Defined the geometry and the material of the muscle, the dimensional and structural parameters are known. The numerical solution of Eq.(11)-(15) permits to evaluate the traction force F of the straight fibres muscle for given supply pressure p and length l.

The experimental validation of the model, i.e. the

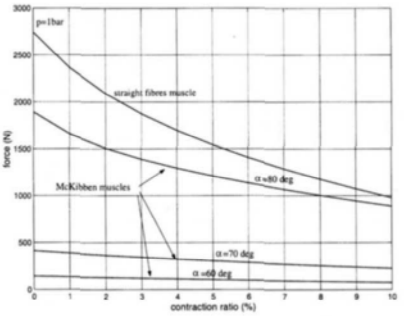

Fig. 11. Traction force of a McKibben muscle, for different winding angles, and of a straight fibres muscle versus the contraction ratio (1 bar supply pressure)

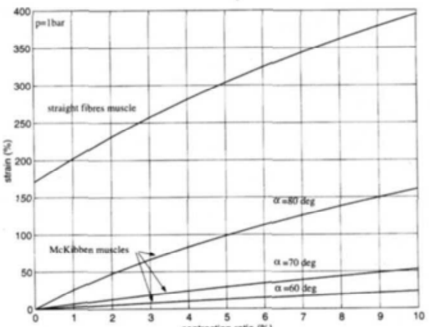

Fig. 12. Elastomeric chamber strain of a McKibben muscle, for different winding angles, and of a straight fibres muscle versus the contraction ratio (1 bar supply pressure)

comparison between the theoretical and experimental traction force as a function of the supply pressure, for different contraction ratios, is shown in **Fig.10**.

3. Comparative Analysis

The mechanical behaviours of the two muscle actuators are substantially different, as partially highlighted by the experimental results. In fact, although the actuators are similar in structure, they have a different operating principle and therefore, even with equal geometry and at same supply pressure and contraction ratio, they provide different traction force, with different stresses in the material of the rubber chamber and the fibres.

An experimental comparison of the two actuators' behaviour, with various values for the geometrical and structural parameters, would be particularly onerous, requiring the construction and characterisation of numerous prototypes. But the availability of the two mathematical models, previously described and experimentally validated, allowed to carry out an extensive comparative analysis, in order to evaluate the main differences and individuate the fields of application for the two typologies of muscle actuators.

The analysis has been carried out starting from a common reference geometry for the two actuators: initial length 0.2m, initial radius 10mm, chamber wall thickness 1 mm. Besides, a Young modulus of 0.5MPa has been

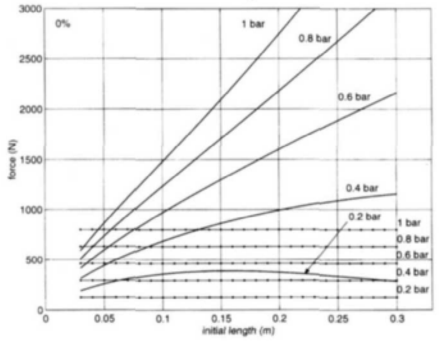

Fig. 13. Traction force of a straight fibres muscle (—) and a McKibben muscle (•-) versus the initial length for different supply pressures (0% contraction ratio)

assumed for the elastomeric material.

The mechanical behaviour of the McKibben muscle is strongly influenced by the fibres' winding angle.

The **Fig.11** shows the traction force exerted by a McKibben muscle with reference geometry, supplied with 1 bar pressure, as a function of the contraction ratio and for different winding angles. As the contraction increases, the traction force decreases. But it is possible, at same contraction ratio, to obtain higher traction forces by increasing the value of the winding angle. In particular, the highest traction force values are generated with an angle of 90 deg, corresponding to fibres disposed parallel to the actuator axis, that is the case of straight fibres actuator.

Actually, in the design of the muscle actuator it is necessary to consider also the extent of the maximum radial strain of the deformable chamber, that must be compatible with the mechanical characteristics of the material. The **Fig.12** shows the maximum strain of the elastomeric material in the same conditions imposed for the results of **Fig.11**. As the actuator's contraction ratio increases, the material deformation increases as well, at the same winding angle of fibres. Besides, for the same contraction ratio and supply pressure, the material of the deformable chamber of actuators with greater winding angles is subjected to higher deformations. In the case under study, the extent of the deformation is lower than 400%, and therefore compatible with the maximum allowable strain of certain elastomeric materials.

McKibben actuators realising a good compromise between the capability of generating high traction forces and limited strain of the material have winding angles of the fibres of about 75 deg. This is therefore the reference value of the winding angle for the McKibben actuator chosen to be compared with the straight fibres muscle.

In the design stage it is necessary to define the typology of actuator and the corresponding geometry able to satisfy the specific needs of traction force and contraction ratio, but on the other hand avoiding an excessive stress in the deformable material. For this reason some comparative simulations of the mechanical behaviour of actuators with same initial radius but different initial length, and with same initial length but different initial radius have been carried out.

The **Fig.13** shows the traction force of both a McKibben and a straight fibres muscle, as the initial length

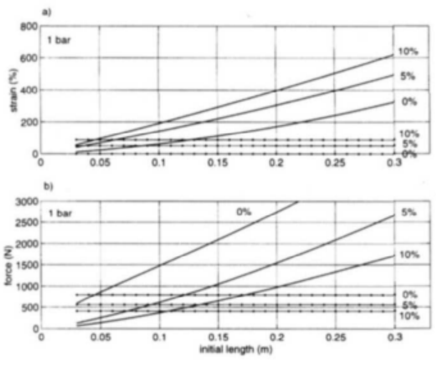

Fig. 14. Maximum chamber strain (a) and traction force (b) of a straight fibres muscle (—) and a McKibben muscle (•-) versus the initial length, for different contraction ratios (1 bar supply pressure)

varies, with contraction ratio imposed to 0% and for different supply pressures.

At same conditions, the traction force always increases as the supply pressure increases. Besides, the traction force of a McKibben actuator is not depending on its length.

On the contrary, straight fibres muscles of greater length usually show greater traction force. As a matter of fact it can be noted that, in case of low supply pressures (0.2 bar), the characteristic of traction force versus initial length shows a maximum.

It can be noticed that, for a great initial length of the chamber, the straight fibre muscle provides, at same conditions, a greater traction force. On the other hand, McKibben actuators with a small initial length seem to be more performing.

The **Fig.14(b)** shows a comparison between the forces given by the two typologies of actuators for a supply pressure of 1 bar, again as a function of the initial length and for different contraction ratios. Every configuration shows a reduction of the traction force as the contraction increases. Also in this conditions, straight fibres muscles with great initial length provide a traction force much greater than the corresponding McKibben muscle.

As a matter of fact, considering also the strain of the chamber (**Fig.14(a)**), it can be noticed that it is not possible, for instance, to use the straight fibres muscle analysed with contraction ratio of 10%, if it has an initial length greater than 0.2m, because in this case the material would be subjected to a strain greater than the 400%.

On the contrary, the McKibben muscle is less problematic from the point of view of material strain. In particular, the strain ε of the chamber depends only on the contraction ratio of the actuator, i.e. on the initial and actual lengths l_o and l, and on the winding angle α, according to the following relation:

$$\varepsilon = \left(\frac{\sqrt{l_o^2 - l^2 \sin^2\alpha}}{l_o \cos\alpha} - 1 \right) \cdot 100 \quad \ldots\ldots\ldots \quad (16)$$

In order to reduce the deformation of the elastomeric chamber of the straight fibres muscle, at same conditions, it is necessary to adopt greater diameters, as shown in **Fig.15(a)**, which reports the strain of the material for both typologies of actuators, supplied at 1 bar, for several con-

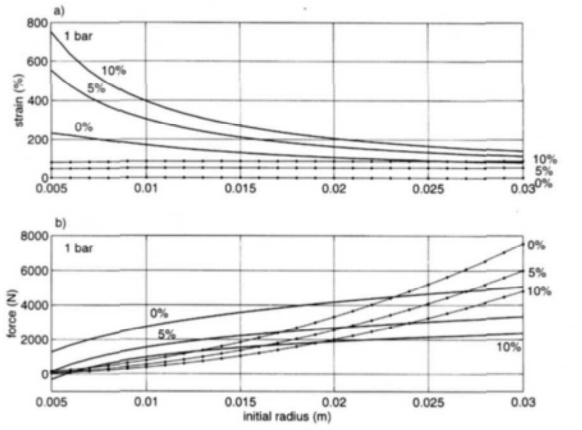

Fig. 15. Maximum chamber strain (a) and traction force (b) of a straight fibres muscle (—) and a McKibben muscle (•-) versus the initial radius, for different contraction ratios (1 bar supply pressure)

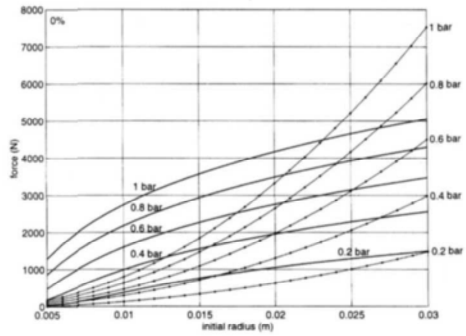

Fig. 16. Traction force of a straight fibres muscle (—) and a McKibben muscle (•-) versus the initial radius, for different supply pressures (0% contraction ratio).

traction ratios, as a function of the initial radius of the chamber.

Straight fibres muscles with great initial radius turn out to be less performing than corresponding McKibben muscles, as shown in **Fig.15(b)**.

The same effect is further on highlighted in **Fig.16**, showing the traction force of both muscles as a function of the initial radius, for contraction ratio equal to zero, and for different supply pressures. It is generally convenient, in order to increase the force performance of the McKibben muscle, to increase its diameter. Also in the case of the straight fibres muscle, actuators with greater initial radius are more performing as regards the force. However, for a given supply pressure and a given contraction ratio, the McKibben muscle is more performing if the initial radius is greater than a definite value.

4. Conclusions

The mathematical models of both a McKibben muscle and a straight fibres muscle have been developed. They allowed to carry out comparisons between the performance and characteristics of both typologies of actuators, analysed at the same operating conditions.

The models have been validated on the base of experimental tests made on two prototypes actually realised.

The analyses showed that the two typologies of muscles, even though they present a similar structure, show a substantially different mechanical behaviour, as regards both the traction force and the strain of the elastomeric chamber.

Muscles with dumpy geometry (low length-diameter ratio) are generally more performing if realised in the McKibben typology. Vice versa, straight fibres muscles provide a traction force greater than McKibben ones in case of slender geometry.

However, it has to be considered also that the models do not take into account the effect of the actuator heads, which are particularly important in case of dumpy geometry. As a matter of fact, dumpy actuators turn out to be less performing of what simulated by the models.

The straight fibres muscle usually shows a force performance greater than that of a McKibben muscle having the same geometry. On the other hand, the material of the straight fibres muscle may be subjected to higher strains, that can easily reach the mechanical resistance limits.

Since the performance of such actuators depends on numerous factors, such as geometrical parameters (initial length and radius, chamber thickness, winding angle), structural characteristics (Young modulus of elastomeric chamber and fibres) and operative conditions (supply pressure, contraction ratio of the actuator), it is very difficult to foresee the behaviour of a prototype before its construction. The models proposed here allow to evaluate theoretically the performance of both kind of actuators as a function of all the aforesaid factors, and therefore can be an effective tool for the choice of typology of the actuator and its design.

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Nomenclature

A:	area of the chamber cross section
A_f:	area of the fibre's cross section
E:	Young's modulus of the elastomeric chamber
E_f:	Young's modulus of the fibre
F:	traction force
l:	actual length of the muscle
l_f:	length of one fibre
l_o:	initial length of the muscle
N:	number of the fibres
n:	coils number of the fibre
p:	supply pressure
R:	curvature radius of the deformed actuator
r:	radius of the generic cross-section
r_i:	initial radius of the chamber of the straight fibres muscle
r_o:	radius of the end-cap
s:	thickness of the chamber
T:	tension of the fibre
a:	angle between the tangent to the fibre and the circumferential direction
σ, σ_c, σ_z:	normal stresses of the elastomeric chamber
x, y, z:	reference frame
ϕ:	angular semi-amplitude of the deformed actuator
θ:	angular coordinate
r, θ, ζ:	reference frame
φ:	angular coordinate

Name:
Carlo Ferraresi

Affiliation:
Full Professor, Technical University "Politecnico di Torino"

Address:
Politecnico di Torino - Department of Mechanics
Corso Duca degli Abruzzi 24-10129 Torino - Italy
e-mail: ferraresi@polito.it

Brief Biographical History:

1980 Degree in Mechanical Engineering
1983 Researcher in Applied Mechanics, Department of Mechanics, Politecnico di Torino
1992 Associate Professor of Applied Mechanics, Politecnico di Torino
1999 Vice-Chairman of the BS Course in Mechanical Engineering
1999 Chairman of the PhD Course in Applied Mechanics
2000 Full Professor of Applied Mechanics, Politecnico di Torino

Main Works:

- "Mechanical Microactuators with photostrictive control", JSME International Journal, Tokyo, Vol.41, No.4, 1998, pp.886-892.
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Name:
Andrea Manuello Bertetto

Affiliation:
Associated Professor, Department of Mechanical Engineering, University of Cagliari-Italy

Address:
Piazza d'Armi, 09123-Cagliari, Italy

Brief Biographical History:

1958-Born in Milan-Italy
1989-Ph.D. in Aerospatial Engineering
1992-Researcher in Applied Mechanics at the Department of Mechanics, Politecnico di Torino
1998-Associated professor at the Department of Mechanical Engineering University of Cagliari

Main Works:

- "Free edge Stress Propagation in Composite Laminates"-Computer and Structures, Pergamon Press, Vol.29, No.3, pp.365-380, 1998
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Name:
Walter Franco

Affiliation:
Researcher, Department of Mechanics, Politecnico di Torino

Address:
Politecnico di Torino-Department of Mechanics
Carso Duca degli Abruzzi 24-10129 Torino-Italy
e-mail: francow@polito.it

Brief Biographical History:

1994-Degree in Mechanical Engineering
1999-Ph.D. in Applied Mechanics
2001-Researcher in Applied Mechanics at the Department of Mechanics, Politecnico di Torino

Main Works:

- "Features of the Lateral Active Pneumatic Suspensions in the High Speed Train ETR470", 6th UK Mechatronics Forum International Conference, Mechatronics '98, Skovde, Sweden, 621-626, 9-11 September (1998)
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