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DEVELOPMENT A NONCONDUCTING MANIPULATOR – MCKIBBEN PNEUMATIC ARTIFICIAL MUSCLE

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Abstract. *When the activity of a mechatronic system is performed near or even within environments with intense electric or magnetic fields, devices must have a low number or no metal parts. Thus the use of electric actuators such as electric motor, become unviable. The initial motivation for this work was to find an actuator that can be built without the use of metallic elements and develop a non-conductive manipulator. In this context, hydraulic and pneumatic actuators are interesting since they use oil and air, i.e. non-conductive materials, as working fluid. Usually, hydraulic and pneumatic actuators contain metal parts, however, there is a pneumatic actuator that has few metallic parts: the pneumatic artificial muscle (PAM). The PAM has features like: few metallic elements, low weight to generated force ratio, force range similar to conventional pneumatic cylinder and simple construction. The PAM is basically comprised of four parts: an internal chamber of elastic material, a plot mesh involving the internal chamber and two terminals, one of these terminals is the passage of the compressed air which generates work. When receiving compressed air inside, the elastic chamber expands, causing the plot mesh to shrink in the longitudinal dimension, thus generating axial traction force. Adopting the PAM as a central element, this work aims to identify problems and solutions in developing a nonconducting of electricity handler. For this, this work firstly develops a PAM free from any metal part. Aiming its application and its control, their characteristics in terms of generated force, time response and accuracy are evaluated through a test bench. Then, a manipulator using the PAM is developed to move the hand of a patient that is placed inside a fMRI equipment.*

Keywords: *non-conductive manipulator; metal-free actuator; pneumatic artificial muscle; electromagnetic isolation*

1. INTRODUCTION

Active mechanical systems are those able to receive information regarding of some running process and exert mechanical intervention on them. Designing an active mechanical system can become extremely complex depending on the treatment to be given to this information. The electronics has been used to solve large-scale treatment of the information system, beyond the application of electricity in magnetic actuators (Rosário, 2005).

However, in some specific applications, the use of electricity as well any metallic electricity conducting structure becomes prohibitive. One example of such application is devices employed in treatments accompanied by Magnetic Resonance Imaging (MRI) (Schenck, 1996). Any metallic part would be submitted to an intense magnetic field giving rise to an undesired force or induced eddy current. This restriction is intended to ensure the integrity of the people involved as much of the equipment used, and should not interfere with the activities carried out by MRI equipment (Gassert et al., 2007). Other example is encountered in the area of electric power transmission and distribution. A sort of activities is conducted in the power lines with the line energized. Here, the use of conventional manipulators having conducting metallic parts also becomes prohibitive for evident reasons. There are several proposals of manipulators for this activity, however they are conventional manipulator, i.e., those that employs metallic and conducting parts, including electrical motors, that is isolated from the ground by a hydraulic power transmission system (Nio and Maruyama, 1993).

All of above mentioned examples converge in the necessity of manipulators or actuators without any metallic component, or in a more strict sense, that do not conduct electricity. As a to guideline the study of non-conducting manipulator, this work will assume the application related to MRI. In such application, the restrictions to the presence of metallic part is so severe that, reaching a solution to case of MRI, this solution can be easily expanded to other applications.

The activities carried out by dedicated equipment to work in conjunction with MRI are: Incisions (biopsy or brachytherapy), mechanical wave generation for elastography tests and stimulation for mapping active brain areas (Gassert et al., 2008). The incisions devices using the MR images and thus achieve small targets, the devices reported in the literature are able to perform both procedures, the biopsy, that is removing a small tissue as the brachytherapy. Brachytherapy is the treatment by implantation of small radioactive seed into the patient (Muntener et al., 2006). As an example we can mention the robotic system that uses pneumatic cylinders and structure built with plastics (Fischer et al., 2008), and the robotic system that uses pneumatic stepper motors (Stoianovici et al., 2007).

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Devices generating mechanical waves act Elastography exams, the exam is based on measuring the speed of propagation of a mechanical wave through the tissue. To illustrate, we quote a piezoelectric device, however as was expected, the presence of the electric field in the vicinity of MRI equipment generates interference images obtained, the proposed correction of this interference is by way software (Uffmann et at., 2002).

And finally we have the devices that generate mechanical stimuli perceived by the patient to the corresponding neurological reaction can be mapped, at this point it is possible to make a breakdown of objectives. In the first situation the devices, which perform a series of precise and repetitive movements of the patient, to produce brain activity corresponding for the MRI equipment monitor it. In the second situation the device are working on the rehabilitation of patients and by the MRI is possible to visualize the reorganization of the brain or some other physiological structure specifically during recovery and thus improve treatment (Yu, 2005). To illustrate a device that generates repetitive movements with the aim of stimulating specific areas of the brain we mention the device that generates 2D patterns in order to stimulate the skin, this device is powered by compressed air (Zappe et al., 2004).

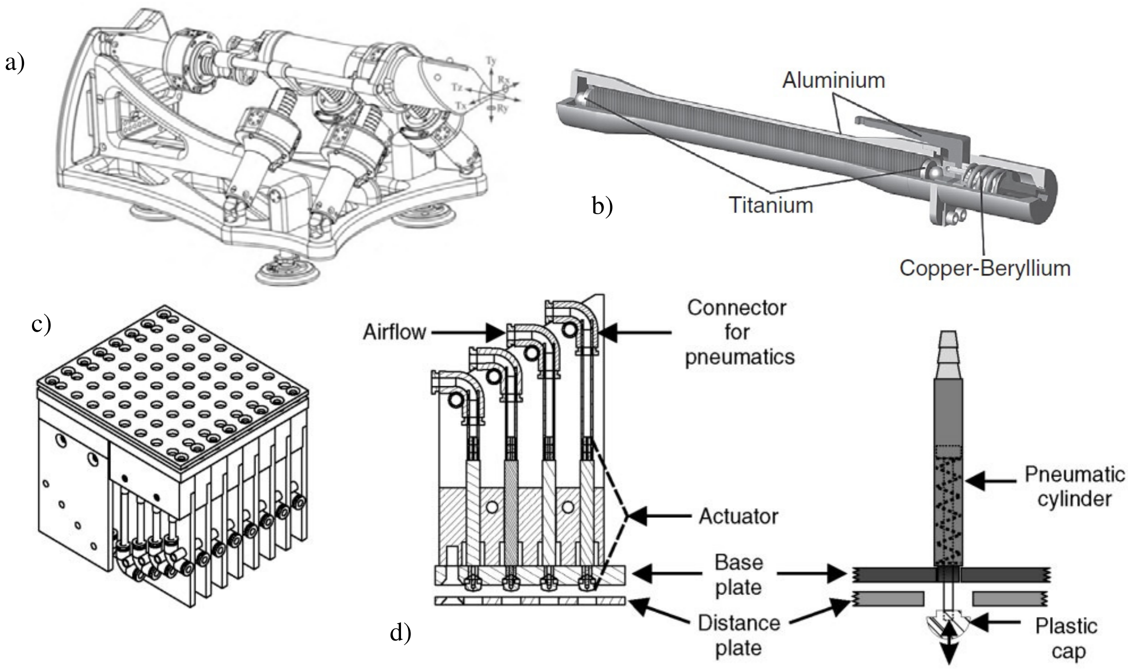

Figure 1. a) Robotic system proposed by the team Muntener. b) Device piezoelectric team Uffmann.
c) and d) Matrix constructed by the team Zappe.

As already mentioned, the choice of the constructive elements of the devices dedicated to MRI environment should be done taking into accounts their operating principle. The MRI technique is based on three steps: alignment, excitation and detection of electromagnetic wave. In the first step, atomic nuclei of the body to be examined are magnetically aligned, an effect similar to a compass with the terrestrial magnetic field. However here, an extreme magnetic field of 1.5Tesla or greater is used for this alignment. The second step is the excitation of atoms. For this, the MRI machine generates an electromagnetic wave. Each atom in a given oscillating field has a different frequency response. The MRI uses the frequency of the hydrogen atoms. And finally, in the third step, the detection is performed through electromagnetic response of atoms (Amaro and Yamashita, 2001).

The revision of literatures showed the existence of a number of devices compatible with MRI using pneumatics as an energy source and commands. The air has advantages, such as: the working fluid, the air, is easy to obtain; the air is a clean working fluid compared to the oil used in hydraulic systems; there is no risk of generating electric sparks as the electric motors; presents reduced noise as piezoelectric systems; if the plain air is used, the return line is not necessary; the actuator can be overloaded until the stroke limit; the construction is simple compared with mechanical transmissions and other advantages. However, several difficulties are encountered in the application of pneumatics. Difficulties to be overcome are: the friction present in the majority of actuators; the lack of linearity caused by uneven flow of the compressed gas; the condensation of water vapor inside actuators, valves and piping; the low viscosity of the air that implies high chances of leakages and; the high compressibility of the air compared with oil, for example. Particularly, the high compressibility of the air associated with high friction results in difficulties to control position under good repeatability. Usual and simple pneumatic actuators, such as pneumatic cylinder, operate so as to reach only two positions: forward limit position and backward limit position. At these two positions, mechanical stoppers are placed.

In order to identify difficulties and guidelines to develop non-conducting manipulators without any metallic component, this work consider the development of a manipulator that working in a MRI environment helping patients in rehabilitation activity. Therefore, this device should be able to apply a controlled force in the hand of a patient during the MRI exam. For this purpose, the pneumatic will be used as energy source. Here, a not so conventional pneumatic actuator, the pneumatic artificial muscle, or PAM, is used. PAM shows interesting characteristics to be used in the device such as light weight and non-metallic body. It is possible to find commercial PAMs, however they are furnished with metallic connections and the available range of forces is much greater than the maximum necessary for developing the proposed device. For these reasons it was decided to develop a PAM, specially built without the use of metal rings or hooks. During this work, the literature concerning the PAM known as McKibben muscle is revised and so will be offered a solution that proves feasible to problems involving both the actuator and its application in MRI.

2. MCKIBBEN PNEUMATIC ARTIFICIAL MUSCLE (PAM)

Pneumatic cylinders and air motors are the most popular pneumatic actuators. However there are several other types of actuators and one of them is the PAM. Even among PAMs, there are a variety of types, each one with different construction and working principle. One of the PAM most frequently seen in the literature is the McKibben PAM. It was first time presented, in the decade of 1950, by the physicist Joseph L. McKibben, aiming to be the actuator of an orthosis (Tondu and Lopez, 1997).

The McKibben PMA is a linear traction actuator, and can be used as a spring. It is characterized by the internal chamber of elastic material, a mesh covering the chamber and connections at both extremities that join the muscle to the remaining of the device. The filaments that compose the mesh form small lozenge cells over the surface of the inner chamber. When filled with pressurized gas, the inner chamber tends to expand in all directions. However, the filaments of the mesh, that covers the inner chamber, only rearranges without suffering any significant elastic or plastic deformation. Thus, the volume of the PAM increases while its length decreases, generating the traction force (Tondu and Lopez, 2000).

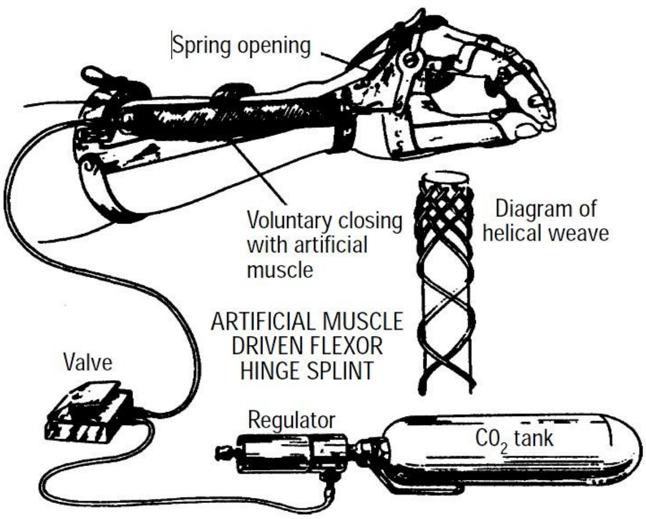

Figure 2. McKibben PAM components (Tondu and Lopez, 1997).

In a first approach toward the model of a McKibben type PAM, losses are not considered and thus, the gas enters the PAM and expands, generating a traction force and a work. To generate the volume increase, the gas performs a work input (W_{in}) that can be described by Eq.1.

$$dW_{in} = \int_{Si} (P - P_{ex}) dl_i . dS_i = (P - P_{ex}) \int_{Si} dl_i . dS_i = P' dV \tag{1}$$

Where P is the absolute pressure, P_{ex} is external pressure, P' is relative pressure, dl_i the displacement of the surface, dS_i is an area vector, S_i the total surface area and dV, the change in volume. As the pressure performs work by volume expansion and it is assumed that the system has no loss, all the work is converted into traction and can be expressed by W_{out}, as shown in Eq.2 (Chou and Hannaford, 1996).

$$dW_{out} = -FdL \tag{2}$$

Where F is the axial tension and dL is the displacement. The energy conservation gives:

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$$dW_{out} = dW_{in} \tag{3}$$

Thus

$$-FdL = P'dV \tag{4a}$$

$$F = -P'\frac{dV}{dL} \tag{4b}$$

With the strength defined in terms of the volume change, just missing define the volume variation permitted by the mesh. The variation stops when volume reaches its maximum. At this moment, the muscle reaches the largest contraction. Observing Fig.3, it is possible to make the length (*L*) and diameter (*D*) as a function of the angle (θ). This angle is one formed between the mesh and the axial length of the muscle. The length of fiber can be named *b* and *n* is the number of turns of the fiber around the muscle. Using *b* and *n*, it is possible to set the length and the diameter of the muscle in Eqs.5 and 6 respectively (Chou and Hannaford, 1996).

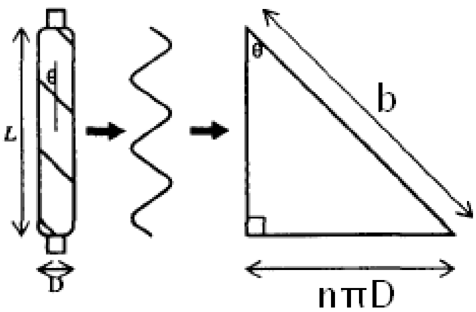

Figure 3. PAM geometry (Tondu and Lopez, 1997).

$$L = b.\cos\theta \tag{5}$$

$$D = (b.\mathrm{sen}\theta)/n\pi \tag{6}$$

Making the volume equation as function of the diameter (*D*) and length (*L*), Eqs.7a and 7b are derived.

$$V = \frac{1}{4}\pi D^2 L \tag{7a}$$

$$V = \frac{b^3}{4\pi n^2}\sin^2\theta\cos\theta \tag{7b}$$

As *b* and *n* are constants, the volume change will be a function of the variation of is θ, being θ an angle between 0 and 90˚. Solving the force equation (Eq.4b), deriving the volume and the length with respect to θ (Chou and Hannaford, 1996).

$$F = -P'\frac{dV/d\theta}{dL/d\theta} \tag{8a}$$

$$F = \frac{P'b^2(3\cos^2\theta - 1)}{4\pi n^2} \tag{8b}$$

Equation 8b has already been demonstrated by Chou and Hannaford in his work. However, it is not practical to work with *b* and *n* values. These parameters are both related to the diameter of the muscle, respectively by Eqs.6 and 8b. Thus, it is possible to formulate the Eq.9.

$$\mathrm{F} = \frac{\pi}{4} P' D^2 \frac{(3\cos^2\theta - 1)}{(1-\cos^2\theta)} \tag{9}$$

Adopting contraction (ε) according to Eq.10 and applying Eq.9, it is possible to reach Eq.11 (Daerden and Lefeber, 2000).

$$\varepsilon = \frac{\mathrm{L} - \mathrm{C}}{\mathrm{L}} \tag{10}$$

$$\mathrm{F} = \frac{\pi}{4} P' D_0^2 \left(\frac{3}{\tan^2\theta_0}(1-\varepsilon)^2 - \frac{1}{\sin^2\theta_0} \right) \tag{11}$$

Where *C* is the length of the muscle contraction at the moment, θ is the angle of mesh when the muscle is relaxed and the diameter D_0 when the muscle is relaxed.

3. PROTOTYPE DEVELOPMENT

As mentioned before, MPA is available in the market and its use is relatively well disseminated in the industry. However, commercial MPAs always contain metal terminals besides other metallic components. Metal terminals are used because of the large force this element is designed to develop. For purposes of comparison only, considering the calculations for the maximum force of the actuator to be developed in this work, a value below 100N traction force is obtained; while the commercial PAM can reach at least 6000N of traction.

On conducting this work, three sets are developed. The first set is the structure of the manipulator, made of non-conductive materials, but strong enough to ensure many efforts during the operation thereof. As mentioned before, the PAM here developed will be used in an orthosis. When complete, it is expected that the orthosis helps patient to close and open the hand. This action will occur by two distinct movements, the first closing his fingers accompanying the palm and the second movement closing the thumb, for these two independents movements, muscles pulling traction cables connected in a special glove, glove where the hand of the patient to be examined, the return of the hand will be made by elastomer springs.

The second set consists of the PAMs that serve as actuators and constitutes the main object of this work. Following the model of the McKibben PAM, an elastic chamber is surrounded by a mesh and terminals are attached to both ends. Fig.4 shows all components. Latex made soft tubes (10mm diameter and 1mm thick wall) are used as elastic chambers. For the mesh plot, a commercial nylon mesh (nominal diameter of 10mm and filaments of 0.2mm diameter) is used. The original end for this mesh is to serve as protection sleeve for hydraulic hoses. Finally, connectors at both end of the PAM are fabricated in polymeric material (PVC). The extremity of the mesh and of the latex tube is firmly tied to the terminal by using nylon thin cords. Fig.5 shows the assembled PAM. The effective length of the constructed PAM is of 200mm.

The third developed set is the pneumatic system and the electrical control (Fig.6). Since this set contains metal parts and electrical components, it is located in a secure distance from the MRI device. The actuators and the orthosis structure will be connected to the power source and the control by pneumatic tubes that do not suffer any interference in the MRI environment.

And the last set is a table of test, where the tests about the muscle were performed prior to the application of him in device (Fig.6).

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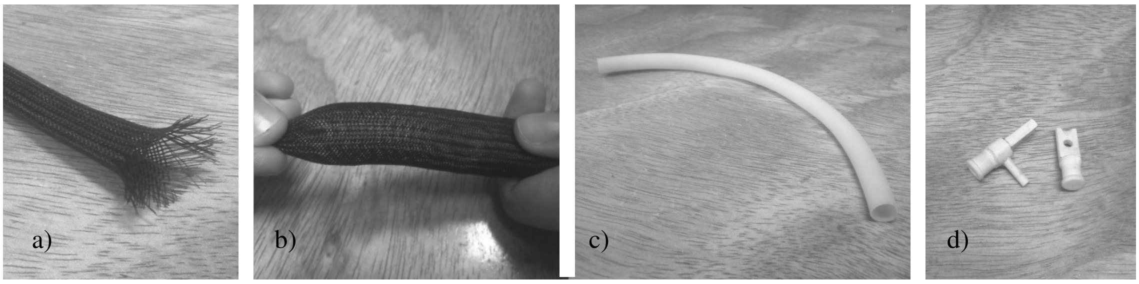

Figure 4. Components of the PAM: (a) mesh plot, (b) mesh with the latex tube, (c)latex tube, (d) terminals

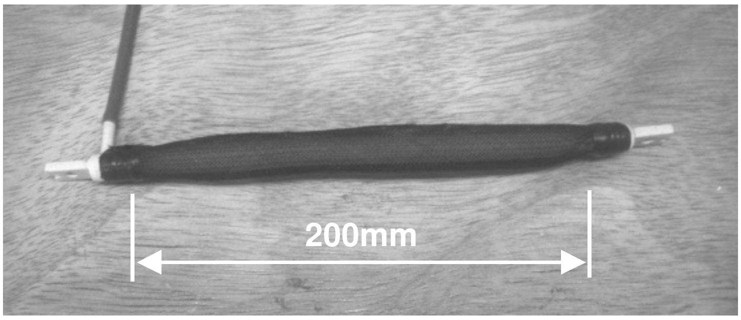

Figure 5. The PAM assembled

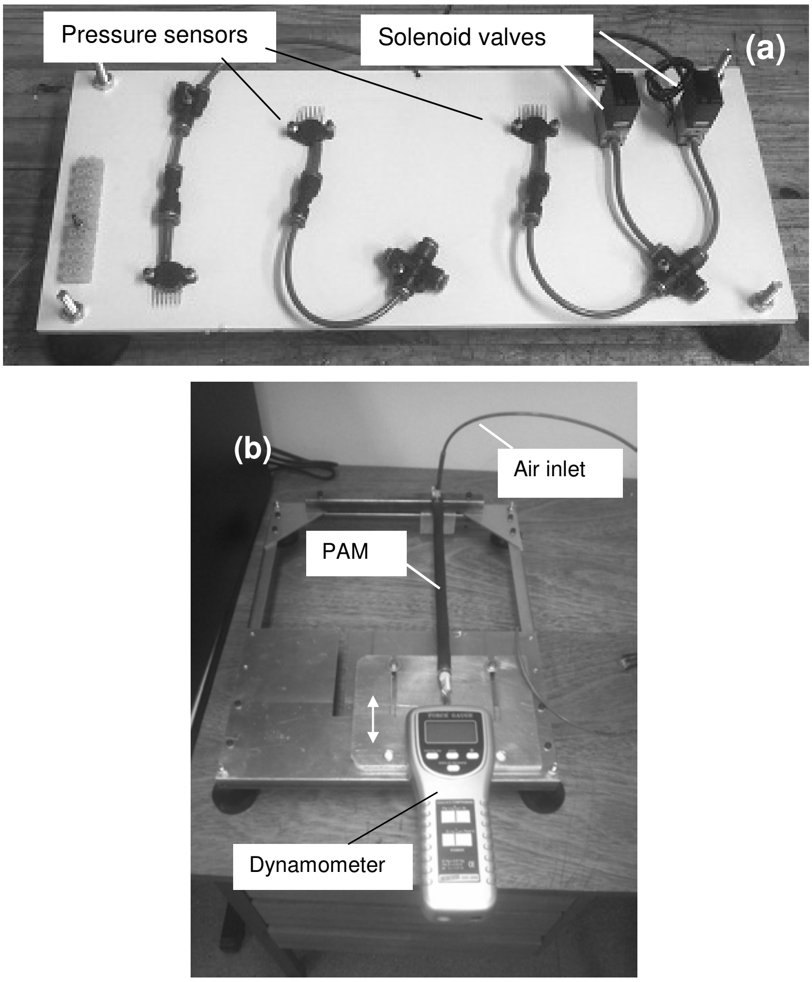

Figure 6. (a) The pneumatic circuit and. (b) The table of tests

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4. TESTS WITH THE ACTUATOR

The first tests developed with the actuator were performed on a table of test, the purpose of this table is to support both the muscle used as the dynamometer, and is a fixed base for measuring the size of the muscle as the tests. The test that generated the graph in Fig.7 was performed as follows. The PAM is fixed, in one extremity to the frame and, in other extremity to the dynamometer. Thus the length of the PAM does not change. Then, a pressure of known magnitude is applied to the PAM and the respective tension force is measured by the dynamometer. Pressures above 310kPa are not applied so as to preserve integrity of the PAM.

Using Eq.11, that relates traction force with the contraction (ε) and the pressure variation (P'), it is possible to obtain the graph of Fig.8. Curves are calculated for same pressure values considered in Fig.7.

A comparison of the curves shown in Figs.7 and 8 shows great differences in the obtained forces. In the experiments, the obtained force is much more larges. For example, when contraction is null, for the same pressure of 233kPa, the traction force is of 11.7N in the theoretical curve and 60N in the experimental one. A difference of over 400% is observed. Even considering measurement errors, the difference in the values are too large and clearly the model adopted in this work and resulted in the Eq.11 is not sufficient to describe the behavior of the developed PAM. The model represented by Eq.11, does not takes into account the elasticity of the elastic chamber. Figs.7 and 8 may be understand as the stiffness of the MPA and the inclusion of the stiffness of the latex tube will affect the final stiffness of the MPA. The model should be refined more.

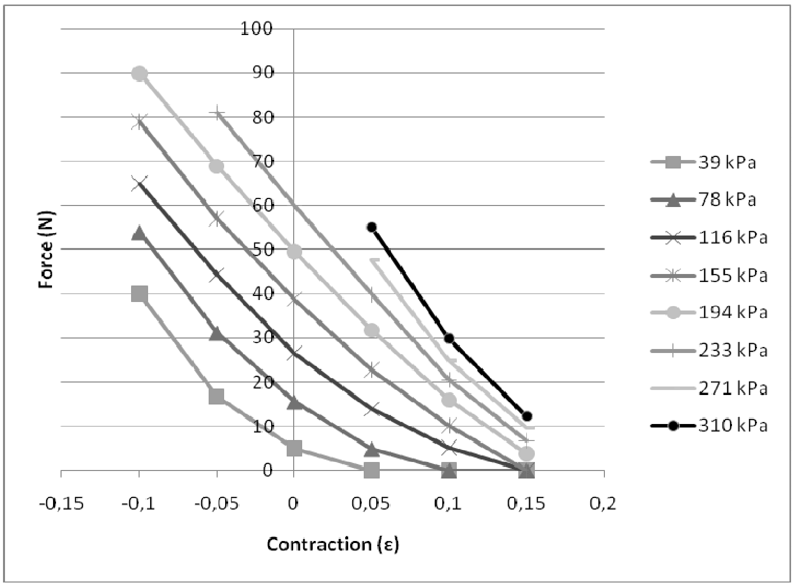

Figure 7. Experimental force vs contraction curve

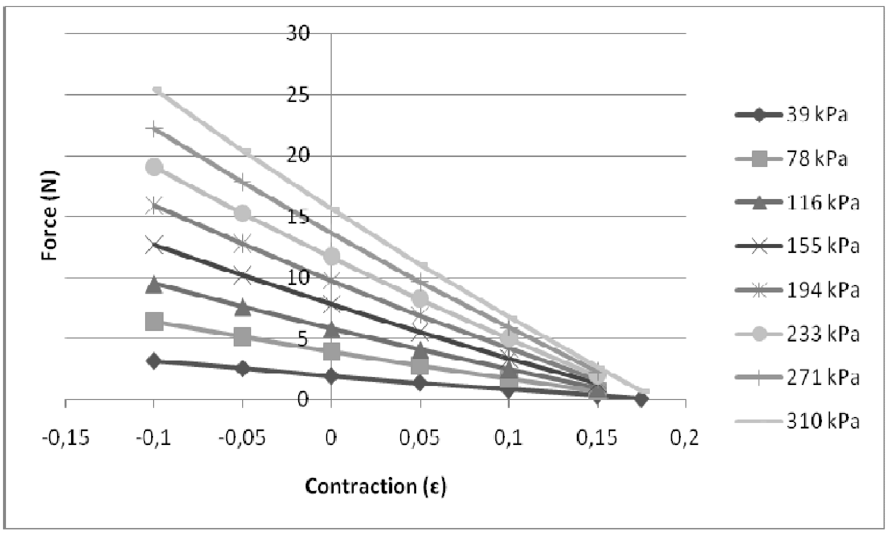

Figure 8. Theoretical force vs contraction curve

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A step response test is conducted with the PAM and the results are shown in Fig.9. In the experiments, the supply pressure is adjusted to a desired value and the valve, that furnishes compressed air to the PAM, is suddenly opened, while the traction force is continuously measured. A rise time of around 0.1s is observed in the case of 40kPa pressure. This is considered enough for the final application considered in this work, i.e. the construction of an orthosis. Similar response is obtained for different pressure values. In Fig.9 it is possible to observe that in all pressures, the force increases stepwise, reaches a maximum value and the force gradually decreases with the time. Results are not shown here but the force decreasing stops after some minutes. This behavior is not described in literatures and the first hypothesis for this decreasing is the air leakage in some portion of the PAM. However, the reason of this effect was not identified yet.

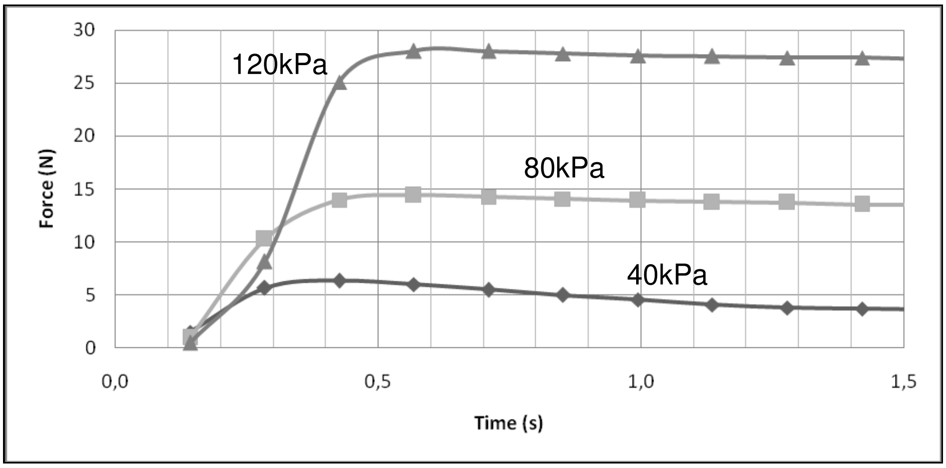

Figure 9. Step response

5. DEVICE CONTROL

As described before, the PAM has a single air passage port. The air flows in or out the PAM according to the pressure at the port. Therefore, one PAM needs a single hose. Since two PAMs are expected to be used in the orthosis, only two hoses will exist between the orthosis and the control panel.

It is possible to adopt a variety of pneumatic circuits for controlling the PAM. One strategy would be the circuit schema based on the use of a three-position solenoid valve. In the first position, the air flows inside the PAM. In the second position, the air flows out from the PAM. And in the last, third position, the passage of the air to the PAM is obstructed. However, this type of valve is not adequate mainly because of its low commutation frequency. For this reason, the scheme depicted in Fig.9 is adopted. Here, two fast response ON/OFF solenoid valves are used. Each of these valves can achieve a working frequency of 500 Hz.

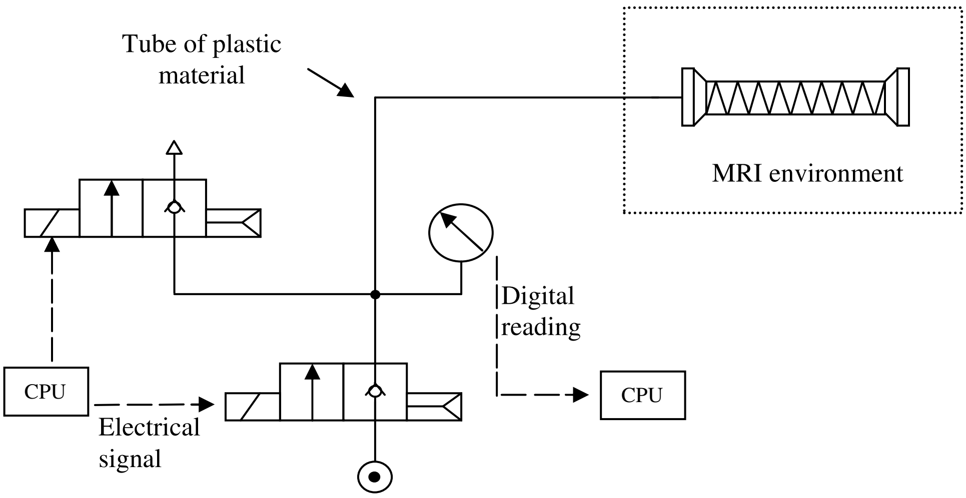

Figure 10. Pneumatic circuit for driving

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6. RESULTS AND CONCLUSIONS

So as to identify difficulties and guidelines to develop non-conducting manipulators without metallic components, this work considered the development of a manipulator that works in a MRI environment helping patients in rehabilitation activity. For this, the pneumatic is adopted as energy source and the pneumatic artificial muscle, or PAM, is choose because of the advantages such as high force to weight ratio and the essentially non-metallic construction. This work described the construction of a PAM known as McKibben type and the experimental measurement of the characteristics of the developed PAM.

The constructed PAM, although developed experimentally, already showed characteristics suitable in terms of developed force, contraction and response time enough to an application as a manipulator to help patients, i.e, an orthosis to be used in a MRI environment. The model adopted to simulate the behavior of the PAM showed to be insufficient and needs refinement. This is one of future activities. Other not expected behavior of the PAM not described in literatures are also object of future investigation.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Amaro, E.J. and Yamashita, H., 2001. "Aspectos básicos de tomografia computadorizada e ressonância magnética". Revista Brasileira Psiquiatria, vol 23.

Chou, C.P. and Hannaford, B., 1996. "Measurement and Modeling of Mckibben Pneumatic Artificial Muscles". IEEE Transactions On Robotics and Automation, vol. 12, February 1996.

Daerden, F. and Lefeber, D., 2000. "Pneumatic Artificial Muscles: actuators for robotics and automation". European journal of Mechanical and Environmental Engineering, vol 47.

Fischer, G.S., Iordachita, J., Csoma, C., Tokuda, J., DiMaio, S.P., Tempany C.M., Hata, N. and Fichtinger, G., 2008. "MRI-Compatible Pneumatic Robot for Transperineal Prostate Needle Placement". IEEE/ASME Transactions on Mechatronics, vol 13, June 2008.

Gassert, R., Burdet, E. and Chinzei, K., 2008. "Opportunities and Challenges in MP-Compatible Robotics". IEEE Engineering in Medicine and Biology Magazine, May 2008.

Gassert, R., Yamamoto, A., Chaouis, D., Dovat, L., Bleuler, H. and Burdet, E., 2007. "Actuation Methods for Applications in MR Environments". Wiley Periodicals.

Muntener, M., Patriciu, A., Petrisor, D., Mazilu, D., Bagga, H., Kavoussi, L., Cleary, K. and Stoianovici, D., 2006. "Magnetic resonance imaging compatible robotic system for fully automated brachytherapy seed placement". Jornal Urology, 68.

Nio, S. and Maruyama, Y., 1993. "Remote-operated Robotic System for Li-line Maintenance Work". ESMO-93, Sixth International Conference on Transmission and Distribution Construction and Live Line Maintenance, pp 425 – 435.

Rosário, J.M., 2005. *Princípios de Mecatrônica*. Prentice Hall, São Paulo.

Schenck, J.F., 1996. "The role of magnetic susceptibility in magnetic resonance imaging: MRI magnetic compatibility of the first and second kinds". Medical Physics, Vol. 23, june 1996.

Stoianovici, D., Patriciu, A., Petrisor, D., Mazilu, D. and Kavoussi, L., 2007. "A New Type of motor: Pneumatic Step Motor". IEEE/ASME Transactions on Mechatronics, vol. 12, february 2007.

Tondu, B. and Lopez, P., 1997. "The McKibben muscle and its use in actuating robot-arms showing similarities with human arm behavior". Industrial Robot, vol. 24.

Tondu, B. and Lopez, P., 2000. " McKibben Artificial Muscle Robot Actuators". IEEE Control Systems Magazine, April 2000.

Uffmann, K., Abicht, C., Grote, W., Quick, H.H. and Ladd, M.E., 2002. "Design of an MR-Compatible Piezoelectric Actuator for MR Elastography". Magnetic Resonance Engineering, vol. 15.

Yu, N. and Riener, R., 2006. "Review on MR-Compatible Robotic Systems". The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, February 2006.

Zappe, A.C., Maucher, T., Meier, K. and Scheiber, C., 2004. "Evaluation of a Pneumatically Driven Tactile Stimulator Device for Vision substitution During fMRI Studies". Magnetic resonance in Medicine, vol. 51.

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