Characterization and Optimization of Usage Conditions of a Chemico-Mechanical Muscle Applicable to Medical Robotics

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Abstract. McKibben pneumatic artificial muscles currently function in a way very similar to skeletal muscles. The McKibben pneumatic muscle constitutes a real artificial muscle with actuator properties more suitable to motorize robot arms, which are closest to human arms than those of typical industrial robots. A McKibben muscle may in fact confer these new robotic arms original qualities of light weight and joint compression and flexibility, while offering the required force.
However, the McKibben muscle does not offer good power autonomy. Its dependence on a pressurized pneumatic source limits its application in the motorization of handling arms, therefore making its use difficult in the medical field.
The present work focuses on an alternative in which biochemical energy is transformed into osmotic energy and this, in turn, into mechanical energy by means of a Chemico-mechanical muscle, as well on the characterization and optimization of usage conditions for application in the medical robotics field.

1 Introduction

Each component of a biorobotics system incorporates many issues known in several sectors like physiology, biomechanics, actuators, circuits, processors and neuromuscular control algorithms. The actuator's flexible technology is focused on the supervision of artificial components, although the medical robotics scope is also considered.

The McKibben pneumatic muscle is currently the only artificial muscle capable of motorizing robot arms efficiently, although other actuators can mimic the skeletal muscle [1], [2]. However, the McKibben muscle does not provide energy autonomy. It depends on a pressurized pneumatic force. Furthermore, this limits the motorization of handling arms, therefore making its use difficult in the medical field.

It was then necessary to work on the adaptation of these muscles in the biological domain, developing chemico-mechanical muscles based on works carried out several years ago at the INSA LESIA laboratory in Toulouse, France, by Dominica VIAL and Mireille CONCIENCE. Compressed air was replaced with chemical products: ion-exchanging resins capable of transforming a pH difference into a force source. They can also transform an osmotic pressure difference into a force source.

In fact, with the classic McKibben muscle, volume increase of the rubber chamber develops a tension obtained because of a pressure difference (compressed air), while with the resin-based chemico-mechanical muscle, volume increase of the chamber is obtained by modifying the volume of these products, modifications derived from pH and/or osmotic pressure variations.

The paper hereto is arranged as follows: first, the McKibben artificial muscle's operation is explained; then, the studies of the properties of the chemical reagents used (ion-exchanging resins) are described and, finally, experimental results of the characterization and optimization of the properties of chemico-mechanical artificial muscles are provided.

2 McKibben artificial muscle

The McKibben Actuator was developed during the 50's by physicist Jose L. McKibben. After several years, the Bridgeston Corporation developed the first industrial artificial muscles, called "Rubberactuators" [3], [4]. These actuators are light weight, naturally flexible and they have a high strength-to-weight ratio. This is the reason why they have countless applications in robotics. Some actuators can imitate natural skeletal muscles [5], [6], but the McKibben pneumatic muscle is currently the only artificial muscle capable of efficiently motorizing robot arms because it offers equal or higher strength-to-weight and strength-to-volume ration than most classic actuators used in robotics. However, there is still much research ahead to control the McKibben actuator due to the non-linear behavior of the artificial muscle and its modeling difficulties. There are interesting results based on non-linear control [7], [8], neuromorphic circuits [9], [10], diffuse logics [11] or adaptive laws [12], but their performance must be demonstrated in 5 or more degrees of freedom in the robot arms to specify a better use for these biomimetic actuators in future applications. Anyway, the efforts carried out to model the McKibben muscle [8], [13], [14], have clearly accentuated its similarity in behavior with the natural skeletal muscle, making it a desirable candidate to manipulate robot arms or legs exhibiting kinematics similar to those of human's natural gestures.

3 Chemico-Mechanical muscle

The chemico-mechanical muscle is a McKibben pneumatic actuator filled with an ion-exchanging resin $RCOO^-$. The structure of chemico-mechanical artificial muscles is the same as the one used for the McKibben pneumatic artificial muscle. However, instead of transforming a pneumatic force into a mechanical force, a chemical force is transformed into a mechanical force, in a way very similar to the biological muscle: compressed air is replaced by the ion-exchanging resin (AMBERLITE IRC 86).

This way, the muscle is a length-wise rubber chamber containing the resin. This chamber is placed within a special braided shell.
In order to work with resin grains and solutions like sodium hydroxide (NaOH) and hydrochloric acid (HCl), it was necessary to replace the caps of each end of the muscle. So, caps used are sometimes made out of aluminum and frequently PVC, materials resistant to NaOH and HCl action. Caps have also nylon grids that trap resin grains within the rubber chamber.

The following table groups the features of the manufactured chemico-mechanical muscle (figure 1):

Table 1. Features of the manufactured chemico-mechanical muscle.

Total mass (resin+rubber + cap + shell)	Resin mass	Initial muscle length, L_0 (between caps)	Initial muscle diameter
70 g	1,8 g	75 mm	7mm

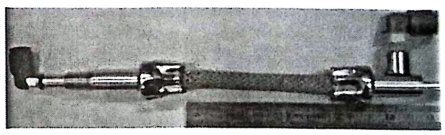

Fig. 1. Chemico-mechanical muscle.

To build the muscle, dry resin is inserted in the rubber chamber: the muscle is in a state equivalent to the resting state of the pneumatic muscle.

Before using the muscle, the resin must be humidified with circulating water: the resin will lightly inflate and the muscle will reach the initial balance state equivalent to that of the pneumatic muscle. Inflation according to humectation is irreversible (unless the resin is heated): during the muscle's lifecycle, the resting state will not longer be reached. Therefore, different from a pneumatic muscle, the resin muscle will not require inflating pressure before its usage.

The flow of sodium hydroxide (NaOH) within the rubber chamber causes the resin to inflate (Na^+ ions are replaced with H^- ions), implying the muscle's contraction: it is equivalent to pressurizing the pneumatic muscle. Expansion results from resin disinflation (Na^- ions are rejected and replaced with H^+ ions) caused by the flow of hydrochloric acid (HCl) in the chamber. Solutions enter through one end of the muscle and exit through the other. The flow of products inside the rubber chamber is possible, even when the resin inflates, and percolation is always observed. However, it is necessary to limit the flow of solutions to avoid accumulation of the resin at the exit of the rubber chamber, therefore preventing it from breaking and leaking into the muscle.

When the pneumatic muscle is placed at a specific position, this position is maintained with a constant predetermined amount of compressed air: when this pressure varies, position varies too. With resin muscle, the attained position is maintained without a solution flow: this is the muscle's position memory. The only way to change the position consists on injecting NaOH or HCl.

4 Experimental results

Ten years ago, the LESIA laboratory studied the behavior of chemico-mechanical muscles and the results were not satisfactory at that time, mainly because the response time was high, therefore not having any change to compete against pneumatic muscles. This year, the reason to retake that project is to attempt enhancing the response time and developed force to compete with the pneumatic artificial muscle and to apply it to medical robotics. The chemico-mechanical muscle uses a circuit that consists of a three-input valve that selects either the sodium hydroxide (NaOH) or the hydrochloric acid (HCl) solutions, and a computer-controlled peristaltic pump that insures the flow of the chosen solution. There is also an optical incremental coder to measure the muscle's contraction during the spinning of a sprocket, through which an inextensible chain supporting the position sensor goes.

4.1 Isometric tests (static contraction)

In isometric tests, the muscle's length (strain) is constant (at L_0 = muscle's initial length) and the force change is measured during the flow of different solutions.

The chemico-mechanical muscle is placed horizontally, its right limb attached to a blocked inextensible chain; this last is also connected to a force sensor. With the assistance of a peristaltic pump, a system of pipes and special caps placed at both muscle's ends, the NaOH or HCl solutions, at a predetermined concentration and flow, circulate through the muscle's rubber chamber. Therefore, the chemical reagent contained in this chamber will inflate it or deflate it (muscle contraction or relaxation). In this test, the force sensor detects every modification and transmits the information to the data collection system. Figure 2 depicts a photograph of the experimental mounting.

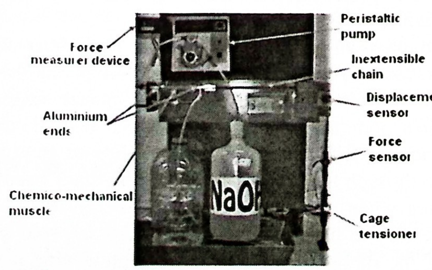

Fig. 2. Chemico-mechanical muscle in isometric contraction.

This system allows plotting the evolution curves of the muscle force in terms of time. These tests were carried out on the chemico-mechanical muscle manufactured in our laboratory, which has the features grouped in table 1.

4.1.1. Flow Optimization. The purpose of this study is to determine the best flow to use the chemico-mechanical muscle. This study is carried out at different concentrations of NaOH and HCl (0.1 mol/l and 0.05 mol/l). In order to determine the optimum flow, it is necessary to determine a satisfactory maximum force and reduced response time by using the minimum amount of solution.

Figure 3 groups different curves related to the force evolution with respect to time during the flow of a NaOH solution at 0,1 mol/l and at different flows.

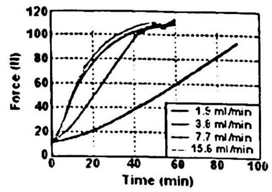

Fig. 3. Force evolution with respect to time when muscle is inflated by a NaOH solution at a concentration of 0.1 mol/l and at different flows.

When a sodium hydroxide solution is circulated at 0,1 mol/l, increasing the flow will decrease the muscle's inflation response time up to a limit flow (7,7 ml/min), beyond which the inflation curve remains the same.

Figure 4 depicts evolution curves of forces with respect to deflation time of the muscle during the flow of hydrochloric acid HCl at a concentration of 0,1mol/l and at different flows.

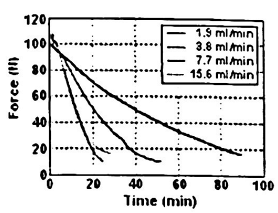

Fig. 4. Evolution of disinflation force during the flow of a HCl solution at 0.1 mol/l at different flows.

The muscle's disinflation time decreases with the increase of the HCl solution production at 0.1 mol/l. Figure 5 shows different curves representing the force evolution with respect to the muscle's inflation time and a sodium hydroxide solution at 0.05 mol/l and at different flows.

When a sodium hydroxide solution is passed at 0.05 mol/l using increasing flows, more or less identical inflation curves are obtained for each of the studied flows.

Figure 6 depicts evolution curves of forces with respect to the muscle's disinflation time during the flow of HCl acid at a concentration of 0.05 mol/l and at diffeient flows.

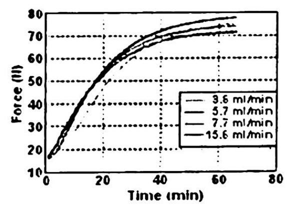

Fig. 5. Force evolution with respect to the muscle's inflation time when a sodium hydroxide solution flows at a concentration of 0,05 mol/l and at different flows.

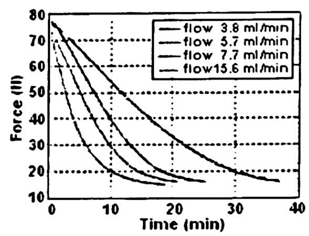

Fig. 6. Curves of force evolution at different flows during disinflation when a HCl solution is circulated at a concentration of 0,05 mol/l.

The muscle's disinflation time decreases with the increase of the HCl solution at 0,05 mol/l. According to tests and the analysis of results (graphs), the optimum flow of chemical solutions (NaOH and HCl) was set at 7,7 ml/min.

4.1.2. Optimization of concentrations. This study is carried out to determine optimum concentrations of NaOH and HCl, therefore allowing for a satisfactory force and response time (using the optimum flow set previously: 7,7ml/min).

Figure 7 represents curves of the force evolution with respect to time in the muscle during the flow of NaOH solutions at different concentrations.

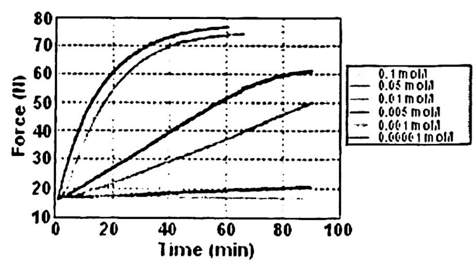

Fig. 7. Force evolution with respect to time for different NaOH concentrations.

Curves in figure 8 represent the force evolution with respect to the muscle's disinflation time with HCl solutions at different concentrations.

At a fixed flow (7.7 ml/min), when decreasing the concentration of NaOH solutions from 0,1 to 10^{-5} mol/l, kinetics of both the film and the particle decreases [15], therefore increasing the muscle's inflation time and the maximum force reached.

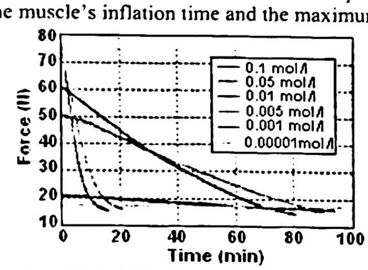

Fig. 8. Evolution of disinflation force at different HCl concentrations.

Note: disinflation curves start at the corresponding inflation positions.

The same phenomenon is observed in disinflation. In fact, at a fixed flow (7.7 ml/min), the decrease on the concentration of HCl solutions from 0.1 to 10^{-5} mol/l diminishes the kinetics of film and particle, therefore increasing the muscle's disinflation time.

At low concentrations (<0.05 mol/l), exchange is determined by the particle' slowest kinetics, therefore very slow inflation and disinflation and high time values. Working with concentrations higher or equal to 0.05 mol/l is therefore preferred. Furthermore, when determining usage limits for medical applications, pH values must be included between 3 and 9. In this way, maximum experimentation values in NaOH and HCl are set at 0.1 mol/l.

The first muscles based on ion-exchanging resin were studied around ten years ago by researchers of our laboratory (Dominique VIAL and Mireille CONCIENCE). However, operation conditions of these devices made them totally ineffective for medical purposes. In fact, these muscles required concentrations of sodium hydroxide solutions for inflation and hydrochloric acid for disinflation of 1 mol/l [16].

In this work, thanks to the type of resin and muscle used, usage conditions were optimized. In fact, NaOH and HCl concentrations of 0.1 mol/l or 0.05 mol/l are capable of inflate and disinflate muscles with adequate times, reaching satisfactory forces (60 N). Although it is true that this pH cannot be used inside the human body, it is acceptable for the skin. This is how this type of devices is now more prone to be used for medical applications.

The present studies of concentrations and flows prove that this is an all or none control in these devices for pH variation. Flow constitutes an adjustment parameter for this control.

4.2 Isometric Tests (Dynamic concentrations).

In isotonic tests, constant force (relative to a known mass) is applied to the muscle and its displacement during the flow of different solutions is measured.

Figure 9 depicts a photograph of the experimental mounting.

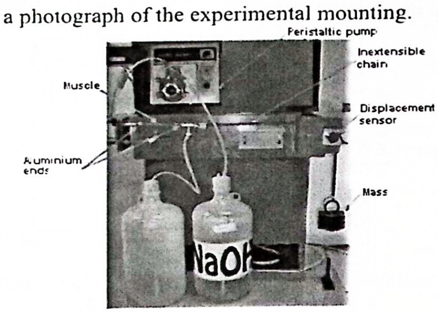

Fig. 9. Isotonic test with a 2kg mass.

The chemico-mechanical muscle is placed horizontally, with its right end attached to an inextensible chain which has different and known mass weights. This chain is attached to the displacement sensor in its other end.

When solutions flow through the muscle at different concentrations and flows, the product modifies its volume and the muscle contracts or relaxes. The displacement sensor detects every modification and sends the information to the data collection system. This system allows for the plotting of displacement evolution curves (muscle contraction) with respect to time. For these tests, the same chemico-mechanical muscle described in table 1 previously mentioned was used.

Figure 10 depicts the muscle's displacement evolution curves (contraction) with respect to time under different loads and during the flow of a sodium hydroxide solution at a concentration of 0,1 mol/l and a flow of 7,7 ml/min.

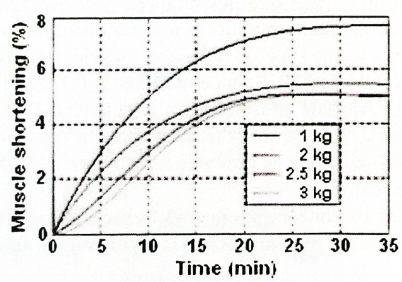

Fig. 10. Contraction curves of muscle in isotonic condition under different loads during the circulation of a NaOH solution at 0,1 mol/l and 7,7ml/min.

4.2.1. Power developed by the chemico-mechanical artificial muscle. Information gathered in isotonic conditions allows calculating the power developed by the chemico-mechanical muscle.

In fact, power is obtained by means of the following formula:

P (W) = V*Mg

where: V = Speed m/s, M = Mass in kg, g = Gravity constant , Speed is calculated from displacement of the muscle under isotonic contraction: $V = \Delta x / \Delta t$.

Therefore, it is possible to plot the power evolution curves (under isotonic conditions) with respect to time.

Curves in figure 11 show the evolution the muscle-developed power with respect to time during the flow of NaOH at 0,1 mol/l, a flow of 7,7 ml/min under loads of 1kg, 2kg, 2,5kg and 3kg.

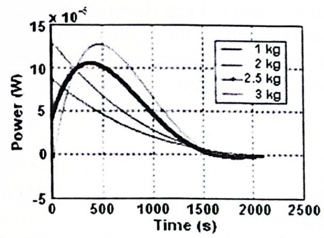

Fig. 11. Muscle-developed power curves.

Curves related to the tests carried out under light loads of 1 and 2 kg were incorrect. In fact, growth of the power curve is extremely fast, the sensor is not offering adequate properties and initial information is not recorded. However, it is possible to say that the power developed by a muscle when inflated with a NaOH solution at 0,1 mol/l and a flow of 7,7 ml/min varies from 0,15 to 0.01 mW under a load going from 1 to 3 kg.

5 Conclusions

In this research, the properties of a chemico-mechanical muscle based on ion-exchanging resin (AMBERLITE IRC 86) were studied and characterized, and usage conditions were optimized. Such muscles can be inflated and disinflated in a reversible way with NaOH and HCl solutions weakly concentrated (0,05 and 0,1 mol/l), with pretty low flows of 7,7 ml/mn and high forces that can reach up to 60 N. Furthermore, the power of 0,15 mW developed by these muscles is completely adequate for medical applications. However, they have several inconveniences. In fact, its response time is still too high for practical use. Furthermore, even if the concentration of solutions decreased from 1 to 0,1 mol/l or 0,05 mol/l, and even if they can be used in the medical field, such concentrations are still too high to implant such muscles in the human body.

Other alternatives are currently under research and there is no doubt that, in the near future, the response time and pH limits will not be an issue anymore and these chemico-mechanical muscles will be applied in medical robotics.

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