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NEW FUNCTION APPROXIMATION FOR THE FORCE GENERATED BY FLUIDIC MUSCLE

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ABSTRACT: *Numerous researchers have investigated the relationship of the force, length and pressure to find a good approximation and theoretical approach for the equation of force generated by pneumatic artificial muscles (PAMs). Some of them report several mathematical models, but significant differences have been noticed between the theoretical and experimental results. This paper presents our newest function approximation for the force generated by Fluidic Muscles.*
KEYWORDS: *Fluidic Muscle, Force Equations, Matlab, Genetic Algorithm*

INTRODUCTION

Many researchers have tried to find an actuator similar to human muscles. The most promising actuator in this field of research is undoubtedly the McKibben pneumatic muscle actuator. The McKibben muscle was invented in the 1950's by physician Joseph L. McKibben to help the movement of polio patients and to motorize pneumatic arm orthotics. There exist several types of pneumatic artificial muscles that are based on the use of rubber or some similar elastic materials, such as the McKibben muscle, the Rubbertuator made by Bridgestone Company, Air Muscle made by Shadow Robot Company, Fluidic Muscle made by Festo Company, Pleated PAM developed by Vrije University of Brussel, ROMAC (RObotic Muscle ACtuator), Yarlott and Kukolj PAM and some others [1] and [2].

A McKibben pneumatic actuator consists of an internal rubber bladder surrounded by a braided shell with flexible yet nonextensible threads according to a helical weaving that is attached at either ends. When inflated, the internal bladder tends to expand, with a consequent increase in the angle between the helical woven fibres of the braid and the axis of the tube and a decrease in axial length [3].

The layout of this paper is as follows. Section 2 (The Study) is devoted to demonstrate the models of force as a function of pressure and length (contraction). Section 3 (Results and Discussion) presents several comparisons between the measured and theoretical data and finally, section 4 (Conclusion) gives the investigations we plan.

For our newest study Fluidic Muscle type DMSP-20-200N-RM-RM (with inner diameter of 20 mm and initial length of 200 mm) produced by Festo Company was selected.

THE STUDY

Good descriptions of our test-bed (Figure 1) and different characteristics of Fluidic Muscles can be found in [4] and [5].

With the specially constructed testing machine, we are able to measure the static and dynamic characteristics of several versions of these pneumatic actuators.

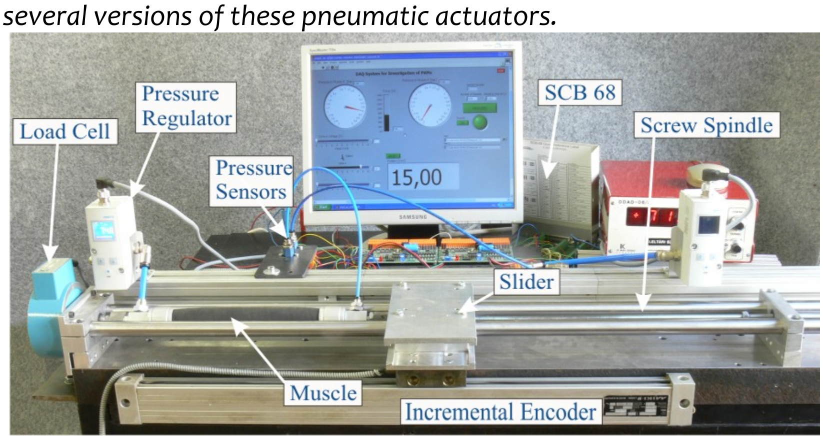

Figure 1. Experimental set-up for analysis of Fluidic Muscles

The general behaviour of PAM with regard to shape, contraction and tensile force when inflated depends on the geometry of the inner elastic part and of the braid at rest (Figure 2), and on the materials used [1]. Typical materials used for the membrane construction are latex and silicone rubber, while nylon is normally used in the fibres.

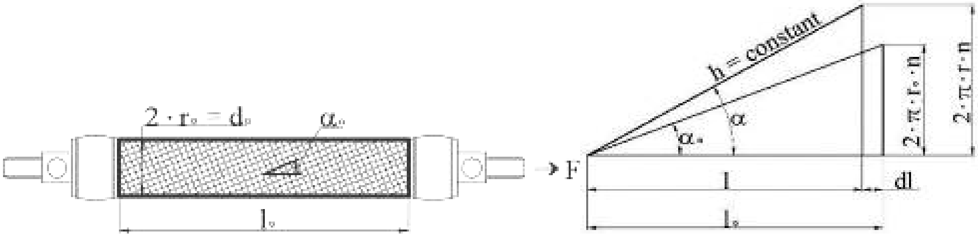

Figure 2. Geometry parameters of PAM

With the help of [6], the input and output work can be calculated:

$$dW_{in} = p \cdot dV \tag{1}$$

The dW_{in} can be divided into a radial and an axial component:

$$dW_{in} = 2 \cdot r \cdot \pi \cdot p \cdot l \cdot (+dr) - r^2 \cdot \pi \cdot p \cdot (-dl) \tag{2}$$

The output work:

$$dW_{out} = -F \cdot dl \tag{3}$$

If

$$dW_{in} = dW_{out} \tag{4}$$

then using equation 1 and equation 3:

$$F = -p \cdot \frac{dV}{dl} \tag{5}$$

and using equation 2 and equation 3:

$$F = -2 \cdot r \cdot \pi \cdot p \cdot l \cdot \frac{dr}{dl} - r^2 \cdot \pi \cdot p \tag{6}$$

On the basis of Figure 2:

$$\cos\alpha_o = \frac{l_o}{h} \text{ and } \cos\alpha = \frac{l}{h} \tag{7}$$

$$\sin\alpha_o = \frac{2 \cdot \pi \cdot r_o \cdot n}{h} \text{ and } \sin\alpha = \frac{2 \cdot \pi \cdot r \cdot n}{h} \tag{8}$$

$$\frac{l}{l_o} = \frac{\cos\alpha}{\cos\alpha_o} \text{ and } \frac{r}{r_o} = \frac{\sin\alpha}{\sin\alpha_o} \tag{9}$$

$$r = r_o \cdot \frac{\sqrt{1 - \cos^2\alpha}}{\sin\alpha_o} = r_o \cdot \frac{\sqrt{1 - \left(\frac{l}{l_o} \cdot \cos\alpha_o\right)^2}}{\sin\alpha_o} \tag{10}$$

$$\frac{dr}{dl} = -\frac{r_o \cdot l \cdot \cos^2\alpha_o}{l_o^2 \cdot \sin\alpha_o} \cdot \frac{1}{\sqrt{1 - \left(\frac{l}{l_o} \cdot \cos\alpha_o\right)^2}} \tag{11}$$

By using equation 10 and equation 11 with equation 6 the force equation is found:

$$F(p, \kappa) = r_o^2 \cdot \pi \cdot p \cdot (a \cdot (1 - \varkappa)^2 - b) \tag{12}$$

where $a = \frac{3}{tg^2\alpha_o}$, $b = \frac{1}{\sin^2\alpha_o}$, $\varkappa = \frac{l_o - l}{l_o}$, $0 \le \varkappa \le \varkappa_{max}$, *and V the muscle volume, F the pulling force, p the applied pressure,* r_o, l_o, α_o *the initial inner radius and length of the PAM and the initial angle between the thread and the muscle long axis, r, l, α the inner radius and length of the PAM and angle between the thread and the muscle long axis when the muscle is contracted, h the constant thread length, n the number of turns of thread and ϰ the contraction.*

Consequently:

$$F_{max} = r_o^2 \cdot \pi \cdot p \cdot (a - b), if\ \varkappa = 0 \tag{13}$$

and

$$\varkappa_{max} = 1 - \sqrt{\frac{b}{a}}, if\ F = 0 \tag{14}$$

Equation 12 is based on the admittance of a continuously cylindrical-shaped muscle. The fact is that the shape of the muscle is not cylindrical on the end, but rather is flattened, accordingly, the more the muscle contracts, the more its active part decreases, so the actual maximum contraction ration is smaller than expected [7].

Tondu and Lopez in [7] consider improving equation 12 with a correction factor (ε), because it predicts for various pressures the same maximal contraction. This new equation is relatively good for higher pressure (p ≥ 2 bar). Kerscher et al. in [8] suggest achieving similar approximation for smaller pressure another correction factor (μ) is needed, so the modified equation is:

$$F(p, \kappa) = \mu \cdot r_o^2 \cdot \pi \cdot p \cdot (a \cdot (1 - \varepsilon \cdot \varkappa)^2 - b) \tag{15}$$

where $\varepsilon = a_\varepsilon \cdot e^{-p} - b_\varepsilon$ and $\mu = a_\varkappa \cdot e^{-\varkappa \cdot 40} - b_\varkappa$.

The significant differences between the theoretical and experimental results were analysed and proved in [9] and [10]. Therefore we have introduced a new approximation algorithm:

$$F(p,\kappa) = (a \cdot p + b) \cdot e^{(c \cdot \kappa + d)} + (e \cdot p + f) \cdot \kappa + g \cdot p + h \tag{16}$$

The unknown a, b, c, d, e, f, g and h parameters can be found using genetic algorithm.

To reduce the numbers of parameters two new functions with 6 and 5 unknown parameters have been introduced:

$$F(p,\kappa) = (a \cdot p + b) \cdot e^{c \cdot \kappa} + d \cdot p \cdot \kappa + e \cdot p + f \tag{17}$$

$$F(p,\kappa) = (p + a) \cdot e^{b \cdot \kappa} + c \cdot p \cdot \kappa + d \cdot p + e \tag{18}$$

The unknown parameters can be found using genetic algorithm, too.

RESULTS AND DISCUSSION

Our analyses were carried out in Matlab environment.

Tensile force of Fluidic Muscles under different constant pressures is a function of muscle length (contraction) and air pressure. The force always drops from its highest value at full muscle length to zero at full inflation and position (Figure 3).

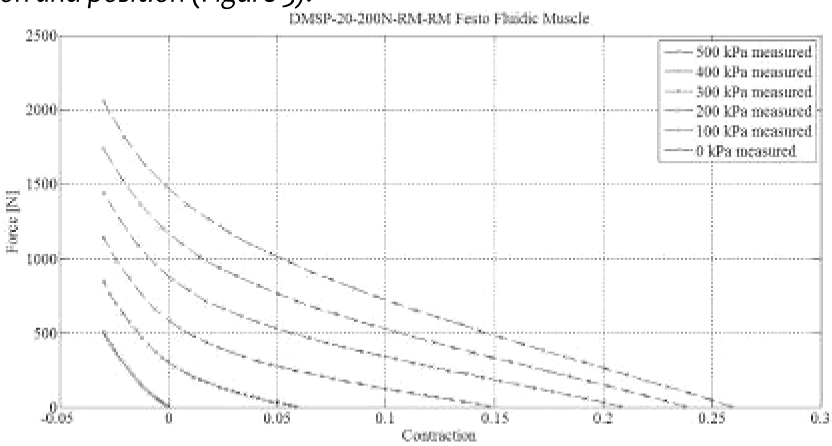

Figure 3. Isobaric force-contraction diagram of Fluidic Muscle

Firstly, we compared the measured data and force model using equation 12.

As it is shown in Figure 4 there is only one intersection point between the measured and calculated results and no fitting.

Secondly, we repeated the investigation using equation 15. The results of equation 15 and measured data can be compared in Figure 5. The coefficients (a_ε, b_ε, $a_\varkappa$ and $b_\varkappa$) of equation 15 were found using genetic algorithm in Matlab environment.

In the interest of better fitting under different pressures including 0 Bar we have introduced a new approximation algorithm (equation 16). The accuracy of equation 16 was demonstrated in [10] and

[11]. Our newest equations (equation 17 and equation 18) predict the correct force for various pressures and contractions, too. The results of equation 17 and equation 18 and measured data can be compared in Figure 6 and Figure 7.

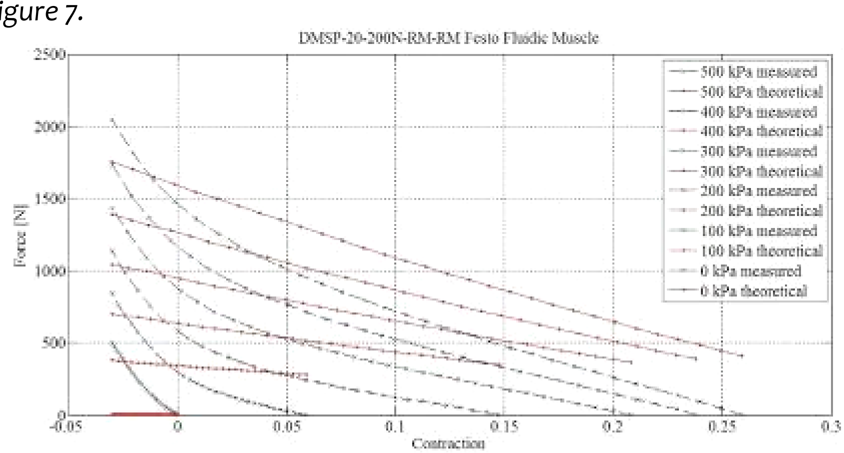

Figure 4. Comparison of measured data and force model using equation 12

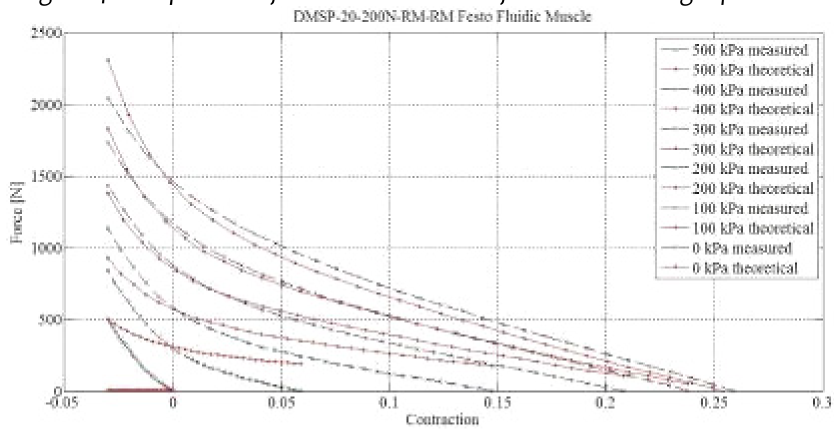

Figure 5. Comparison of measured data and force model using equation 15

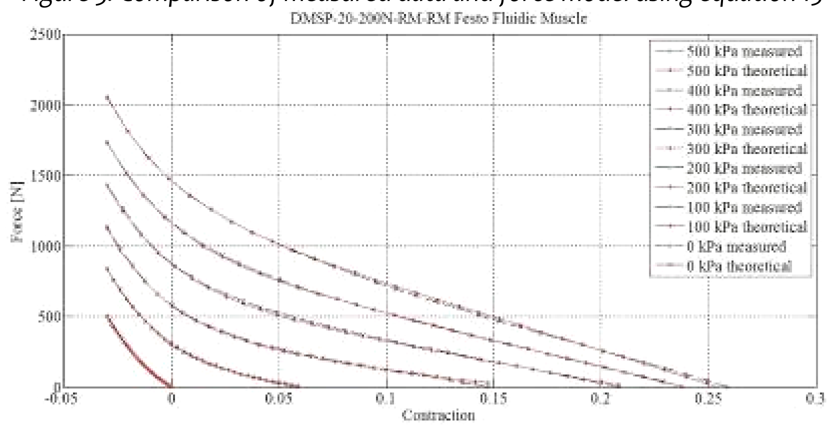

Figure 6. Comparison of measured data and force model using equation 17

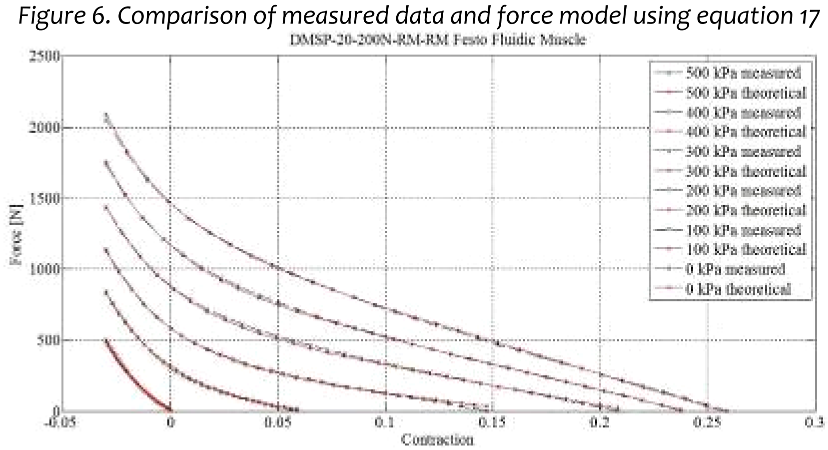

Figure 7. Comparison of measured data and force model using equation 18

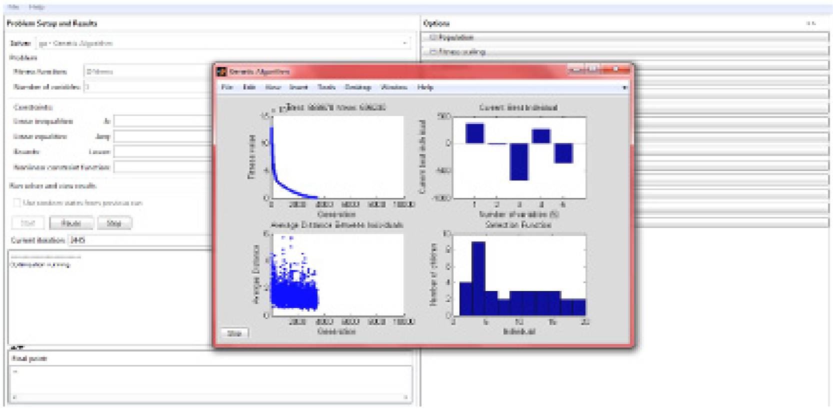

Figure 8. Determination of unknown parameters in Matlab environment

The precise positioning of PAMs requires accurate determination of the dynamic model of pneumatic actuators. Therefore the hysteresis in the tension-length (contraction) cycle of PAMs was analysed. Chou and Hannaford in [6] report hysteresis to be substantially due to Coulomb friction, which is caused by the contact between the bladder and the shell, between the braided threads and each other, and the shape changing of the bladder. Some experiments were made to illustrate the hysteresis (Figure 9).

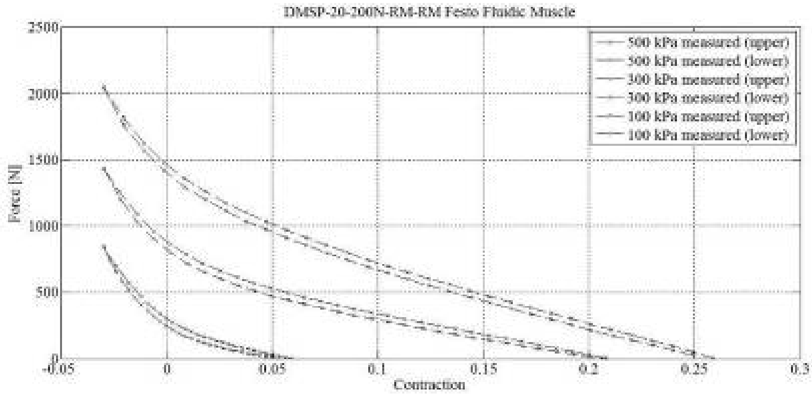

Figure 9. Hysteresis in the tension-length (contraction) cycle

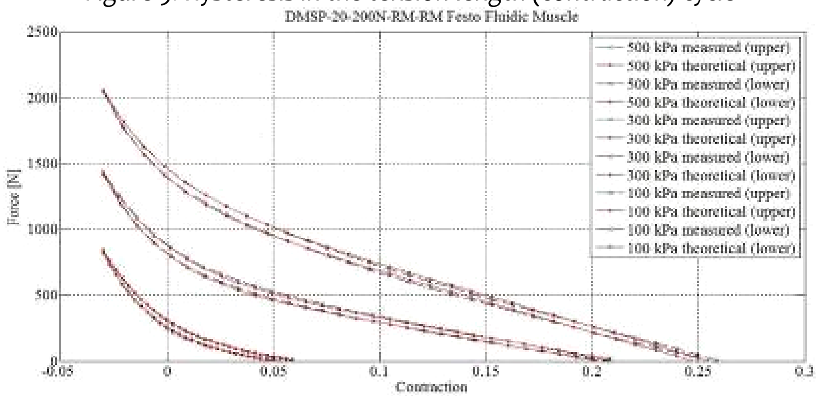

Figure 10. Approximation of hysteresis loop using equation 17

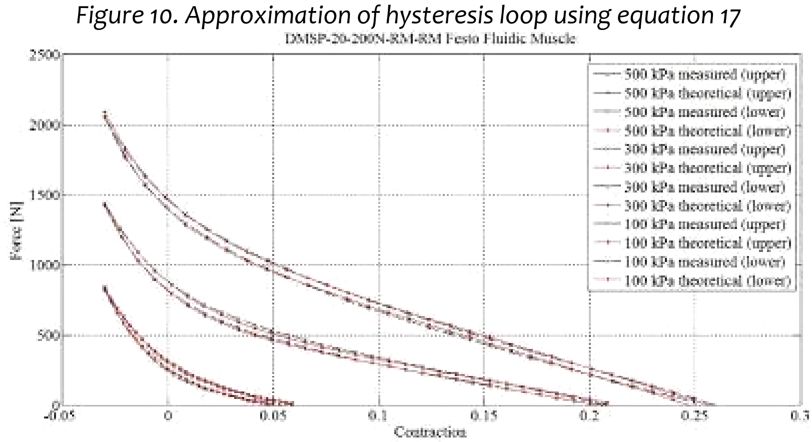

Figure 11. Approximation of hysteresis loop using equation 18

To prove versatility of equation 17 and equation 18, comparisons were done between the measured data and force model. The accurate fitting is demonstrated in Figure 10 and Figure 11.

CONCLUSIONS

In this work some comparisons of theoretical and measured forces generated by Fluidic Muscles have been shown. As we can see there is a substantial difference between the measured and predicted forces, for this reason two new equations were introduced. Our aim is to develop a new general mathematical model for pneumatic artificial muscles on the basis of our new models.

REFERENCES

[1.] Daerden, F. (1999), Conception and Realization of Pleated Artificial Muscles and Their Use as Compliant Actuation Elements, PhD Dissertation, Vrije Universiteit Brussel, Faculteit Toegepaste Wetenschappen Vakgroep Werktuigkunde, pp. 5-33.

[2.] Daerden, F. and Lefeber, D. (2002), Pneumatic Artificial Muscles: Actuator for Robotics and Automation, European Journal of Mechanical and Environmental Engineering, Volume 47, pp. 10-21.

[3.] Plettenburg, D. H. (2005), Pneumatic Actuators: Comparison of Energy-to-mass Ratio's, Proceedings of the 2005 IEEE, 9th International Conference on Rehabilitation Robotics, Chicago, Illinois, USA, 28 June-1 July, 2005, pp. 545-549.

[4.] Sárosi, J., Gyeviki, J., Endrődy, T., Szabó, G. and Szendő, P. (2009), Characteristics of the Pneumatic Artificial Muscles, International Conferences in Agricultural Engineering "Synergy and Technical Development", Gödöllő, Hungary, 30 August - 03 September, 2009, Conference CD, pp. 1-6.

[5.] Sárosi, J., Gyeviki, J., Szabó, G. and Szendrő, P. (2010), Laboratory Investigations of Fluid Muscles, International Journal of Engineering, Annals of Faculty of Engineering Hunedoara, Volume 8 (1), pp. 137-142.

[6.] Chou, C. P. and Hannaford, B. (1996), Measurement and Modeling of McKibben Pneumatic Artificial Muscles, IEEE Transactions on Robotics and Automation, Volume 12 (1), pp. 90-102.

[7.] Tondu, B. and Lopez, P. (2000), Modeling and Control of McKibben Artificial Muscle Robot Actuator, IEEE Control System Magazine, Volume 20, pp. 15-38.

[8.] Kerscher, T., Albiez, J., Zöllner, J. M. and Dillmann, R. (2005), FLUMUT - Dynamic Modelling of Fluidic Muscles Using Quick-Release, 3rd International Symposium on Adaptive Motion in Animals and Machines, Ilmenau, Germany, 25-30 September, 2005, pp. 1-6.

[9.] Sárosi, J., Gyeviki, J. and Csikós, S. (2010), Mesterséges pneumatikus izomelemek modellezése és paramétereinek szimulációja MATLAB környezetben, Jelenkori Társadalmi és Gazdasági Folyamatok, Szegedi Tudományegyetem Mérnöki Kar, Volume 5 (1-2), pp. 273-277.

[10.] Sárosi, J., Szépe, T. and Gyeviki, J. (2009), New Mathematical Model for Pneumatic Artificial Muscles. Hungarian Agricultural Engineering, Volume 22/2009, pp. 49-52.

[11.] Sárosi, J., Szabó, G. and Gyeviki, J. (2010), Investigation and Application of Pneumatic Artificial Muscles, Biomechanica Hungarica, Volume 3 (1), pp. 208-214.