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Article Type: Original Article

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Numerical modelling and experimental validation of a McKibben pneumatic muscle actuator

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Abstract

The McKibben muscle belongs to the type of muscles known as braided muscles. It is made of an inner hyper-elastic tube, surrounded by a braided shell made of inextensible threads; both ends provide for mechanical and pneumatic seal.

A finite element model of a McKibben pneumatic muscle was built and experimentally validated. The model is based on characteristic parameters of McKibben muscles. It takes into account the non-linearity of the constitutive material of the inner tube. It does not simulate backslashes between the tube and the shell at rest condition, but it models threads and rubber that are always connected. However, it does not consider friction among threads.

In order to build and to validate the proposed numerical model, an experimental prototype of the muscle was designed and built. Both isotonic and isometric tests were carried out. Same tests were simulated in the finite element environment. The model validation was performed by comparison between experimental and numerical results.

Keywords

McKibben pneumatic muscle; non-linear FEM analysis; soft actuators; isotonic and isometric tests; robotics

1. Introduction

Industrial robotic applications require high positioning precision, high durability, high speed, cycles with high frequencies and high repeatability that can be satisfied by conventional actuators, electric drives and fluid power actuators (Caldwell et al., 1995). However, due to the high weight, high stiffness and rigid moving components, such devices are not recommended when the working space of the robot has to be shared with humans (Bicchi and Tonietti, 2004), in a biomedical and bio-inspired robot (Durante et al., 1999, Koceska et al. 2013) where intrinsic safety, compliance, high power to weight ratio, no relative sliding motion, no lubricants and dynamic seals are required (Manuello Bertetto and Ruggiu, 2004). Furthermore, some applications require soft and flexible actuators that are able to perform soft increasing of the movement, that are provided with higher compliance during movement and that are able to be adapted to various geometries (Faudzi et al., 2012).

These requirements are met by pneumatic artificial muscles (PAMs). They are made by a closed reinforced elastic deformable membrane attached to ends: generally, air inflation causes a radial expansion followed by an axial membrane contraction, with a pulling force which is externally applied. Since part of the powering pneumatic energy is spent to strain the membrane, PAMs in an *at rest-working-at rest* cycle show a hysteretic behaviour whose amplitude depends on the membrane material properties (Ferry, 1980).

There are several advantages to use PAMs: they are extremely lightweight, easy to be directly connected and replaced to a structure to be powered, safe from fire and explosions, suitable to be used in dusty environments, in presence of vibrations and within electromagnetic fields. Moreover, due to the intrinsic adjustable compliance, PAMs do not add significant stresses in assemblies with misalignments and can perform a soft touch in man-machine interactive devices (Sirolli, 2015). Finally, PAMs are generally free from friction and air loss for the absence of dynamic seals, are easy to be commanded because only one chamber requires air inlet/outlet. They also provide for a lower air consumption than traditional cylinders and provide force changes with regard to length so that the PAM acts as a non-linear variable stiffness spring (Hannaford and Winters, 1990).

Several types of PAMs were studied: braided muscles (Schulte, 1962; Caldwell et al., 1993; Winters, 1995; Chou and Hannaford, 1996; Tondu and Lopez, 2000; Davis and Caldwell, 2006), pleated muscles (Daerden et al., 1998; Daerden, 1999; Daerden and Lefeber, 2001; Villegas et al., 2012), netted muscles (Immega, 1987), embedded muscles (Baldwin, 1967; Scott Caines, 1991; Marcinčin et al., 1995), straight fiber pneumatic muscle (Morecki, 2001; Raparelli et al., 2000) and bellow muscles that develop a force resulting in an axial membrane extension (Noritsugu et al., 2005; Antonelli et al., 2010; Belforte et al., 2014; Antonelli et al., 2016). Some of them were patented (Morin, 1953; Kleinwachter and Geerk, 1972; Yarlott, 1972; Paynter, 1988; Beullens, 1989; Immega and Kukolj, 1990; Scott Caines, 1991) and some are commercially available by Bridgestone Rubber Company (Rubbertuator), Festo AG (MAS and DMSP fluidic muscle) and Shadow Robot Company (Shadow Air Muscles).

The Mckibben muscle (MKM), belonging to the braided muscles type, is the most used and published PAM (Daerden and Lefeber, 2002). It's made of an inner elastomeric tube surrounded by a braided shell and two ends. Several works deal with MKM modelling. On the one hand, several researchers defined theoretical modelling and experimental relations in terms of the amount of maximum contraction (Schulte, 1962), effects of rounding of the terminal ends (Tsagarakis and Caldwell, 2000; Doumit et al., 2009; Sorge and Cammalleri, 2013), and fatigue life (Klute and Hannaford, 1998; Kingsley and Quinn, 2002). The observation of hysteresis phenomenon led some researchers to study thread-on-thread friction that acts inside the muscle braided shell (Tondu, 2012), excluding friction between the internal tube and the braided shell. In particular, Chou and Hannaford (1996) suggested that a typical experimental friction force value is equal to 2.5 N. Tondu and Lopez (2000) modelled friction as a function of the contact surface of the threads, the internal pressure and a constant k, used to match experimental and modelled data. Davis and Caldwell (2006) substituted the k constant considering the real threads envelopment of the braided shell. Finally, non-linear quasi-static models (Wang et al., 2015; Jouppila et. Al., 2010; Sárosi, 2012) and dynamic models (Hošovský and Havran, 2012; Sárosi et al., 2015) were developed to capture the actuation force versus the behaviour of the contraction ratio.

On the other hand, several models were developed by the finite element (FE) method: the non-linearity of the expanding rubber inner tube, simulated by the 2 coefficients Mooney-Rivlin formulation, and the mechanism for transferring load to the braided shell were modelled (Manuello Bertetto and Ruggio, 2004). Another model was based on a cylinder with orthotropic material properties representing the layers of membrane and braids (Ramasami et al., 2005). In addition, a non-linear model, adopted to analyse the relationship between MKMs placed in parallel and the total contraction ratio of each of them, considered only the geometric non-linearity while a linear material property was adopted for the non-linear rubber material (Wakimoto et al., 2011). Another non-linear model was built to predict the direction and bending angles of a MKM with two different braid angles (Faudzi et al., 2012). Still, a model to optimize the angle of the braided shell (Iwata et al., 2012) and another to establish a quantitative design optimization method were proposed (Nozaki and Noritsugu, 2014). Finally, for an application of MKMs as control devices in parachute soft landing systems and parachute steering control systems, a special cable element was developed to model the mechanical behaviour of the muscle; the model considers the relationship between internal pressure, threads bias angle, radius and length and resultant axial force, based on kinematic assumption of inextensible threads (Zhou et al., 2004). In another approach, the outer tube was modelled as an anisotropic membrane comprised of threads in two directions. In this model the material properties of the membrane were calculated as a combination of the threads material properties (Zhang et al., 2005).

An analysis of literature showed the lack of a numerical model of the MKM built on the real geometric characteristics of the braided shell, as commercially available. Typically, the real geometrical parameters of the tube and the real properties of its material were only considered; for braided shell, average literature parameters are considered.

The aim of the present work is the development of a FE model of the MKM and the experimental validation of it. A non-linear finite element model, based on real parameters of the MKM, is proposed in order to predict the behaviour of the MKM and to be used as a validated and reliable design tool before prototyping. For the validation of the numerical model, an experimental prototype of the MKM has been designed and constructed. This work is divided as follows: general peculiarities of the McKibben muscle will be described in Section 2; the numerical model will be detailed in Section 3; the experimental prototype will be described in Section 4 and the validation of the numerical model will be presented and discussed in Section 5.

2. The McKibben pneumatic muscle

Invented in 1950s, the MKM is made of an internal hyper-elastic rubber tube surrounded by a braided mesh shell, made of flexible and inextensible threads (strands) according to helical weaving, and has two ends for the air inlet/outlet and for the fittings with external loads or constrains. When pressurized, the internal tube pushes against the external shell. Due to the high longitudinal stiffness, the threads act like a pantograph that converts circumferential pressure forces into an axial contraction force in which the muscle shortens according to its increase in volume. With reference to Figure 1, the pantograph operating principle led to consider three basic parameters (Tondu and Lopez, 2000): 1) θ_0 (the at rest angle of the braided mesh shell), 2) L_0 (the at rest working length of the muscle) and 3) D_0 (the at rest internal diameter of the inner tube). They are related in the following expressions:

$$\frac{\mathrm{L}}{\cos\theta} = \frac{\mathrm{L}_0}{\cos\theta_0} \tag{1}$$

$$\frac{D}{\sin\theta} = \frac{D_0}{\sin\theta_0} \tag{2}$$

Chou and Hannaford (1996) developed the following expression for force F:

$$F = \frac{\pi D_0^2 P}{4}\left(\frac{1}{\sin\theta_0}\right)^2 [3(1-\varepsilon)^2\cos^2\theta_0 - 1] \tag{3}$$

where $\varepsilon = 1 - L/L_0$ and P is the internal pressure, with the assumptions of infinite length of muscle, absence of stretching of the threads, negligible friction between threads and internal tube and absence of effects of rounding of the terminal ends.

Other significant parameters are H_0 (the axial diagonal of the single rhombus shaped braided structure) and h_0 (the circumferential diagonal of the single rhombus shaped braided structure), measured as shown in Figure 1 and related by:

$$h_0 = H_0\tan\theta_0 \tag{4}$$

$$h = H\tan\theta \tag{5}$$

[insert Figure 1]

Figure 1. The McKibben muscle: principal components and operating principle, at rest (upper view) and working (middle view). On the right side, a scheme of a single braided structure where one can notice the single strand made of a series of threads.

3. The Numerical Model

The muscle shows non-linearity due to geometrical (large strain) and material behaviour, (non-linear constitutive behaviour of the tube material). Furthermore, it is made of three materials: rubber for the tube, plastic for the threads of the shell and metal/plastic for the ends. Finally, effects of rounding of the ends of tube depend on the stiffness and the density of the braided shell. For this reason, a convenient numerical model was developed with the aim to provide a design tool of MKMs to be realized by commercial braided shells and rubbers.

Due to the helical envelopment of the threads and to take into account the pantograph operating principle, a 3-dimensional model was implemented: due to the symmetry on the plane perpendicular to the muscle axis and due to the axisymmetric geometry, it was possible to simulate 1/8 of the real prototype geometry. The model was built in order to simulate two types of experimental tests: quasi-static isotonic tests (at a constant load, the muscle is free to shorten and the displacement versus the pressure is computed) and quasi-static isometric tests (at a constant length, the muscle keeps its length by axial constraints at the ends and the axial force versus the pressure is computed).

The numerical model construction starts from material type definition; hence, node and element set definitions. The construction is based on the above mentioned basic parameters, namely θ_0, L_0 and D_0, the wall thickness s of the tube, H_0 and the height p of the end. Moreover, control and performance parameters like the maximum pressure value P and the applied load F, for isotonic tests simulation, or the allowed displacement ΔL, for the isometric tests simulation, have to be considered.

The model reproduces the original braided shell, divided by rhombus shaped elements. Since threads in contact with the tube can be assumed rigidly locked with it during the contraction (Tondu and Lopez, 2000), each side of the external rhombus shaped element is a portion of a strand of threads. For this reason the numerical model does not simulate possible backslashes between the tube and the shell at rest condition. Instead, it models strands and rubber always connected and it does not consider friction among strands. The construction of the model geometry has been carried out by an ad hoc algorithm running on a freeware computing language: the output result is a script file to be used as input for the finite element code.

3.1 Material types definition

A preliminary test was carried out for the assessment of the constitutive law of the silicon rubber Dow Corning Silastic® S to be adopted as material of the inner tube. It's a high strength silicone rubber made of two components, base and curing agent in 10:1 weight ratio, and suggested for thickness over 2 mm. A cylindrical specimen was used in uniaxial tension test, taking 18 data points in the full range of displacement. Figure 2 shows the true stress-strain curve, typical of hyper-elastic materials.

The non-linear behaviour of these kinds of materials can be modelled according to the Mooney-Rivlin's energy function W. On the basis of the shown stress-strain curve, as proposed by Klute and Hannaford (2000) and improved by Manuello Bertetto and Ruggio (2004), c_{10} and c_{01}, coefficients of the first order Mooney-Rivlin formulation, were assessed (Raparelli et al., 1999). Energy function W of an isotropic and incompressible material, as silicone rubber, can be written as:

$$W = c_{10}(I_1 - 3) + c_{01}(I_2 - 3) \tag{6}$$

where I_1 and I_2 (and I_3) are the strain invariants, expressed as function of the principal stretches λ_1, λ_2 and λ_3:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{7}$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_1^2\lambda_3^2 + \lambda_2^2\lambda_3^2 \tag{8}$$

$$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{9}$$

For incompressible material, I_3 is equal to 1 and (9) becomes:

$$\lambda_1\lambda_2\lambda_3 = 1 \tag{10}$$

In uniaxial tension, $\lambda_1 = 1 + \varepsilon_1$ is the stretch in direction being loaded and calculated by the engineering strain in that direction, and $\lambda_2 = \lambda_3 = \lambda_1^{-1/2}$ are the stretches in direction not being loaded. On the basis of this assumptions, (7) and (8) can be expressed as:

$$I_1 = \lambda_1^2 + 2\lambda_1^{-1} \tag{11}$$

$$I_2 = 2\lambda_1 + \lambda_1^{-2} \tag{12}$$

The principal Cauchy stresses in 1 and 2 directions can be expressed as:

$$\sigma_{11} = -p + 2\frac{\partial W}{\partial I_1}\lambda_1^2 - 2\frac{\partial W}{\partial I_2}\lambda_1^{-2} \tag{13}$$

$$\sigma_{22} = -p + 2\frac{\partial W}{\partial I_1}\lambda_1^{-1} - 2\frac{\partial W}{\partial I_2}\lambda_1 = 0 \tag{14}$$

and subtracting (14) from (13), the principal true stress for uniaxial tension can be expressed as:

$$\sigma_{11} = 2(\lambda_1^2 - \lambda_1^{-1})\left[\frac{\partial W}{\partial I_1} + \lambda_1^{-1}\frac{\partial W}{\partial I_2}\right] \tag{15}$$

Since true strains of an experimental muscle should not exceed 90%, for the Mooney-Rivlin formulation the stress-strain curve was taken into account until this limit was reached. The assessed value of c_{10} and

c_{01} are 0.0694 and 0.0628, respectively. The Poisson ratio, computed by measurements of the diameter of the specimen during test, is equal to 0.46.

[insert Figure 2]

Figure 2. Experimental and numerical true stress-strain curve of silicone rubber.

The material type of the threads is considered as linear isotropic, described by the Young's modulus of Polyamide 66 (2200 MPa) which is the material used for the shell of the prototype for the experimental validation.

The end material type is considered as linear isotropic, described by the Young's modulus of Aluminium (70000 MPa) and the Poisson ratio (0.33).

3.2 Node set construction

As for nodes for the tube, the number *n*, of nodes along the half of the working length L_0, and the number *m*, of nodes along the external quarter of the circumference, are computed as:

$$\mathrm{n} = \mathrm{int}(\mathrm{L}_0/\mathrm{H}_0) + 1 \tag{16}$$

$$\mathrm{m} = \mathrm{int}\left(\frac{\pi(\mathrm{D}_0/2 + \mathrm{s})/2}{\mathrm{h}_0}\right) + 1 \tag{17}$$

Then, L_0, h_0 and H_0 values were optimized for counting the exact *n* and *m* nodes and for satisfying (4); moreover, the number of circumferential nodes at height zero and at height L_0 is the same. The nodes are placed as shown in Figure 3; the wall thickness of the tube counts four nodes.

As for nodes for the end, they are placed as the nodes of the tube at height L_0, but also at height $L_0 + p$; moreover, two nodes were placed along the symmetry axis, at height L_0 and $L_0 + p$.

Finally, as for isometric tests simulation, one node is placed along the symmetry axis, at height $L_0 + p + q$ in order to apply the length constraint.

[insert Figure 3]

Figure 3. Unrolled frontal view of node set.

3.3 Element sets construction

The first set of elements was created to simulate the rubber tube. All elements are bricks type, defined by eight nodes with three degrees of freedom (dofs) for each node. The elements have a prismatic shape with a rhombus shaped base except for the boundary elements that have a triangular shaped base. The wall thickness has 3 elements. Material properties were defined in terms of the 2 coefficients Mooney-Rivlin formulation and Poisson ratio, previously cited.

The second set of elements was created to simulate the braided shell. All elements are trusses, defined by two nodes with three dofs for each node, coincident with nodes of each edge of the external surface of the tube elements. Each element models a whole strand, made of six threads, whose section area is equal to 0.3 mm^2.

The third set of elements was created to simulate the end. All elements are brick type, defined by eight nodes with three dofs for each node.

Only for isometric test, a truss element, of the same type of the braided shell, was added in order to simulate an infinitely rigid truss, acting when the muscle reaches the allowed displacement. It is defined by the node of the upper surface of the end, along the symmetry axis, and the node at the height q, shown in Figure 3. The elastic modulus was fixed equal to E=10^6 MPa; the section was fixed equal to 1 mm^2.

3.4 Constrains and load definition

Symmetrical constrains were applied to take into account geometrical symmetries; pressure value P was applied to act perpendicularly to each of the internal surfaces of the model (tube and end internal elements). In isotonic tests, a force F, opposing to the shortening of the muscle, was applied on the node of the upper surface of the end, along the symmetry axis. Figure 4 shows a scheme of the model with constrains and loads.

[insert Figure 4]

Figure 4. An example of a high mesh density numerical model with applied constrains and loads. In the case of isometric test simulations, force is replaced by a truss element.

The non-linear analyses were based on the Newton-Raphson method. Pressure P was applied to all the internal surfaces according to a ramp, from zero to the input value, during the defined time step. The same procedure was adopted for the force F, in the model for isotonic test simulations. The axial truss element, for isometric test simulations, is activated when the allowed displacement is performed.

The numerical model was implemented in the APDL environment of the commercial code Ansys 16.2, Academic Release.

Before validation of the model, a preliminary analysis of the mesh size, in terms of the suitable H_0 input value, was carried out in an unloaded isotonic model simulation. Results based on five values of H_0 were compared: 0.5, 1, 2, 5 and 10 mm, while all the other parameters remained constant. Figure 5 shows the compared results. Model built on 0.5 mm did not converge over 0.085 MPa. Models built on 1 and 2 mm carried out similar results (also model built on 0.5 mm, until its validity, provided for the same results of 1 and 2 mm ones). Over this values, results diverge of about 5% and 14%, respectively, for H_0 equal to 5 and 10 mm. In order to reduce calculation time and to assure best approximating results, the analysis suggested to adopt the suitable dimension equal to 2 mm as input value for H_0.

[insert Figure 5]

Figure 5. Mesh size comparison.

Figure 6 shows a particular of the developed numerical model.

[insert Figure 6]

Figure 6. A view of a high mesh density numerical model.

4. The experimental McKibben muscle

It was necessary to adopt a reference experimental prototype for the validation of the numerical model. A prototype has been designed and built according to the classical scheme of MKM: a Dow Corning Silastic® S silicone rubber tube, previously described, within a commercial braided shell with two ends, later called upper and lower ends, respectively (with and without air duct).

The tube was made by casting the silicon rubber, in the viscous phase, into a suitable injection mould. The tube length is equal to 308 mm, the internal diameter D_0 is equal to 24 mm and the wall thickness is equal to 3 mm; these dimensions were selected because of a previous research activity on robotics applications of pneumatic muscle actuators (Raparelli et al., 2004).

The braided shell, shown in Figure 7(a), is made of strands composed of six Polyamide 66 threads, previously cited, to form a double-helix weaving of 42 spirals. When the shell is made to be in contact with the tube, the bias, along the symmetry axis of the shell, of the single rhombus shaped braided structure is equal to about 4 mm and θ_0 is equal to 28°.

The ends are made of the components shown in Figure 7(b).

[insert Figures 7a and 7b]

Figure 7. Components of the experimental prototype of McKibben muscle: a) details of the braided shell; b) assembled upper end.

A section of the terminal end of the muscle is presented in Figure 7(b). A fork is placed over the cup for external fitting. All the components are made of Aluminium 7075 except for the fitting fork which is made in steel S235. As can be seen in Figure 7(b), the muscle prototype is not made of pressed terminal ends, adopted in some MKM on the market, to obtain the mechanical fixing and the pneumatic seal. This solution allows to easily assemble and disassemble the muscle for manufacturing or for changing the components of the prototype on the basis of different requirements of material and geometrical properties. As regards the MKMs as actuator of orthoses, exoskeletons or other devices, this solution allows to use part of their structures as cup of the terminal ends with the reduction of the encumbrance of the not active parts and the increase of the active length of the muscle.

The experimental prototype, shown in Figures 8, has the following dimensions: total length equal to 460 mm; working length equal to 285 mm; weight equal to 0.598 kg. Due to its assembly, the prototype shows a light initial backslash between the tube and the shell.

[insert Figures 8a and 8b]

Figure 8. Experimental prototype of McKibben muscle: a) at rest; b) at maximum inflation state.

A test was carried out for a preliminary assessment of the shortening value and the corresponding pressure value at the maximum inflation state: maximum shortening was equal to 76 mm, corresponding to 27% of the working length, at a pressure value equal to 0.25 MPa.

5. Numerical model validation

A model validation was carried out by comparison of experimental and numerical results in quasi-static isotonic and isometric tests. A suitable experimental set-up was built: it's made of a portal frame, made by commercial aluminium profiles, a pressure transducer (Motorola MPX700, 0.7 MPa full scale), a linear position transducer (Celesco PT101-0015-111-2110, 410 mm full scale) in isotonic tests or a load cell (AEP Transducers TS/116, 1000 N full scale) in isometric tests, and a support frame for weights to be joined to the lower end of the muscle. Transducer signals were acquired by a 16 bit data acquisition board (NI AT-MIO-16) at a sampling frequency equal to 3 Hz; nevertheless, since tests were carried out in quasi-static conditions, the sampling dynamic can be neglected. A pressure regulator and a manometer completed the experimental set-up. Figure 9 shows the adopted set-up.

[insert Figures 9a, 9b and 9c]

Figure 9. Experimental set-up: a) for isotonic; b) for isometric tests; c) the pneumatic circuit.

In both sets of tests the upper end was fixed to the portal frame; coaxiality of muscle and transducers were checked in each test.

In the isotonic tests, the load was applied to the lower end. Three load conditions were applied: 20 N, 80 N and 150 N. In each test, the air pressure was increased from zero to 0.25 MPa (it was set up by preliminary tests). Hence, the tests were done from this value to zero.

In isometric tests, the load cell was placed between the portal frame and the upper end. The allowed displacement was fixed by adjusting the position of a plate along a threated rod, joined to the lower end. Three length conditions were applied; since the developed force decreases with increasing of the displacement, according to (3), and in order to prevent damages of the muscle, the final pressure value of each test was different. Test conditions were: $\Delta L/\Delta L_0 = 0\%$ at the maximum pressure value equal to 0.12 MPa; $\Delta L/\Delta L_0 = 45\%$ at the maximum pressure value equal to 0.18 MPa; $\Delta L/\Delta L_0 = 90\%$ at the maximum pressure value equal to 0.25 MPa, where ΔL is the test displacement and ΔL_0 is the maximum muscle shortening. Air pressure was increased from zero to the maximum test value; hence, from this value to zero.

The same values of the basic parameters of the experimental MKM were implemented into the FE model. The optimization procedure to compute *n* and *m*, as described in Section 3, provided for a value of the FE model working length lower of 1.5 mm than the real working length, with an error approximately equal to 1%. Table 1 reports the numerical model specifications.

Table 1. Model specifications and element type from Ansys library (* is the final optimized value)

Geometrical constant input parameters

$\theta_0 = 28°$	$L_0/2 = 142.5$ mm	$D_0 = 12$ mm	$H_0 = 4$ mm
s = 3 mm	$*L_0/2 = 140.997$ mm	l = 30 mm	$*H_0 = 4.028$ mm

Node numbers

Tube	3268
Ext. Shell	817
End	50
Total	3318

Element types and numbers

Tube	SOLID 185	2448
Ext. Shell	LINK 180	1540
End	SOLID 185	44
Total		4032

The same test conditions were applied to the numerical models.

Figures 10 show the comparison between experimental and numerical results.

[insert Figures 10a and 10b]

Figure 10. Comparison between experimental and numerical results in: a) isotonic tests (positive values of ΔL mean shortening); b) isometric tests.

The validation of the numerical model was carried out by qualitative, on the basis of the observation of the plots of the curves, and analytical, based on correlation and regression analyses, comparisons between the experimental and numerical results of the isotonic and isometric tests.

Before discussing the compared results, it is proper to provide some considerations about the behaviour of the experimental prototype. In each test, two distinct curves, a lower and a higher curve, respectively increasing and decreasing with the pressure inside the muscle, show a hysteretic behaviour of the muscle. The more is the deformation the more is the closed area. This result agrees with results found in literature; moreover, as described in scientific literature (Ferry, 1980), viscoelastic phenomenon is at the basis of hysteretic behaviour. This phenomenon is time dependent but for the purpose of the present work it was not considered: only increasing pressure curves were considered.

Initial backslash between the braided shell and the tube was assessed: as evident in 20 N isotonic test curves of Figure 10(a), until a pressure value equal to 0.011 MPa no muscle displacement ΔL was detected. Moreover, the application of a load equal to 20 N did not provide for a stretching of the muscle; for the same reason, no force was developed by the muscle until 0.008 MPa in $\Delta L/\Delta L_0 = 0\%$ isometric test curves of Figure 10(b). The backslash acts as a delay of the necessary pressure to be applied in order to put in function the pantograph operating principle. This means that the rubber tube undergoes a deformation until tube and braided shell contact occurs. On the contrary, the numerical model provides for threads and rubber always to be connected. This effect was considered during the post-processing of numerical simulations; in particular, isotonic curves were shifted of the unnecessary 0.011 MPa and isometric curves were shifted of 0.008 MPa.

The qualitative examination of the compared results suggests the following considerations.

About the isotonic curves, there is a good agreement between experimental and numerical data. With the exception of the starting point, where experimental data are affected by initial backslash, numerical curves have the same behaviour of experimental ones during pressure increasing: the experimental and numerical concavity agree and displacement values are quite to be similar. The initial stretching is different for the above mentioned reasons. The same considerations can be extended to the comparison of the isometric curves where the slopes of the them and the force values are quite similar.

The analytical comparison was carried out by correlation and regression analyses between the experimental and numerical results of the same test. In particular, before analyses, experimental data were interpolated in order to find the value of the experimental displacements (in isotonic tests) and of the experimental forces (in isometric tests) corresponding to the pressure values of the numerical data; then correlation and regression analyses were carried out. Figures 11 show the results of the analyses.

[insert Figures 11a, 11b, 11c, 11d, 11e and 11f]

Figure 11 – Correlation (circles) and regression (dashed line) analyses for experimental and numerical results of: a) isotonic test at F = 20 N; b) isotonic test at F = 80 N; c) isotonic test at F = 150 N; d) isometric test at $\Delta L/\Delta L_0 = 0\%$; e) isometric test at $\Delta L/\Delta L_0 = 45\%$; f) isometric test at $\Delta L/\Delta L_0 = 90\%$.

The good agreement between experimental and numerical results suggests that friction effects on the experimental model are negligible. Hence, the choice not to simulate friction effects has been proved to be right.

Figure 12 shows an example of the numerical results.

[insert Figures 12a, 12b, 12c and 12d]

Figure 12. Examples of numerical results of an isotonic test simulation: a) muscle at rest; b) during shortening; c) at the maximum inflation rate (lateral and top view); d) top view at the maximum inflation rate (end of the muscle was hidden, for sake of clarity).

6. Conclusions

The McKibben muscle, belonging to the braided muscles type, is the most used and published pneumatic artificial muscle. Several studies are available in literature about the theoretical and numerical modelling of it. The present work was focused on the development of a non-linear numerical model of a McKibben muscle based on a commercial braided shell and a hyper-elastic tube whose constitutive behaviour was experimentally achieved. The construction of the numerical model, implemented by finite element code, was based on six geometrical parameters (internal diameter of the tube; wall thickness of the tube; axial diagonal of the single rhombus shaped braided structure; angle at rest of the braided mesh shell; working length of the muscle; height of the end) and control and performance parameters (pressure inside the tube; allowed displacement; external applied load). For the validation of the numerical model, an experimental prototype of the McKibben muscle was designed and made. All the numerical parameters values were implemented with the same values of the experimental prototype and of the functional values of isotonic and isometric tests carried out by it. The tube, made of silicon rubber, was modelled by the 2 coefficients Mooney-Rivlin formulation (c_{10} = 0.0694; c_{01} = 0.0628) and the Poisson ratio (0.46). The material of the braided shell was modelled by the elastic modulus of Polyamide 66 (E = 2200 MPa) and the section of a strand made of six threads (0.3 mm^2). The material of the end was modelled by the elastic modulus of Aluminium (E = 70000 MPa) and the Poisson ratio (0.33).

Experimental and numerical results, during isotonic and isometric tests, showed good agreement. Correlation and regression analyses for experimental and numerical results provided for a high value of the accuracy of the numerical results in comparison to the experimental ones. Experimental and numerical concavity agree and displacement values are quite similar in isotonic tests. The maximum error is about 3% of the total displacement; similar curves were obtained in isometric tests: maximum error is about 2%

of the maximum force. Initial backslashes of the experimental prototype were taken into account during the post-processing of the numerical results: isotonic and isometric numerical curves were shifted towards higher pressure values in order to neglect the initial pressure value necessary for the backslash recovery.

The results obtained in this experiment suggest that the presented methodology can be used to develop models as predictive tools for McKibben muscle design.

Funding Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors

Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest

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