Pneumatic Artificial Muscles: actuators for robotics and automation

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Abstract

This article is intended as an introduction to and an overview of Pneumatic Artificial Muscles (PAMs). These are pneumatic actuators made mainly of a flexible and inflatable membrane. First, their concept and way of operation are explained. Next, the properties of these actuators are given, the most important of which are the compliant behavior and extremely low weight. A classification and review is following this section. Typical applications are dealt with in the last but one section and, finally, some concluding remarks are made.

Keywords: actuators, pneumatics, pneumatic artificial muscles, McKibben muscles, pleated pneumatic artificial muscles, compliance, lightweight.

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1 Introduction

Pneumatic actuators, usually cylinders, are widely used in factory floor automation. Lately, robotics as well is starting to use pneumatics as a main motion power source. One of the major attractions about pneumatics is the low weight and the inherent compliant behavior of its actuators. Compliance is due to the compressibility of air and, as such, can be influenced by controlling the operating pressure. This is an important feature whenever there is an interaction between man and machine or when delicate operations have to be carried out (e.g. handling of fragile objects). Thanks to compliance a soft touch and safe interaction can be easily guaranteed. Hydraulic and electric drives, in contrast, have a very rigid behavior and can only be made to act in a compliant manner through the use of relatively complex feedback control strategies.
Several types of pneumatic actuators—e.g. cylinders, bellows, pneumatic engines and even pneumatic stepper motors—are commonly used to date. A less well-known type is that of the so-called Pneumatic Artificial Muscles (PAMs). These are in fact inverse bellows, i.e. they contract on inflation. Their force is not only dependent on pressure but also on their state of inflation, which makes for a second source of spring-like behavior. They are extremely lightweight because their core element is but a membrane, and yet, they can transfer the same amount of energy as cylinders do, since they operate at the same pressure ranges and volumes. For these reasons they carry a great potential to be used to power mobile robots, where they have additional advantages, such as direct connection, easy replacement and safe operation, as will be seen later.

2 Concept and operation

PAMs are contractile and linear motion engines operated by gas pressure. Their core element is a flexible reinforced closed membrane attached at both ends to fittings along which mechanical power is transferred to a load. As the membrane is inflated or gas is sucked out of it, it bulges outward or is squeezed, respectively. Together with this radial expansion or contraction, the membrane contracts axially and thereby exerts a pulling force on its load. The force and motion thus generated by this type of actuator are linear and unidirectional. This contractile operation distinguishes the PAM from bellows, which extend upon inflation.
Throughout literature different names are found for PAMs: Pneumatic Muscle Actuator [1], Fluid Actuator [2], Fluid-Driven Tension Actuator [3], Axially Contractible Actuator [4, 5], Tension Actuator [6, 7].
A PAM's energy source is gas, usually air, which is either forced into it or extracted out of it. This way the actuator is powered by the pressure difference of the inside gas with regard to the surroundings. Although it is possible to design an underpressure operating muscle [8, 9], PAMs usually operate at an overpressure: generating and supplying compressed gas is easier to accomplish and, with ambient pressure mostly at about 100 kPa, a lot more energy can be conveyed by overpressure than by underpressure. Charging an overpressure PAM with pressurized gas enables it to move a load, discharging it, conversely, makes it yield to a load.
To see how the device operates, two basic experiments can be considered. In both cases a PAM of an arbitrary type is fixed at one end and has a mass hanging from

the other. In the first experiment, shown in Figure 1, the mass M is constant and the pressure difference across the membrane, i.e. its gauge pressure, is increased from an initial value of zero. At zero gauge pressure the volume enclosed by the membrane is minimal, V_{min}, and its length maximal, l_{max}. If the muscle is pressurized to some gauge pressure p_1, it will start to bulge and at the same time develop a pulling force. The mass will thus be lifted until the generated force equals Mg. The membrane's volume will then have grown to V_1 and its length contracted to l_1. Increasing the pressure further to p_2 will continue this process. From this experiment two basic actuator behavior rules can be deduced: (1) *a PAM shortens by increasing its enclosed volume*, and (2) *it will contract against a constant load if the pneumatic pressure is increased*.

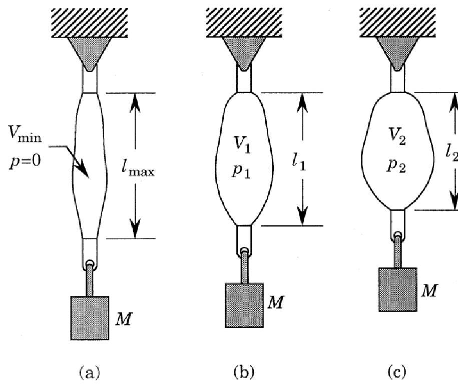


Figure 1: PAM operation at constant load.

The other rules can be derived from the second experiment, shown in Figure 2. The gauge pressure is now kept at a constant value p, while the mass is diminished. In this case the muscle will inflate and shorten. If the load is completely removed, as depicted by Figure 2 (c), the swelling goes to its full extent, at which point the volume will reach its maximum value, V_{max}, the length its minimal value, l_{min}, and the pulling force will drop to zero. The PAM cannot contract beyond this point, it will operate as a bellows at shorter lengths, generating a pushing instead of pulling force. This means that (3) *a PAM will shorten at a constant pressure if its load is decreased* and (4) *its contraction has an upper limit at which it develops no force and its enclosed volume is maximal*.

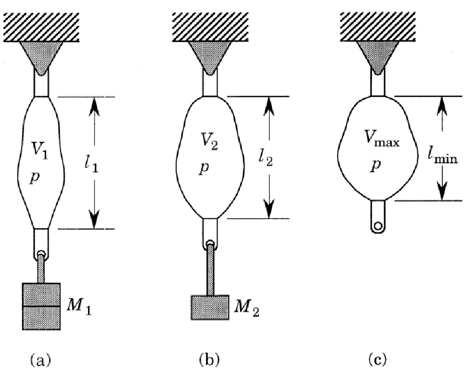


Figure 2: PAM operation at constant pressure.

Concluding from both experiments a fifth rule can be added: (5) *for each pair of pressure and load a PAM has an equilibrium length*. This behavior is in absolute contrast to that of a pneumatic cylinder: a cylinder develops a force which depends only on the pressure and the piston surface area so that at a constant pressure, it will be constant regardless of the displacement.

3 Properties

3.1 Static load characteristics

The equilibrium length of a PAM at static conditions will be determined by the pressure level, the external load and the volume-to-length change of that particular muscle. To see how, one can consider a muscle at gauge pressure p which has an infinitesimal mass dm of gas forced into it during a time interval dt. Thereby, the membrane's volume increases by dV and a net amount of work of pdV crosses its boundary. During the same period dt , the actuator's length changes by dl (<0 for shortening) and a load F is displaced over the same distance, requiring an amount of work $-Fdl$. Disregarding the work needed to deform the membrane and assuming quasi-static conditions one can then write

$$F = -p\frac{dV}{dl} \tag{1}$$

In reality, however, the developed force will have a lower value mainly due to membrane deformation. Comparing the PAM force-length expression to that of pneumatic cylinders $-dV/dl$ is defined as the actuator's "effective area" [3].

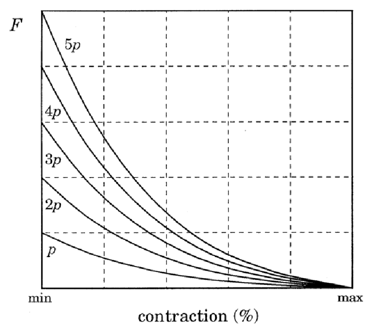


Figure 3: PAM isobaric force-contraction diagrams.

Defining contraction as the change in length relative to its maximum value l_{max}—e.g. a contraction of 10% denoting a shortening to 9/10th of the maximum length—the static load characteristics can be diagrammed as is done in Figure 3. Each curve plots the values of generated muscle force as a function of contraction and at a constant value of pneumatic pressure. All curves are similar, the pressure is actually a scale factor as can be concluded from (1). The basic curve is characteristic of the type of membrane and its way of inflating. Whatever the type being considered, the force will always drop from its highest value at full muscle length to zero at full inflation and contraction. It is because of this characteristic that these actuators are referred to as being muscle-like since skeletal muscles also have a monotonically decreasing load-contraction relation.

3.2 Compliance

Because of gas compressibility all pneumatic actuators show a compliant behavior. On top of this, a PAM has its dropping force to contraction curve as a second source of compliance: even if the pressure is maintained at a fixed level, the muscle acts spring-like due to the change of force with regard to length. Compliance, C, can be expressed as the inverse of stiffness, K:

$$C^{-1} = K = \frac{dF}{dl} = -\frac{dp}{dV}\left(\frac{dV}{dl}\right)^2 - p\frac{d^2V}{dl^2} \tag{2}$$

Assuming a polytropic process going on inside the muscle this can be written as

$$C^{-1} = -n\frac{p+P_0}{V}\left(\frac{dV}{dl}\right)^2 - p\frac{d^2V}{dl^2} \tag{3}$$

with P_0 the ambient pressure and n the polytropic exponent. Both terms depend on the pressure and, therefore, compliance can be adapted by controlling the pressure.

3.3 Antagonistic set-up

Fluidic Actuators are contractile devices and can, consequently, generate motion in only one direction. Just as with skeletal muscles, two actuators need to be coupled in order to generate a bidirectional motion, one for each direction. As one of them moves the load, the other one will act as a brake to stop the load at its desired position. To move the load in the opposite direction the muscles change function. This opposite connection of the muscles to the load is generally referred to as an antagonistic set-up. The antagonistic coupling can be used for either linear or rotational motion, as is shown in Figure 4.

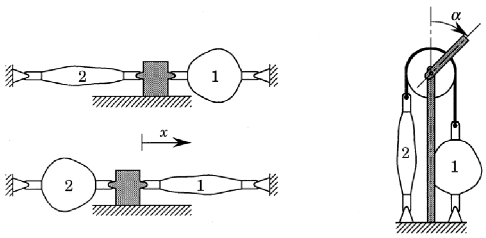


Figure 4: Antagonistic set-up.

Because the generated force of each muscle is proportional to the applied pressure, the equilibrium position of the effector driven by the antagonistic couple will be determined by the ratio of both muscle gauge pressures. This can be readily seen from the graph in Figure 5, which shows the force characteristics of the muscle pair in case of a linear motion.
Muscle (1) is at a gauge pressure p while the pressure of muscle (2) varies. As this muscle's pressure changes, its force graph is scaled accordingly and the equilibrium will move to the new points of intersection of the graphs. If, on the contrary, both pressures are scaled by the same factor, the force graphs will be so equally and their intersection point will remain at the same value of position. Hence, only the ratio of gauge pressures will determine the equilibrium position.

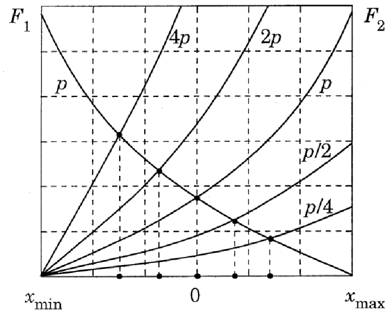


Figure 5: Equilibrium position as a function of gauge pressure ratio.

3.4 Skeletal Muscle Resemblance

PAMs resemble skeletal muscle insofar that both are linear contractile engines having a monotonically decreasing load-contraction relation (although this is not always the case for skeletal muscle). Both have to be set up antagonistically in order to get bidirectional motion and both are able to control joint compliance. A lot of differences, however, exist [10]: skeletal muscles

- do not change volume during contraction;
- have a modular structure, they are in fact a vast parallel and series connection of microscopic contractile systems;
- are organized in units whose activation depends on the level of external load;
- come in fast and slow types, depending on the need of sustained action and speed;
- have integrated multiple force and strain sensors;
- have energy stored in them and running through them;
- can serve as energy source or even building material for muscles of other biological systems, in other words, they are comestible.

The latter distinctive feature is perhaps the most extraordinary: one biological system can disintegrate another one's actuators down to the molecular level and use this to power or build its own actuators.

3.5 Lightweight and strong

As already mentioned before, these actuators are extremely lightweight because their main component is a membrane. Yet, they can be made very strong with forces ranging up to several thousands Newtons. Power to weight ratios are in the order of magnitude of several kW/kg.

3.6 Direct connection

In many applications, e.g. positioning systems, electric drives need a speed reduction because of their high revolution speeds and low values of torque. Such gearing introduces unwanted phenomena in the system, such as backlash and extra inertia. PAMs can be directly connected to the structure they power: they easily fit in because they are small and, more importantly, their values of speed and force generally are in the range of what is needed.

3.7 Ready replacement

Because of the direct connection, replacement of a defective muscle is very easily and rapidly done. It takes only uncoupling one muscle from the machine and pneumatic tubing and connecting the new one.

3.8 Hazard-free use

Concerning its effects on operating surroundings, it is clear that as long an innocuous gas is used, these actuators cause no pollution, hazards, detrimental or harmful effects. As is the case for all pneumatic devices there are no hazards of fire or explosion. Furthermore, because of its intrinsical and adjustable compliance it can be made to have a soft touch and is consequently well suited for safe man-machine interaction.

4 Classification–review

Since their first conceiving, which according to Marcinčin and Palko [8] was in 1930 by a Russian inventor named S. Garasiev, various fluid-driven muscle-like actuators have been developed. They can be distinguished, according to their design and operation: (1) pneumatic or hydraulic operation, (2) overpressure or underpressure operation, (3) braided/netted or embedded membrane and (4) stretching membrane or rearranging membrane.
Hydraulic operation is taken into consideration for completeness' sake. The key attribute of these artificial muscles is their inflation and deformation. Due to the flexibility needed for this and, consequently, the limited material strength, the pressure difference across the shell needs to be limited. Typical maximum values range at about 500 kPa to 800 kPa. At these values hydraulic operation suffers from a bad power to weight ratio, making it not very attractive. The third characteristic refers to the tension carrying element of the muscle: a structure either embracing the membrane or embedded in the membrane. The last characteristic refers to the manner in which the membrane inflates: to be able to expand radially, either the membrane material has to stretch or the radial section has to change by rearranging the membrane's surface. In case of pure rearranging, the total membrane surface is constant regardless of contraction and volume. This allows for a greater tension to be developed as no energy is put into stretching membrane material.
This review will focus on two types of PAM: the Braided Muscles, which are the most frequently used, and the Pleated Pneumatic Artificial Muscle, which was recently developed as an improvement with regard to the drawbacks of the braided design. Other designs, usually old ones, will be only briefly discussed.

4.1 Braided muscles

Braided muscles are composed of a gas-tight elastic tube or bladder surrounded by a braided sleeving (weave, braid, sleeve) as is shown in Figure 6 for a special kind of this type of muscle. The braid fibers run helically about the muscle's long axis at an angle (pitch angle, braid angle, weave angle) of $+\theta$ and $-\theta$. When pressurized the tube presses laterally against the sleeve. Thereby the internal pressure is balanced by braid fiber tension due to fiber curvature about the tube. Fiber tension is integrated at the braid's end points to balance an external load. As the pressing contact between tube and sleeving is absolutely necessary to convey load, braided muscles cannot operate at underpressure: passing through the meshes of the braid, surrounding gas would only act on the tube that, consequently, would be squeezed without transferring a noticeable amount of work to the clamps.

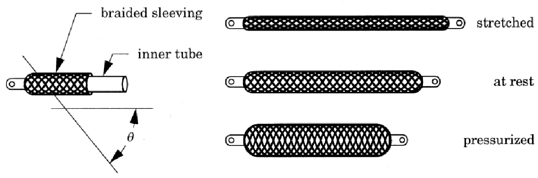


Figure 6: Braided muscle, McKibben Muscle.

This type of muscle was derived from a patented design by Morin [9], who actually embedded the fibers into a rubber diaphragm (cf. § 4.4). According to Baldwin [11], J. L. McKibben introduced it as an orthotic actuator in the late 1950's: due to the similarity in length-load curves between this artificial muscle and skeletal muscle, it seemed an ideal choice for this purpose [12, 13]. However, practical problems, such as pneumatic power storage or availability and poor quality valve technology at that time, gradually reduced interest from the prosthesis/orthotics community in McKibben Muscles. In the late 1980's this type was reintroduced by Bridgestone Co. in Japan as the Rubbertuator [14], and used to power an industrial use robot arm, Soft Arm. Since then several research groups have been using this type of PAM to power robots, mainly of anthropomorphic design, prostheses and orthotics [15, 16, 17, 18, 19, 20].
The general behavior of these muscles with regard to shape, contraction and tension when inflated will depend on the geometry of the inner elastic part and of the braid at rest (meaning neither pressurized nor loaded), and on the materials used. Usually, braided muscles have a cylindrical shape because of a cylindrical bladder and a constant pitch angle throughout the braid. Two basic types of braided muscles can be distinguished: one that has both its inner tube and braid connected to fittings at both ends and another that only has the braid connected to end fittings and whose inner tube is an unattached bladder. The former type is generally referred to as the McKibben Muscle. The latter has no particular name so, for the sake of clearness, it will be referred to as the Sleeved Bladder Muscle.

4.1.1 McKibben Muscle

This type of pneumatic artificial muscle is the most frequently used and published about at present. It is a cylindrical braided muscle that has both its tube and its sleeving connected at both ends to fittings that not only transfer fiber tension but also serve as gas closure. Typical materials used are latex and silicone rubber and Nylon fibers. Figure 6 shows its structure and operation.
By changing its pitch angle the braid changes its length and diameter. Notating l_s as the length of each strand of the braid and N the amount of encirclements it makes about the tube, one can easily deduce the volume enclosed by the diaphragm:

$$V = \frac{l_s^3}{4\pi N^2} \cos\theta \sin^2\theta \qquad (4)$$

Maximum volume is thus attained at a weave angle of about 54.7°. Increasing the angle beyond this value is only possible by axially compressing the muscle. This will not be considered as it is not stable: the flexible muscle shell has no flexural stiffness and thus it would immediately buckle. When stretching, the pitch angle decreases to a lower limit, which is determined by fiber thickness, the amount or density of fibers, the number of encirclements and the diameter of the end fittings. Typical values of pitch angles, given by Caldwell et al. [16], are 59.3° for the maximum inflation state and 20.0° for the fully stretched state.

Tension can be related to weave angle [12, 22] using (1):

$$F = \frac{\pi {D_{\max}}^2 p}{4}\left(3\cos^2\theta - 1\right) \tag{5}$$

with D_{max} the muscle's diameter at a braid angle of 90°, which is the limiting case. Defining contraction as

$$\varepsilon = 1 - \frac{l}{l_0} \tag{6}$$

where l stands for muscle actual length and l_0 muscle length at rest, tension can also be related to contraction [14, 23]:

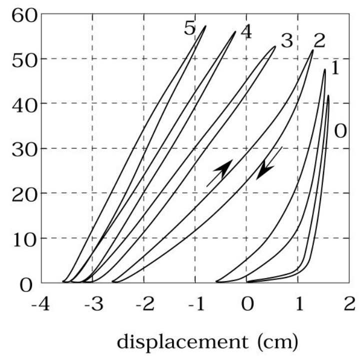
$$F = \frac{\pi {D_0}^2 p}{4}\left(\frac{3}{\tan^2\theta_0}(1-\varepsilon)^2 - \frac{1}{\sin^2\theta_0}\right) \tag{7}$$

with D_0 and θ_0 the diameter and the weave angle at rest, respectively. The state of rest is determined by the original tube size and braid characteristics. Elongation beyond the rest size is possible, as stated before, until the minimum pitch angle is reached. The range of contraction-extension depends on the lower pitch angle limit and, consequently, on the density of strands in the weave and on their thickness. Chou and Hannaford [21] report ranges of 0.75–1.1 of initial length for Nylon fiber McKibben Muscles, 0.86–1.14 for fiberglass McKibben Muscles and 0.79–1.02 for the Rubbertuator (see also Inoue [14]).

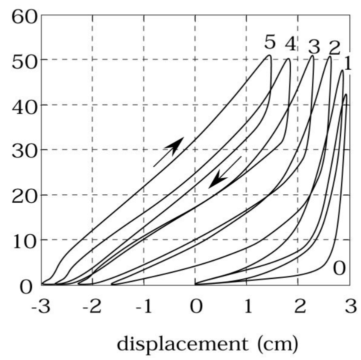
As for typical values of force, Tondu et al. [22] found 650 N at rest length, 300 N at 15% contraction and 0 N at 30% contraction, all at pressures of 300 kPa, for a muscle of 150 mm rest length, 14 mm diameter and a weight of 50 g. Inoue [14] cites 220 N at rest length, 100 N at 10% contraction and 0 N at 20% contraction, equally at a pressure of 300 kPa for a muscle of 150 mm rest length and a weight of 32 g.

The tension expressions can be expanded to take into account friction—between sleeving strands and tube and between the strands themselves—and deformation of the inner tube [12, 21]. Friction and non-elastic deformation of the diaphragm will show up as hysteresis and threshold pressure (i.e. the pressure difference to be exceeded in order to start radial diaphragm deformation), while elastic lateral deformation will lower tension. The force needed to elongate or compress the tube with regard to its rest length can be modeled as a passive spring force acting in parallel with the active force calculated by equation (1). This passive force will increase tension at $l > l_0$ and lower it at $l < l_0$.

Chou and Hannaford [21] report a threshold pressure of 90 kPa, hysteresis width of 0.2–0.5 cm and height of 5–10 N for a Nylon braid muscle of 14 cm rest length and 1.1 cm rest diameter and more or less double these figures for an approximately equal sized fiberglass braid muscle (cf. Figure 7). They also show hysteresis to be substantially due to dry friction. Caldwell et al. [23] report forces attaining only 53% of their values predicted by equation (1). The typical operating gauge pressure range of McKibben Muscles is 100–500 kPa. The maximum allowable gauge pressure is determined by the strength of the tube: too high a pressure would make the tube bulge through the meshes of the net and it would subsequently burst. The higher this pressure the more energy can be transferred, but equally the higher the threshold pressure because of the increasing toughness of the diaphragm. As a result of this, low forces cannot be generated.



(a)



(b)

Figure 7: McKibben Muscle tension (N) and hysteresis at isobaric conditions (0, 100, 200, 300, 400 and 500 kPa), (a) Nylon braid, (b) fiberglass braid. [21]

As for power to weight ratios of McKibben Muscles, values cited by Caldwell et al. [23] range from 1.5 kW/kg at 200 kPa and 3 kW/kg at 400 kPa. Hannaford et al. [15] cite a value of 5 kW/kg and Hannaford and Winters [24] even 10 kW/kg. To determine these values, no auxiliary elements such as valves, were taken into consideration. The weight of McKibben Muscles is typically about 50 g ([22], l_0=34 cm, D_0=1.4 cm), but can be as low as 5.5 g ([1], l_0=9 cm, D_0=1 cm).

As mentioned earlier, this type of muscle is the most frequently encountered one to date. The main reason for this seems to be its simple design, ease of assembly and low cost. On the other hand life expectancy of this muscle, of which no written reports were found, seems not very high. Users complain about early braid fiber failure at the point of clamping. A major disadvantage of the McKibben Muscle is its inherent dry friction and threshold pressure. Because of these, accurate position control is difficult to achieve. Additionally, due to friction temperature affects muscle operation: warm muscles behave different from cold ones [16], Hesselroth et al. [19] report a positional drift of the Rubbertuator that occurs when the actuator pressure is oscillating about a fixed value. As already mentioned before, other disadvantages are the limited displacement and the energy needed to deform the rubber membrane, lowering the output force.

4.1.2 Sleeved Bladder Muscle

This type differs from the McKibben type in the design of the inner bladder: it is not connected to the sleeving. This means that no passive spring force is added to muscle tension. Winters [20], whose McKibben-like muscles simply consist of a bladder surrounded by a braid directly attached to tendon-like cords, reports motion ranges of 5–30% shortening and less than 10–20% lengthening depending on pitch angle at rest. The main advantage of this PAM is its extreme ease of assembly. A Sleeved Bladder Muscle is also subject of the patent of Beullens [25].

4.2 Pleated PAM

This actuator, which was only recently developed by Daerden [26, 27], is of the membrane rearranging kind. This means no material strain is involved when it is inflated. The way this is done is shown in Figure 8. The muscle membrane has a number of pleats in the axial direction—just like a car engine filter—and when it expands it does so by unfolding these. No friction is involved in this process. Furthermore, membrane stresses in the parallel direction (perpendicular to the axis) are kept negligibly small and decrease with an increasing number of folds. As a result, practically no energy is needed to expand the membrane. Because of the absence of friction this design shows practically no hysteresis. Only the membrane's flexion when it bulges needs some energy. This is a very small amount, as can be deduced from the generally low values of threshold pressure, e.g. less than 10 kPa for the muscle described at the end of this section (cf. Figure 12).

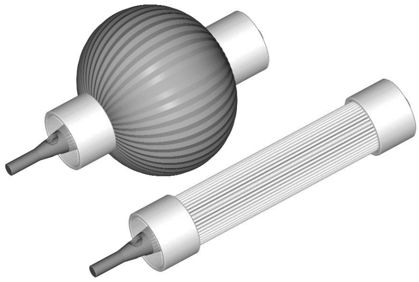


Figure 8: Pleated Muscle, fully stretched and inflated.

Fully inflated, the muscle gets a pumpkin-like shape as can be seen from Figure 9.
The characteristics of this type of muscle depend on the ratio of full length to minimum diameter, on the strain behavior of the membrane's material, on the contraction rate and, finally, on the applied pressure. Contraction force can be derived mathematically [26] and put as

$$F_t = pL^2 f_t(\varepsilon, \frac{L}{R}, a) \tag{8}$$

in which L represents the muscle's full length, R its minimum radius (as in the left side sketch of Figure 9) and a a dimensionless factor that accounts for the membrane's elasticity. As can be seen, f_t is a dimensionless function, depending only on contraction rate, geometry and material behavior. Other properties, such as volume and diameter, can be similarly expressed.

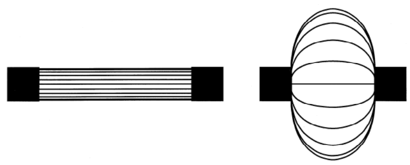


Figure 9: Pleated Muscle shape.

Using high tensile strength and stiffness material for the membrane, one can omit the influence of elasticity and set a to zero. Figure 10 shows f_t in that case for different values of muscle thickness R/L. Experimental results agree extremely well with the values derived from the mathematical model.

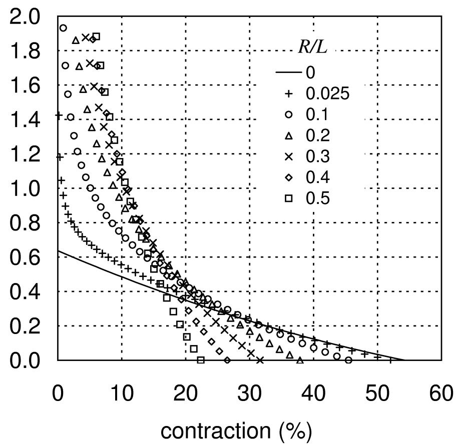


Figure 10: Pleated Muscle dimensionless force function.

It is clear how thick muscles contract less than thin ones, but generate higher forces at low contraction rates. An infinitely thin muscle has a maximum contraction of about 54%, this is the highest shortening this type of muscle ever can reach. In practice a minimum thickness of about R/L = 0 has to be assured in order to be able to assemble the muscle. This results in a practical value of maximum contraction of about 45%. Figure 11 diagrams travel or maximum contraction as a function of thickness. As an example, Figure 12 shows the measured force diagrams for a range of operating pressures of a muscle of L = 10 cm and R = 1.25 cm (R/L = 0.125). Its membrane is made of a para-aramid fiber unidirectional fabric made air-tight by a polypropylene liner. The end fittings are made of aluminum. Its total weight is about 60 g. The maximum contraction of this muscle was experimentally found to be 41.5%, as can be checked from the diagrams. The pressure was limited to 300 kPa although short bursts of up to double that value were found not to be harmful. The maximum force was limited to about 3500 N in order not to damage the actuator. The threshold pressure is below 10 kPa, although the operation at that pressure is far from the mathematically predicted one.

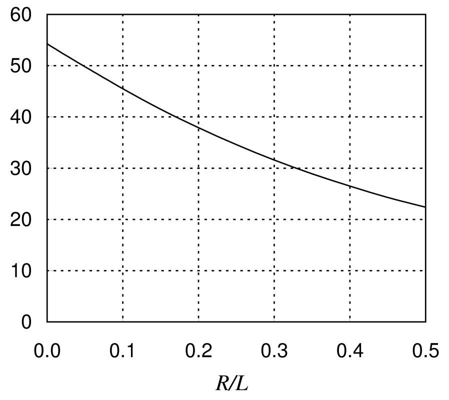


Figure 11: Pleated Muscle maximum contraction (%) as a function of thickness.

Two of these muscles were used to drive a 1 DOF rotative robot joint [26, 28]. Due to the absence of hysteresis, positioning accuracy was better than 0.1° for a motion range of 60°. Positioning times are about 40 ms for a displacement of 3°, 100 ms for 10° and 500 ms for a full range displacement. Besides positioning, compliance control was performed [28]. In an open loop control the effector could be made to yield to a load once this reached a preset value. Classic linear PI-control techniques were used both for position control and compliance control. This was possible mainly because of the absence of hysteresis.

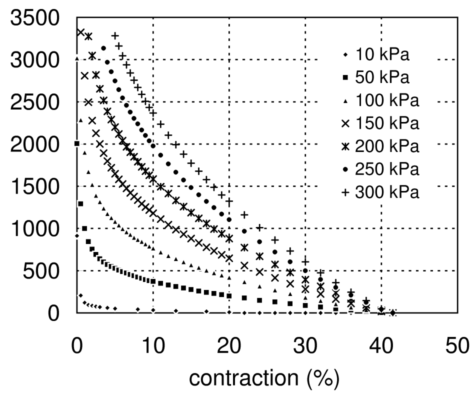


Figure 12: Measured muscle force (N), $L = 10$ cm and $R = 1.25$ cm.

Similar 1 DOF rotative robot joint positioning experiments have been performed using McKibben Muscles [1, 14, 16, 19, 30]. In spite of using more or less complex control algorithms, e.g. pole placement, feed forward, adaptive control, fuzzy control or neural networks, the step response times are in the order of magnitude of 1 s and higher and positioning accuracy worse than 1° for similar motion ranges as above. This shows the tremendous impact hysteresis due to friction has on controlling these actuators.

4.3 Netted Muscles

The difference between braided and netted muscles is the density of the network surrounding the membrane, a net being a mesh with relatively large holes and a braid being tightly woven. Because of this, if the membrane is of the stretching kind, it will only withstand low pressures. Therefore this type of fluid actuator will usually have a diaphragm of the rearranging kind.

4.3.1 Yarlott Muscle

This type of fluid muscle is disclosed in a US patent by Yarlott [31]. It comprises an elastomeric bladder of a prolate spheroidal shape netted by a series of cords or strands that run axially from end to end. The bladder is radially reinforced by strands to resist elastic expansion. This can also be done by a single cord wound helically about the shell as shown in Figure 13. In its fully inflated state, this actuator takes the spheroid bladder shape. When elongated, the axial strands straighten out and push the bladder into a shape characterized by a series of ridges and valleys as can be seen from the front view in Figure 13. The shell's surface area remains more or less constant and a surface rearranging ensues on inflating. As shell stretching is thus reduced, more pneumatic energy can be transformed into mechanical power. If completely elongated, the axial strands will be fully straightened and pressurization would then lead to an infinitely high tension. However, due to strand material yielding this will not be attained. Apparently, Yarlott designed this muscle to operate at low gauge pressures—a value as low as 1.7 kPa is cited.

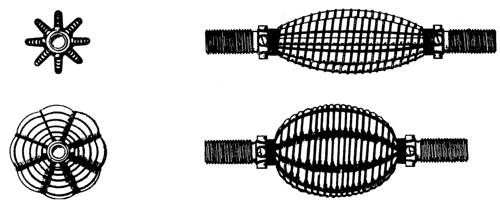
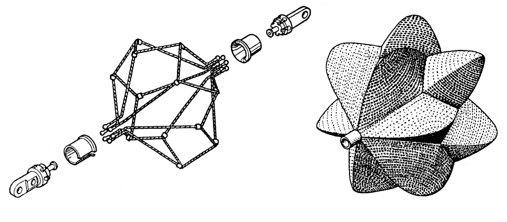


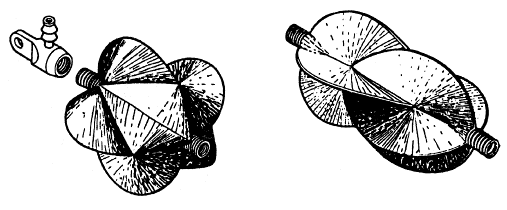
Figure 13: Yarlott Muscle. [31]

4.3.2 ROMAC

This RObotic Muscle ACtuator was designed by G. Immega and M. Kukolj in 1986. It is the object of a US patent [4] and is treated briefly in [32, 33]. It consists of an articulating polylobe bladder harnessed by a wire netting and closed at either ends by fittings, as is shown in Figure 14. The bladder is made of a sheath, that is characterized by its high tensile stiffness, its flexibility and its fluid-tightness (e.g. impregnated para-aramid fiber fabric). The netting or harness is comprised of non-stretchable flexible tension links which are joined at nodes so as to form four-sided diamond shaped apertures in the network, as shown in Figure 14. The harness expands radially and contracts axially, thereby changing the base of each protruding lobe. As a result of this mechanism the enclosed volume changes. The total surface of this actuator is constant regardless of contraction-elongation due to the tensile stiffness of the membrane material. Each base side of a protrusion or lobe is connected to a base side of an adjacent lobe by a flexible seam or continuous fold running underneath a wire element. Due to the absence of friction and membrane stretching, a much higher force and nearly negligible hysteresis is attained compared to muscles of the stretching membrane type.



(a)



(b)

Figure 14: ROMAC, standard version (a) and miniature version (b). [32]

Two versions of ROMAC are made: a standard one, having lengths of 6–30 cm and a miniature one, having lengths of 1–6 cm. The miniature version and also low pressure operating standard versions do not, in effect, need to be harnessed. For standard sizes, muscle forces of 4500 N to 13600 N at gauge pressures of 700 kPa, and maximum contractions of up to 50% are cited.

4.3.3 Kukolj Muscle

This type of actuator, which is described in [5], is in its basic embodiment a variation of the McKibben Muscle. The main difference between them is the sleeve: McKibben Muscles have a tightly woven braid while the Kukolj design uses an open-meshed net. In its non-loaded condition, there is a gap between the net and the membrane, which only disappears at a suitably high extending load. The condition of non-pressurization and load, such that the net fits the diaphragm, is the fully extended condition. The reason for the gap, mentioned by the inventor, is the tendency of the network to contract faster than the membrane, resulting in buckling of the latter near its ends. The initial stretch prevents this from happening.

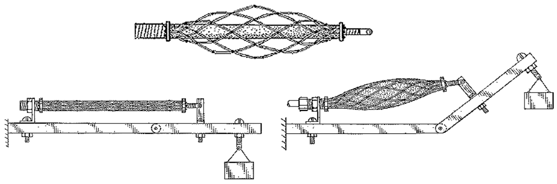


Figure 15: Kukolj Muscle. [5]

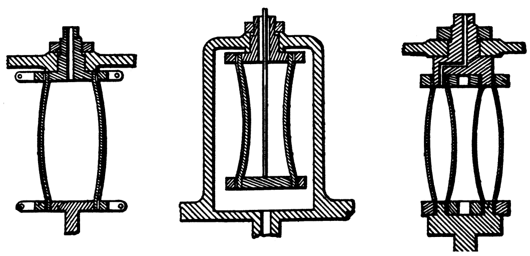
Figure 15 shows the Kukolj Muscle in its uninflated, non-loaded condition, and in a set-up, lifting a weight mounted hanging from a hinged arm, with the actuator in fully stretched and intermediate inflation conditions.

4.4 Embedded Muscles

As mentioned earlier, the load carrying structure of this type of fluid muscles is embedded in its membrane. Among this type figure several designs, most of which will be referred to by their inventor's name.

4.4.1 Morin Muscle

This early design of fluid muscle, described in [9], had for its object "an elastic diaphragm adapted to be subjected to the pressure of any fluid and adapted to transmit any change in the pressure of said fluid to a controlling device, such as measuring instruments, valves and similar devices." With this in mind one cannot really call it an artificial muscle but, as it has the same principle of operation and is the origin for McKibben's design, it is included in this review.
In this design a rubber tube is embedded by threads of a high tensile stiffness. These threads can be directed along the actuator's long axis or in a double helix about that axis. As fiber material Morin cites cotton, rayon, asbestos or steel; a choice that is clearly marked by that time. The two-phase membrane is clamped by two end fittings, serving to seal and to attach the load. Full tensional load is taken by the fibers while the elastomer stretches to allow for inflation. Possible operating fluids suggested by Morin are compressed air, water, oil or even steam.



(a) (b) (c)

Figure 16: Morin Muscle Designs. [9]

In his patent he proposes three designs having different ways of operation regarding pressure: an overpressure design as shown in a longitudinal cross-section in Figure 16 (a), an underpressure design, Figure 16 (b) and a concentric membranes design, Figure 16 (c). In the underpressure design the diaphragm is housed inside a vessel. The diaphragm is at ambient pressure while the vessel is pressurized. Power is transduced via a rod attached to the lower diaphragm end fitting and sliding through an orifice in the upper end fitting.
Typical operating pressures or other characteristics are not mentioned.

4.4.2 Baldwin Muscle

This type of muscle [11] is based on the design of Morin. It consists of an elastomeric membrane, a very thin surgical rubber, embedded by glass filaments in the axial direction. The resulting membrane has a modulus of elasticity in the fiber direction that is much higher than that in the direction perpendicular to the fibers. Figure 17 sketches this type of muscle.

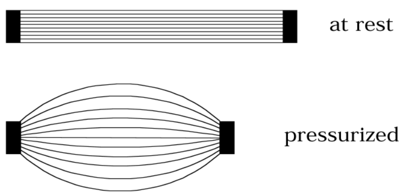


Figure 17: Baldwin type muscle.

Due to the absence of friction and the very thin membrane, this muscle shows less hysteresis and a very low threshold pressure compared to braided muscles but, as radial expansion is quite high, gauge pressures have to be limited to low values, typically 10–100 kPa. Baldwin [11] cites forces of up to 1600 N at these low pressures. Life tests which consisted of the continuously lifting and lowering of a weight of 45 kg at a gauge pressure of about 100 kPa indicated an operating life of some 10 000 to 30 000 cycles. A similar but earlier design, developed by K. Nazarczuk in 1964 at the Warsaw Polytechnic, is mentioned in [8].

4.4.3 UPAM

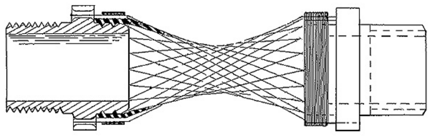
The UPAM, which stands for UnderPressure Artificial Muscle, has in fact a similar design as the Morin type showed in Figure 16 (b). It is described very superficially in [8, 34, 35, 36, 37]. As gas is sucked out of the membrane it collapses in a non-axisymmetrical way, i.e. it is squeezed and flattened in the middle. Contractions of 20% for muscles of a maximum diameter of 50 mm and length of 100 mm are mentioned. Since contraction stops when the membrane sides touch, these actuators have to be designed quite thick in order to obtain reasonable values for maximum contraction. Forces vary between 20 N and 140 N, but it is not mentioned at what underpressure. These values are rather low because of the maximum pressure difference of 100 kPa with regard to ambient conditions.

4.4.4 Paynter Knitted Muscle

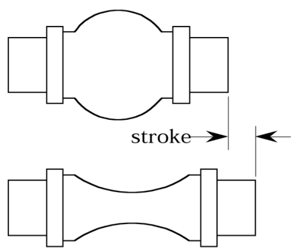
This design is the object of a US patent [7]. The actuator has a spherical bladder that is reinforced by a knitted structure of strong, tough and flexible fibers. This structure is made to have the same spherical shape as the bladder so that it conforms to it and can be easily bonded to it. The bladder is made of an elastomeric material. During inflation the bladder does not stretch as is the case for McKibben Muscles. When fully inflated the muscle takes on the shape of the original bladder and knitting sphere. If extended from thereon, it will gradually take on a fluted shape. Unpressurized, the muscle can be extended to a length equalling half the circumference of the sphere. Therefore, maximum contraction with regard to this fully extended state is 36.3%. Operating gauge pressures can be as high as 800 kPa. Life expectancy is mentioned to be "many hundreds of thousands of cycles".

4.4.5 Paynter Hyperboloid Muscle

An alternative design by Paynter, also described in a US patent [3] concerns a type of muscle whose membrane, in its fully elongated state, has the shape of a hyperboloid of revolution. The elastomeric membrane is embedded by a sleeve of inextensible, flexible threads that are anchored to the end fittings. With the actuator at its longest, these threads run in straight lines from end to end, thus defining the hyperboloid surface. A set of strands runs in one sense about the axis, an equal amount of strands run in the opposite sense. Figure 18 (a) shows a sketch of this type of muscle. When inflated, the membrane bulges into a nearly spherical surface at full contraction, as shown in Figure 18 (b).



(a)



(b)

Figure 18: Paynter Hyperboloid Muscle. [3]

Paynter [3] cites metal wires, cord, polyester fibers and para-aramid fibers as possible strand materials. For the membrane he suggests neoprene rubber or polyurethane. The muscle can be powered both pneumatically or hydraulically. The maximum bulging diameter is about two times the end fittings diameter, while tension is proportional to the square of this value. A maximum contraction or stroke of about 25% and tensions of some 500 N at 200 kPa at zero contraction are mentioned for a muscle 2.5 cm long and of 1.25 cm end fitting diameter.

4.4.6 Kleinwachter torsion device

Kleinwachter and Geerk [38] describe in their US patent how the inflatable membrane technique can be used in designing a torsional device, which they refer to as torsion muscle. It is shown in Figure 19. It has a toroid diaphragm attached at its outer edge to a ring shaped structure and at its inner edge to a shaft. The diaphragm is embedded with stiffening filaments that run obliquely across the radial direction from the outer structure to the shaft. When inflated the membrane bulges and the filaments thereby rotate the shaft in the direction of φ, as indicated on the figure. One-way rotation and torque are thus achieved.

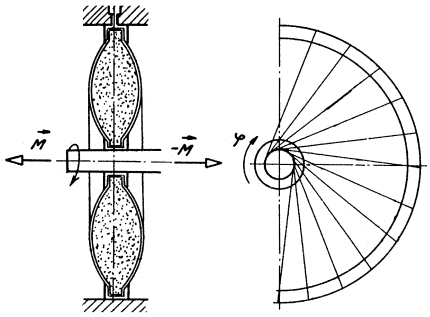


Figure 19: Kleinwachter torsion device. [38]

5 Applications

To the authors' knowledge, PAMs have never really been commercially produced, except for the Rubbertuators, which were manufactured and marketed by Bridgestone Co. for some time. At the present, McKibben-like muscles are being brought to the market by Festo Ag. & Co., showing a general renewed interest in these devices. PAMs, nowadays, are mainly used as robotic actuators in applications where compliance and low power to weight ratio are important, e.g. walking/running machines or even humanoid robots. Prosthesis/orthotics applications are less frequently seen today as was the case some thirty years ago when Schulte [12] used it to drive an arm brace. To the authors' knowledge only Winters [20] mentions Sleeved Bladder Muscles as having potential as a suitable power system in prosthetics.

Caldwell et al. [1] used 18 small (90 mm long, 10 mm diameter, 5.5 g) McKibben Muscles to power a dexterous four-fingered manipulator, with each finger powered by four muscles, and the thumb by six. Caldwell et al. [16] report on how to use McKibben Muscles for powering the elbow and wrist of an anthropomorphic arm. Caldwell et al. [17] take it one step further to the start of a design of a full humanoid robot. Another full humanoid project is the Shadow Robot Project [39].

Hannaford et al. [15] built an anthropomorphic arm, having fifteen McKibben Muscles. The Anthroform Biorobotic Arm, as they call it, is controlled by simulated spinal neural networks. Their purpose, in a first instance, is "to improve the understanding of the reflexive control of human movement and posture".

Grodski and Immega [18] used ROMACs to control a 1 dof teleoperated arm by means of the myoelectric signals taken from a human operator's biceps and triceps. The operator can thus make the robot arm move without having to move his own. Independent position and stiffness control of the robot arm is achieved by regulating the ROMAC gauge pressures proportional to the operator's EMG signal output. Visual feedback to the operator is necessary.

Inoue [14] describes the Soft Arm, developed by Bridgestone Co. which is powered by Rubbertuators. It has a shoulder, an upper arm, a lower arm and wrist, 4 to 5 DOFs, and a useful payload of maximum 3 kg. Possible applications that are cited are painting or coating, both needing gentle handling by the robot and explosionproof operation.

Yoshinada et al. [40] use hydraulically actuated McKibben Muscles to power an underwater manipulator. This is one of the rare occasions where using a hydraulic actuation makes sense. The surrounding fluid is the same as the driving fluid, eliminating the weight problem. In these conditions, using gas would actually create problems due to the upward force that would act on the gas. The manipulator has a seven DOF arm and a three-fingered hand. It is designed to carry a payload of 5 kg and has a weight of 18 kg.

Several authors suggested other, somewhat far-fetched applications that never really found any practical use. Examples of these are rotary engines, driven by radially set up muscles, a set-up to generate biological actions such as that of a sphincter, an active vehicle suspension and a borescope steering section.

In our laboratory Pleated Muscles have been used to power a hopping leg [41]. These muscles perform excellently in this application as they are extremely lightweight and allow for a spring-like operation of the leg. Energy is stored as a pressure increase in the extensor muscle: as the leg hits the ground it bends and the extensor is stretched and thereby its volume decreases. This energy is released as work when the leg starts moving upwards and the extensor contracts. Hopping heights can be maintained by setting the muscle pressures to fixed values as the leg reaches its upper position and by adding small amounts of air right after touchdown in order to account for energy losses. By adapting the muscle pressures the spring-like behavior can be adapted to the required hopping heights and system payloads. The stiffer the muscles are, the higher the leg will hop. The system is actually kept in resonance by this procedure and, therefore, energy efficiency is optimal for this way of actuation.

6 Conclusions

Although PAMs have been around for quite some time now, these actuators have not been widely used to date, which is not easily explained for. Possible reasons the authors see are the lack of large-scale need for this specific type of actuator and resulting from this a lack of technological effort to improve the existing designs. The most commonly used design to date, the McKibben Muscle, has some important drawbacks, mainly with regard to its control, as was mentioned before, but also with regard to service life: the flexible membrane is connected to rigid end fittings which introduces stress concentrations and therefrom possible membrane ruptures. Cylinders, being entirely composed of rigid materials, do not suffer from this problem. Using adequate designs and materials these problems can, however, be solved.

In view of the problems robotics has in finding suitable actuators, the need for the strong and lightweight PAMs could very well mount in the near future: Pleated Muscles have been proven to be able to perform very accurate positioning tasks, using PAMs the structure of a robot arm can be made a lot lighter and consequently its payload to weight ratio a lot higher compared to electric drives, PAM operation characteristics make it inherently apt and easy to use for delicate handling operations or to power an adjustable firmness gripper. Especially for mobile robots—demanding lightweight actuators, able to generate high torques at low and moderate speeds, able to be connected to the structure without gearing, having a natural compliance and shock resistance and a possible autonomous operation—Pneumatic Artificial

Muscles seem a better choice than present day electric or other drives.

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