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PNEUMATIC MUSCLE WITH SMART BRAID USED IN ORTHOSIS

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Abstract. *Pneumatic Muscles – PAMs (“Pneumatic Artificial Muscles”) – are linear actuators strongly used in biomechanical applications due to their similarity with human muscles. Their low weight, actuation force and flexibility are the main characteristics that allow them to be considered great actuators for orthosis used by patients in need of physiotherapy. However, there are some challenges in the process of controlling the PAMs, since there is a necessity of knowing the instantaneous length of the muscle, which will be used as input for the orthosis' position and speed control system, without affecting the actuator's flexibility. The use of Smart Braids allows the measurement of the compression rate of a pneumatic muscle by varying the induction and resistance on its conductive fibers. inductance varies linearly with the contraction of the fibers, providing a newer and more practical way of controlling position and speed of the pneumatic muscles. The purpose of this article is presenting the fabrication of the muscles as well as the mathematical model used for measuring the length of the muscle via induction and its closed loop control, providing both accuracy and actuation speed measurements when applied to a model orthosis.*

Keywords: *Pneumatic Muscles, PAMs, Linear Control, Conductive Fiber, Orthosis*

1. INTRODUCTION

In recent years, the use of sensors and actuators has found its way into diverse fields, such as engineering and medical applications. The usage of Artificial Muscles for orthosis has helped many patients in need of orthosis and prosthesis all over the world, and, among those Artificial Muscles, Pneumatic Artificial Muscles, or PAMs, are worth citing. The controlling process for PAMs, however, has some challenges, since there's a need of knowing specifics about the muscle conditions, like its instantaneous length, used for controlling speed and position. In order to obtain a strict and accurate control, external transducers have been used such as sensors connected to potentiometers or optical encoders (for calculating the instantaneous length). Although they provide a good calibration for the PAMs, to be able to exempt the use of these transducers would improve the practicality and aesthetics of the PAMs, not to mention a possible reduction in weight, price and complexity.

One way found of dispensing the use of transducers is the use of soft sensors with Smart Braids (Felt et al., 2014). Smart Braids are conductive reinforcing fibers that can sense deformation and force-output of fiber reinforced actuators without the use of transducers. With a small current going through the conductive fibers, it is possible to measure inductance and from that recognize the muscle contraction, achieving the main goal for muscle control: the instantaneous length.

By measuring the resulting inductance on the actuator (measured in different frequencies), the Smart Braids can recognize the contraction of the muscle by themselves, making possible a simpler and less expensive muscle control.

This usage of Smart Braids in PAMs has been studied for some authors, such as Felt et al.(2017), whose work is taken as a base for this paper, as well as Davis S (2006), and Chou and Hannaford (1996), that provides more details on the mathematics of the process. From the manufacturing of the Smart Braid and testing made on it, we tend to evaluate the possibility and efficacy of getting the instantaneous length (muscle contraction at different points) from the measured inductance due to applied voltage on the conductive fiber.

2. EXPERIMENTAL PROCEDURE

2.1 Inductance measuring methods

The PAM muscle is fabricated using a flexible tube (made of latex) together with a reinforced mesh made of conductive Fiber. The tube used in this project is the most uniform and resistant found at pharmacies, with a pre-tested diameter to be able to endure the input air pressure of a maximum of 4atm. The reinforced mesh, on the other hand was fabricated following the guide available on-line at the soft-robotics website (SMARTBRAID, 2017). Basically, a conductive wire was weaved over a 3D-printed template designed to make actuators that have a 20-degree winding angle when around a tube with an approximated outer diameter of 10mm. The conductive wire used is a 22AWG flexible wire. The last step for assembling the PAM actuator is fixing together the conductive mesh and the tube, in a simple process also explained on the website and shown in Fig.1.

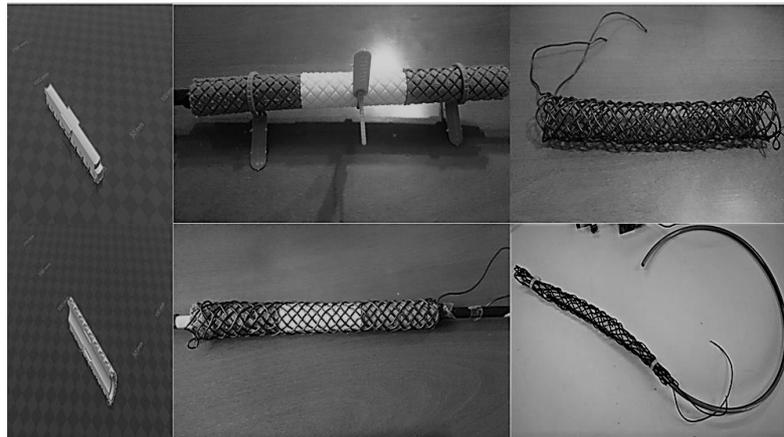


Figure 1: Assembling Smart Braid into an Actuator (Source: Soft Robotics Website, 2013)

Once we have the actuator, the tests and calculations can be made and evaluated. In order to get a relation between inductance and muscle contraction, the first variable to be found is inductance. For this paper, we measure the inductance in the circuit by using two methods: a LCR meter of our own manufacturing – Fig. 2 –, and an ESR-V5 tester –Fig. 3 – for comparing results. With the first method, by applying a voltage to the terminals of the conductive mesh, we were able to measure the inductance, as shown in Fig. 5, and, based on the Long Solenoid Approximation method (Knight, 2016), it was possible to evaluate an approximated relation between inductance and contraction of the muscle (Smart Braid). Our manufactured LCR meter is controlled by Arduino and measures inductances from μH to mH scales, allowing an approximate value from the real inductance on the circuit. As for the second method, the ESR-V5 tester measures inductance in three different frequencies with an accuracy of $3\% + 0.04 \mu H$. The measured values between the chosen measuring methods differ due to calibration and frequency of data gathering.

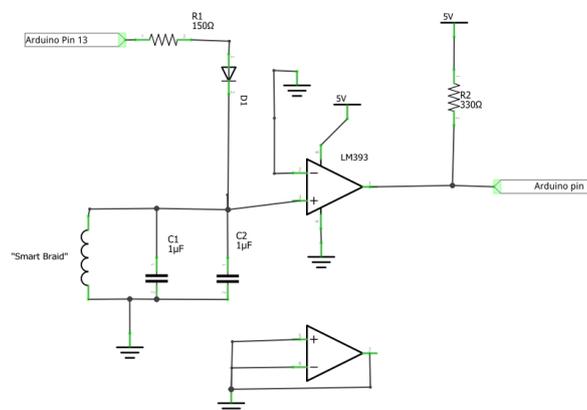


Figure 2: Diagram of the RLC circuit used for measuring inductance (Methode 1) with Arduino

Method 1 is based on LM393, a low voltage dual comparator, which connects to the microcontroller Arduino through a RLC circuit. Arduino sends pulses to the inductor being measured (in this project, the Smart Braid), and

receives the inductance measurements for every moment a pulse is sent at the serial port. This method was tested and proved to be valid, although not very accurate, due to the small values of inductance being measured. For the tests made, our inductor was connected to an alternated voltage power source at 24 Vac and to the measuring circuit described above. For reducing the current on the mesh, a 8.2k ohms resistor was connected in series with the Smart Braid and with the inductance sensor.

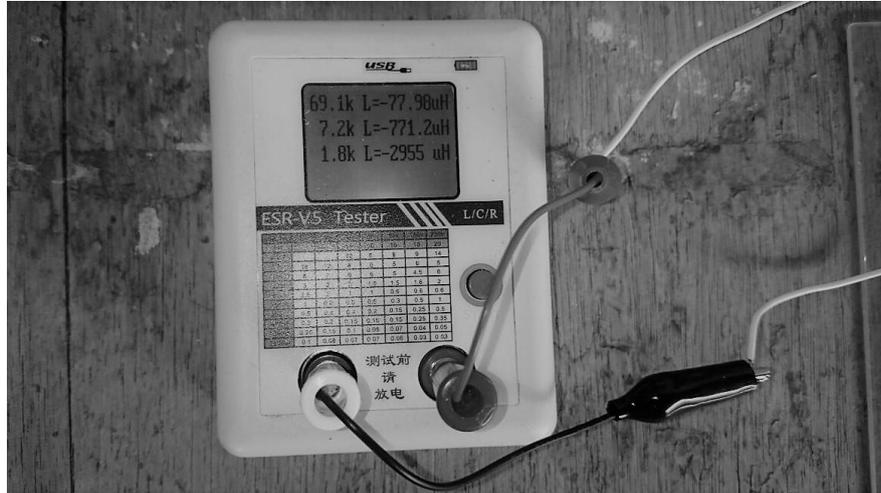


Figure 3: ESR-V5 tester with connectors used on Method 2 to measure inductance on the Smart Braid

Method 2 makes use of a more straight-forward measuring technique, based on getting inductance values from measured Inductive Reactance at three different frequencies. The following shows how inductance (L) is affected by Frequency (F), since this parameter is used for finding Inductive Reactance (X_L) and, from there, inductance itself.

$$L = \frac{X_L}{2 * \Pi * F} \quad (1)$$

The tester is connected directly to the Smart Braid conductive wire and as we insert or remove air, the length variance of the braid returns different values of inductance, shown directly in the tester. Figure 4 shows the test bench used for measuring inductance on Method 2.

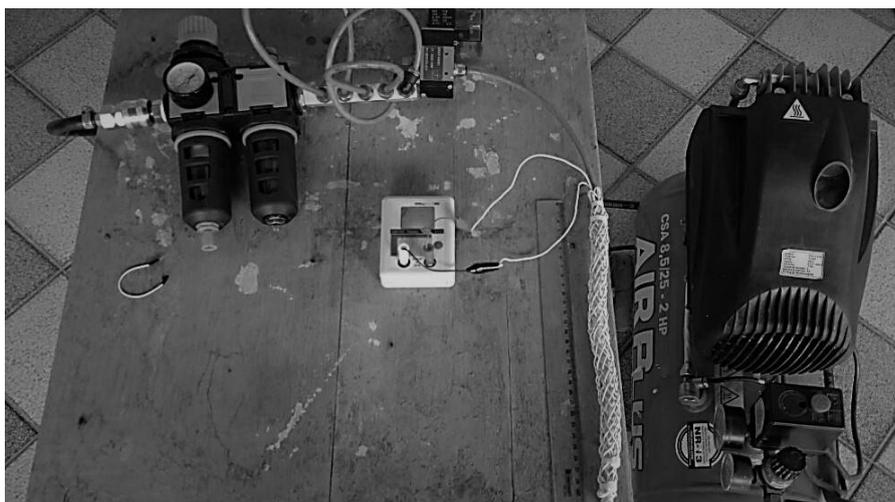


Figure 4: Test bench for Method 2, with Smart Braid PAM connected to ESR-V5 tester and to the air input system

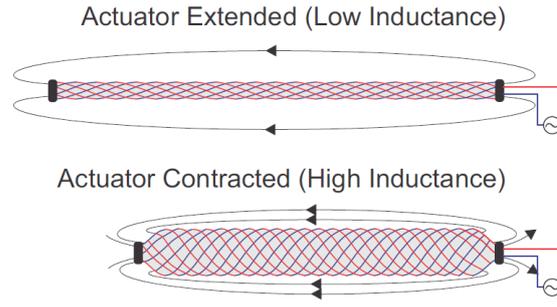


Figure 5: Smart Braid Sensing Method (Source: Contraction Sensing with Smart Braid McKibben Muscles [3], 2015)

2.2 Long Solenoid Approximation

For measuring the muscle contraction from the calculated inductance, the circuit of the PAM is considered as a long solenoid, which allows the use of the inductance approximated calculation formula for long solenoids presented by David W. Knight (Knight, 2016). From there, the inductance will be approximately given by

$$L = \frac{\mu N^2 A}{l} \quad (2)$$

Where μ is the core's magnetic permeability, N is the number of turns, A is the cross sectional area of the solenoid and L the cross sectional length. By simple multiplication we get that

$$l = \frac{\mu N^2 A}{L} \quad (3)$$

With simple mathematical equations, and considering that:

$$l = b \cos(\Theta) \quad (4)$$

$$b = \frac{L_e}{\cos(\Theta_e)} \quad (5)$$

$$n = \frac{b \sin(\Theta_e)}{De \Pi} \quad (6)$$

$$D = \frac{b \sin(\Theta)}{n \Pi} \quad (7)$$

Table 1 – Variables used for calculating Long Solenoid Approximation parameters

b [m]	Helix length
Θ [rad]	fiber angle with respect to the long axis of the actuator
n [turns]	number of turns made by each helix
nh [turns]	number of helices on the braid
L_e [m]	Length of fully extended actuator
Θ_e [rad]	Winding angle of fully extended actuator
De [m]	Diameter of fully extended actuator

We can write an equation to get the current actuator length in function of the inductance, the fully extended length and the other geometrical parameters cited above:

$$\frac{Le^2}{l} - (l \cos^2(\Theta_e)) = \frac{[L4\pi \cos^2(\Theta_e)]}{\mu(n_h)^2} \quad (8)$$

From which we can calculate the muscle length in function of the measured inductance. As we aim to find the artificial muscle contraction variance from the inductance change in the PAM, this is the relation we use. Its validation is assured for long solenoid approximation in inductance value, and improved by adding some corrections for factors dependent and independent of the frequency, such as self-inductance correction for round wire, axial inductance for wide-spaced coils and internal inductance of the wire. These are better explained by David W. Knight (Knight, 2016). The PAM actuator was tested as being free of load, for analysis of the inductance and contraction.

3. RESULTS AND DISCUSSION

We have successfully fabricated a PAM actuator using Smart Braids, which allow a better control of the muscle contraction in terms of flexibility, since we dispense the use of external transducers for measuring contraction. The use of the Long Solenoid Approximation for elaborating the mathematic formulation for length calculation was effective, due to the assumption made in this method that the angle of the wires is close to 90°, which increases inductance as the length of the braid diminishes. The closed loop control of the actuator was observed by using the proposed techniques and the expected response of linearity was observed in both cases of measured inductance.

3.1 Method 1

The tests on inductance made using Method 1 (Arduino with a LM393 and a RLC circuit) provided results according to what was expected. A total of 4 sequences of 100 measurements of inductance were obtained with the Smart Braid under different pressure and length conditions. The averages of the obtained values were taken, and assembled on a table for better evaluation, as seen in Fig. 6 and Fig. 7.

Table 2: Average of the measured inductance values and length obtained, with l being the length in meters and $L1$, $L2$, $L3$ and $L4$ the inductances in μH (micro Henry)

l	$L1$	$L2$	$L3$	$L4$
0.30	10.33	11.99	15.81	10.95
0.29	24.06	30.26	27.49	16.20
0.27	35.12	33.22	32.27	21.33
0.25	60.29	64.33	62.55	60.20

Table 3: Average of the measured inductance values for different pressures applied to the muscle, with P being the pressure given in MPa (mega Pascal) and $L1$, $L2$, $L3$ and $L4$ the inductances in μH (micro Henry)

P	$L1$	$L2$	$L3$	$L4$
0.10	10.33	11.99	15.81	10.95
0.20	24.06	30.26	27.49	16.20
0.30	35.12	33.22	32.27	21.33
0.40	60.29	64.33	62.55	60.20

Method 1 provided a way of measuring values with a lower level of accuracy, but it still allowed us to validate the theory of linearity between inductance and muscle contraction, at a certain level, as can be seen on Fig. 7 and Fig. 8.

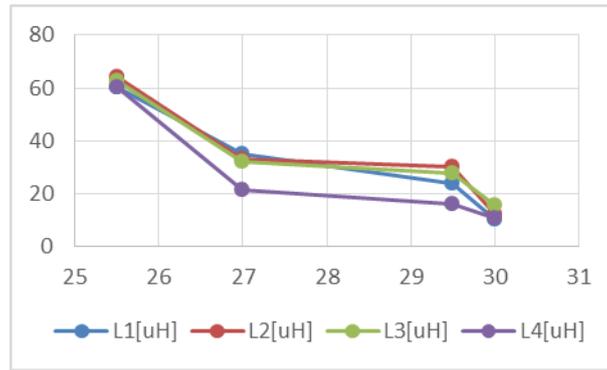


Figure 7: Graph of linearity between length in centimeters and measured inductance in uH

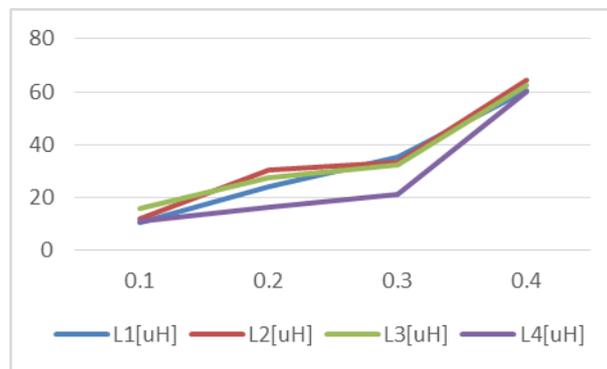


Figure 8: Graph of linearity between applied pressure in MPa and measured inductance in uH

3.2 Method 2

With Method 2, we were able to get more accurate values of inductance at different points of contraction and applied Pressure in the muscle, at 3 different frequencies. Since Pressure values vary continuously with the Length values, we assume that the same behaviour of inductance due to Contraction changes is valid for inductance due to Pressure changes, so in this work we only graph the relation between the last one. We registered a total of 28 values per frequency, for each pressure applied and a continuous variance of length being reached. Figure 9 shows the strong correlation found between the averaged values of inductances found and muscle contractions for the three different frequencies considered.

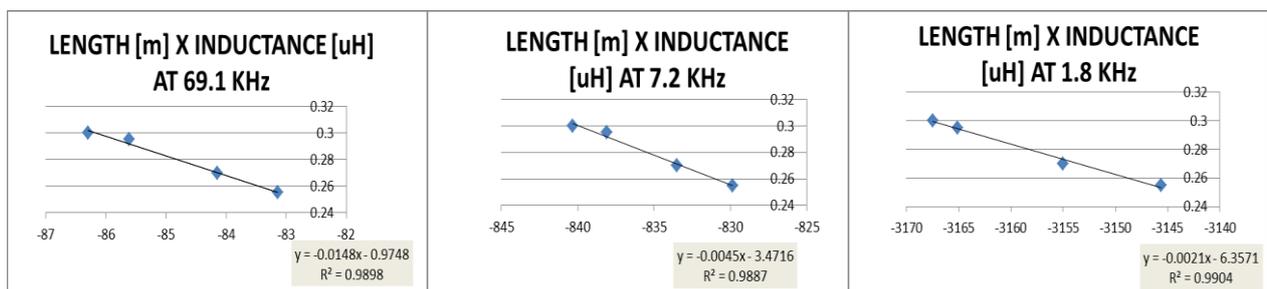


Figure 9: Graphics of correlation between Muscle Length and Average of inductances measured at 69.1 kHz, 7.2 kHz and 1.8 kHz

As a result, three linearity graphs were obtained and can be seen on Fig. 10, Fig. 11 and Fig. 12. The values for frequency, length, inductance and pressure are respectively given in *kHz* (kilo Hertz), *m* (meters), *uH* (micro Henry) and *MPa* (mega Pascal).

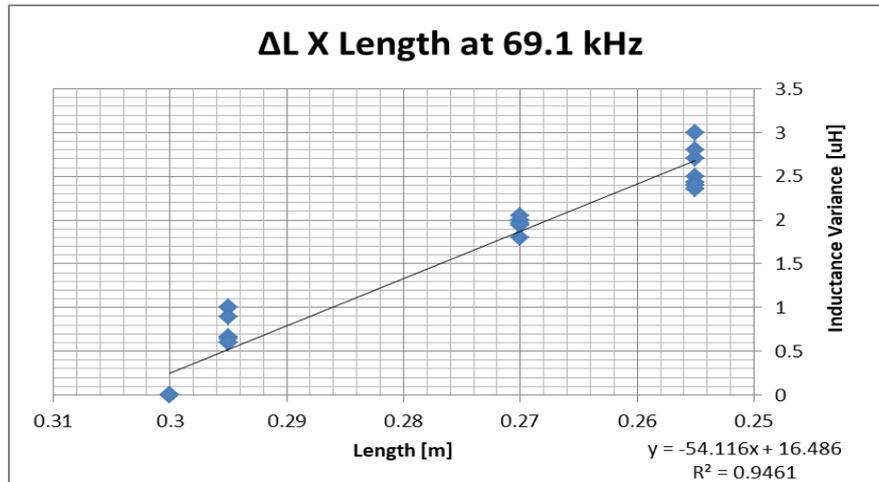


Figure 10: Graph of linearity between Inductance Variance and Muscle Length, measured at 69.1 kHz frequency

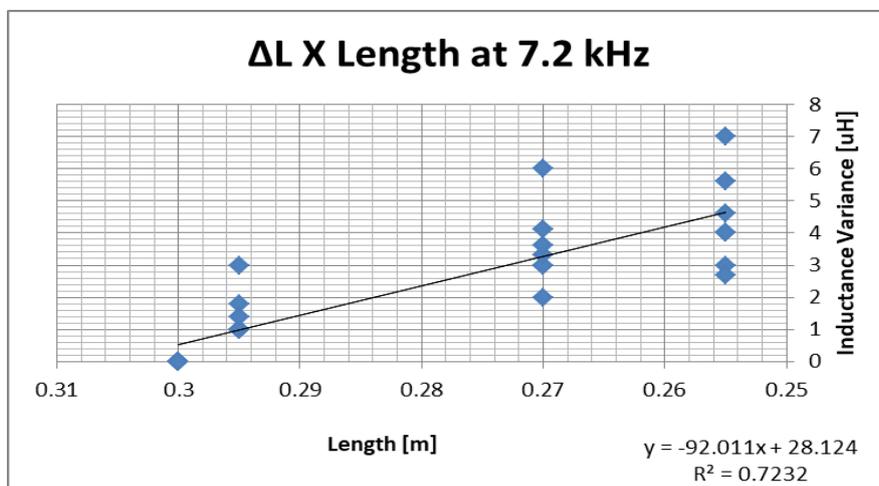


Figure 11: Graph of linearity between Inductance Variance and Muscle Length, measured at a 7.2 kHz frequency

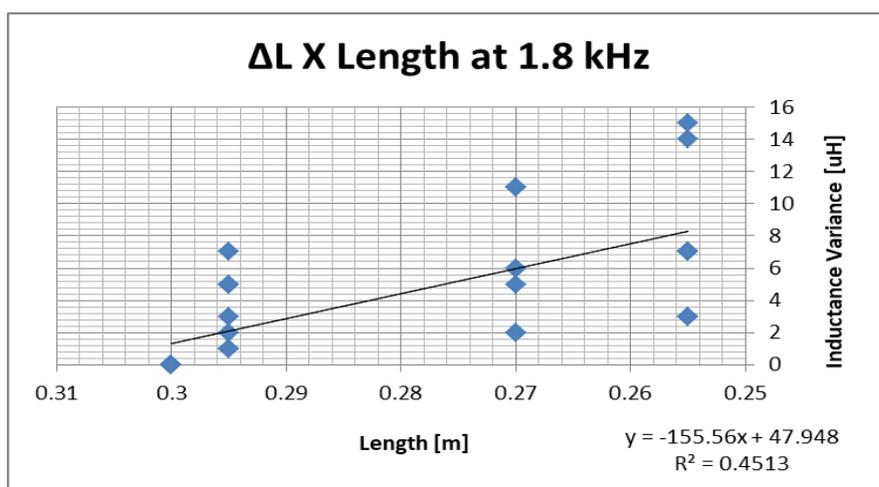


Figure 12: Graph of linearity between Inductance Variance and Muscle Length, measured at a 1.8 kHz frequency

There is the possibility of using conductive fibers applied to other types of actuators as well, for sensing and reinforcement roles. They have various applications that can be considered in future work.

4. CONCLUSIONS

In this work, we tested a way of manufacturing a Pneumatic Artificial Muscle actuator based on the method described by Felt (Felt et al., 2016), capable of measuring its instantaneous length without using any external transducers. For that we fabricated Smart Braids assembling together a flexible tube with a mesh made of conductive fiber, from which inductance can be measured and length can be calculated. This permits the PAM actuator to show improvements in its weight, aesthetics and simplicity.

Method 1 has showed a low accuracy for measuring inductance, but it provides fast and more easily digitalized values, which facilitates data analysis.

The second method used for measuring inductance demonstrated a better performance than Method 1, even though it was slower. The analysis of inductance variance at different frequencies revealed that, for this usage, higher frequencies have a better correlation than lower ones, therefore, we recommend that the equipment used for measuring inductance works at a frequency equal to or higher than 69.1 *kHz*, for achieving better results and better control of the PAM.

Working with inductance as a way to find a PAM contraction, by using Smart Braids is an innovative and sensible improvement for PAMs' research, yet there are some setbacks to be considered. The materials chosen must be at really good conditions, so one can avoid issues such as air bubbles being formed on the latex tube, which will eventually lead to muscle damage. Also, the inductance measuring method must be thought of carefully and well calibrated before usage, since the correlation between inductance and muscle Contraction is a very sensitive one.

It was noted that the relationship between contraction of the actuator and measured inductance is linear, since the contraction causes the wires in the braid to align in a way that leads to higher values of inductance, which provides a more straight-forward route for controlling the actuator. Therefore, we can conclude that the use of Smart Braids in Pneumatic Artificial Muscles is indeed a great improvement for its closed loop control, but must be thought of carefully before applied to real life PAMs.

5. REFERENCES

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