Pleated pneumatic artificial muscles: actuators for automation and robotics

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Abstract— **This contribution reports on a type of pneumatic artificial muscles (PAMs) that was recently developed at the Vrije Universiteit Brussel, department of Mechanical Engineering. Its distinguishing feature is its pleated design. Due to this, it has a very high contraction force and an equally high travel. The weight of these pleated PAMs is very low: a muscle of only 60 gr can pull up to 3500 N and contract by an amount of 42%. Furthermore, dry friction and associated hysteresis, typical of many other designs, is avoided by the folding–unfolding action. This significantly simplifies position control using these actuators. Although the force–displacement characteristics of our actuators are non–linear, they can be effectively controlled using basic linear PI techniques. Another advantage of these actuators is their inherent and controllable compliance, making them ideally suited for walking/running machines or whenever delicate tasks, e.g. handling fragile objects, have to be performed. In view of all characteristics pleated PAMs are very well suited for automation and robotic applications.**

I. Introduction

One of the key elements in robotics and automation is selecting the appropriate actuators. In general the choice is restricted to electric drives, hydraulic cylinders and pneumatic cylinders. These actuators are extensively used, well known and readily available, but this does not imply the perfect actuators for each application to exist. On the contrary, a lot of efforts are constantly being put into looking for new kinds of actuators not only to improve existing ones but also to be used in new applications altogether.

A case in point is walking and running robots or, in fact, all human motion mimicking machines. Weight, power, compliance and direct connection to the joints are the dominating considerations here. Low weight and high power are needed if such a machine is to be agile and strong. Compliance is a prerequisite for several reasons. First of all, moving on legs is characterized by impacts that need to be absorbed and softened, impacts not only damage the machine parts but they also waste valuable energy. Secondly, a smooth and elegant way of walking and running cannot be brought about by rigid drives. This can be understood intuitively and it can be witnessed from existing, generally electrically driven walking robots. Thirdly, compliance can be used effectively to store and release energy during separate phases of running: stored as elastic potential energy when flexing immediately after touchdown, and released subsequently during the stretching or jumping phase. This will evidently lead to a more efficient way of robot motion. In addition to this, compliance is a way of making a machine safer with respect to itself and its surroundings because of the enhanced flexibility. The drives are preferably directly connected to the joints because using a transmission will increase weight and introduce extra inertia and unwanted phenomena like backlash. Consequently, the developed force (torque) must be high and typical speed of operation low to moderate. The traditional types of actuators all fail on account of one or several of these requirements, e.g. electric drives are heavy, not at all compliant and they produce low torques at high speeds and thus require a transmission. Pneumatic artificial muscles, on the other hand, meet these demands: they are extremely lightweight, produce high levels of force at low to moderate speeds and are inherently compliant.

Another example is force control. Most of the existing actuators need rather complicated and state–of–the–art feedback control and sensory equipment in order to achieve this. As will be seen further on, a PAM's output force is proportional to the applied pressure and decreases with ongoing contraction. Because of this, force control is easily accomplished by controlling the level of activation or pressure.

II. Pleated Muscle Concept

Pneumatic artificial muscles are contractile devices operated by pressurized air. Their core element is an inflatable membrane. When pressurized, they inflate, shorten and thereby generate a contraction force. This force depends on the applied pressure and on the muscle's length, ranging from an extremely high value at maximum length, i.e. zero contraction, to zero at maximum contraction or full inflation. Because of the one–way operation a paired or antagonistic setup is needed in order to generate bidirectional force or movement.

Inflation can happen either by muscle membrane strain or by muscle membrane rearranging, meaning unfurling the membrane in some way. The so–called McKibben muscle [1] is of the straining kind. It is basically a rubber tube that expands against a netting, needed to transfer force. Because rubber deformation is not entirely elastic and, more important, because a lot of friction occurs between the rubber tube and the netting and between the wires of the netting themselves, this type of muscle shows substantial hysteresis [1]. This obviously has an adverse effect on actuator behavior [2] and necessitates using complex models [3], [4] and control algorithms [5]. Material stretching also lowers the output force because of the energy used for it, this reduction can be as high as 60% [5].

In an effort to eliminate hysteresis and material deformation we developed a muscle of the rearranging type. Its membrane has a high tensile stiffness in order to eliminate rubber–like strain, but it is at the same time highly flexible. It is uniformly folded together along the long axis, quite like a car engine air filter, stashing away the membrane material needed to expand inside the folds. At both ends the membrane is tightly locked to fittings, which also carry the gas inlet and outlet ducts. When such a muscle is pressurized it shortens and starts to bulge. As the membrane has a high tensile stiffness, the expansion is highest in the middle of the membrane and gradually goes down toward both ends where no expansion at all can occur. This concept is illustrated in Fig. 1. Because the fold faces are laid out radially no friction is involved in the folding–unfolding process and no friction related hysteresis will occur. Furthermore, unfolding needs no appreciable amount of energy so no loss of output force will ensue from this.

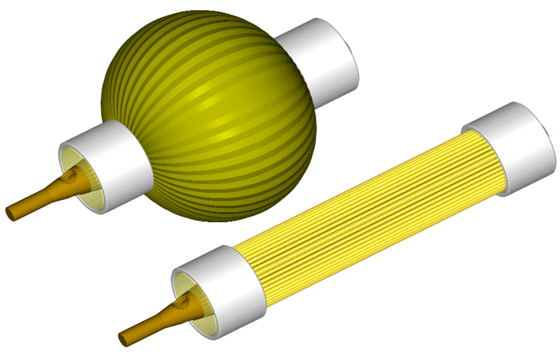


Fig. 1. Pleated muscle concept.

An extra objective of this pleated arrangement was to have no parallel stress, i.e. perpendicular to the long axis, holding back the elongation along that direction so that a maximum expansion and, hence, contraction could be expected. The ideal way of achieving this is by using an orthotropic membrane having a high tensile stiffness in one direction and being able to extend freely—zero E–modulus—perpendicular to that direction. Folding the membrane is a means of approximating this mode of inflation: the higher the number of folds and the shallower they are, the better the approximation will be.

III. Characteristics

A mathematical analysis of the pleated PAM was made by assuming the ideal orthotropic membrane, which can actually be seen as a pleated membrane having an infinite amount of infinitely shallow folds. A rigorous and detailed report of this analysis can be found in [6]. The analysis basically comes down to solving a differential equation of the first order and the first degree and involves elliptic integrals of the first and second kind. It allows determining the shape this type of muscle takes on as it is inflated: it gradually moves from its original cylindrical form toward an oblate spheroid or pumpkin–like form, as is sketched by Fig. 2. It also allows determining all other characteristics regarding geometry, membrane tensile stress and contraction force. These are found to depend on the membrane's initial length l, its initial diameter D, the degree of contraction ϵ, the applied pressure p and the longitudinal elasticity of the membrane. As an example, contraction force is expressed as

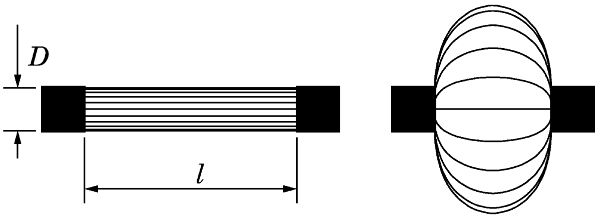


Fig. 2. Pleated muscle shape.

$$F = p\, l^2\, f(\epsilon, \frac{l}{D}, a) \tag{1}$$

with l/D the muscle slenderness and a a dimensionless factor taking into account the membrane elasticity. Other characteristics can be expressed in the same way. This implies that pleated PAM behavior is basically determined by the value of slenderness and the membrane elasticity. Using a high tensile stiffness material, the influence of the latter becomes negligible and a can accordingly be omitted. All characteristics are then seen to depend only on a dimensionless function of slenderness and contraction and on a proper scaling factor. Force, maximum diameter and volume can respectively be put as

$$F = p\, l^2 f(\epsilon, \frac{l}{D}) \tag{2}$$

$$\tilde{D} = l\, d(\epsilon, \frac{l}{D}) \tag{3}$$

$$V = l^3 v(\epsilon, \frac{l}{D}) \tag{4}$$

Fig. 3 diagrams the force function f for various values of slenderness. It illustrates the typical muscle behavior: applying an internal pressure at full muscle length causes an extremely high pulling force to be generated, at increasing contraction this force gradually drops until it reaches zero, at which point the muscle is maximally contracted. Thick muscles contract less than thin ones, but develop higher forces at low values of contraction. An infinitely thin muscle ($l/D = \infty$) has a maximum contraction of 54.3%, this is the highest shortening this type of muscle ever can reach. In practice a minimum thickness (D/l) has to be assured in order to be able to assemble the muscle. We found this minimum to range between 0.1 and 0.2, depending on the assembly method, resulting in a maximum contraction range of about 45–50%. A 'square' muscle, i.e. $l = D$, has a stroke of only 22.3%.

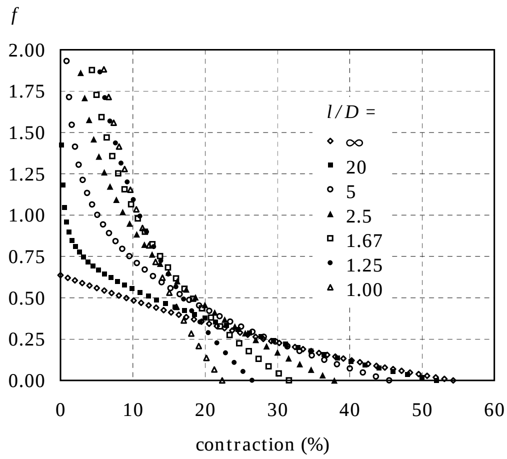


Fig. 3. Dimensionless force function f.

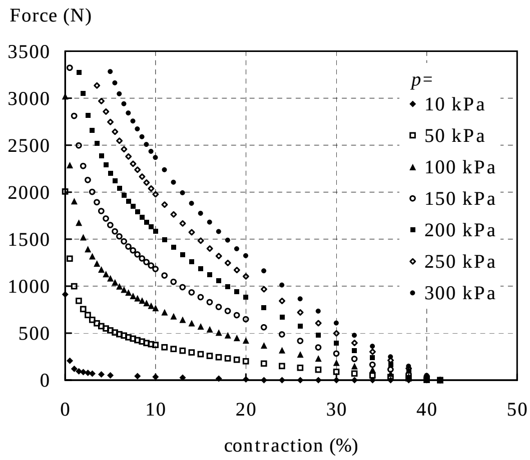


Fig. 4. Measured values of force–contraction at various levels of pressure ($l = 10\,\text{cm}$, $D = 2.5\,\text{cm}$).

The diagram also marks the fundamental difference between pneumatic muscles and pneumatic cylinders: whereas cylinders generate a force depending only on pressure and bore, not on displacement, muscle generated force drops with displacement. The implication of this is stressed if one considers the position control of a mass in a horizontal plain. Using a double–acting cylinder the pressures in both chambers are equal once the equilibrium position is reached, which can be anywhere within the actuating range. Using an antagonistic muscle pair, on the other hand, the equilibrium position depends on the ratio of the pressures in both muscles: raising the pressure in one muscle causes the equilibrium to shift toward that muscle, lowering it causes the opposite effect.

The expressions in Eqs. (2), (3), (4) make it easy to compare geometrically similar muscles of different sizes. For instance, if one wants to double the contraction force at the same levels of pressure, muscle length has to increase by 41%. This will, however, multiply the volume and air consumption by a factor of 2.83. Total contraction will be increased like length by 41%, which is not necessarily wanted. On the other hand, if one does not need high forces, it is possible to replace one long muscle by a series connection of n similar but smaller ones so that total length and contraction are preserved but total volume, like force, is divided by n^2.

The agreement between theory and practice was found to be very good. Noticeable deviations were only found in the lower and upper regions of contraction. At small contractions, the increase in developed force and membrane stress is so strong that the membrane elasticity cannot be omitted. For high values of contraction the force drops somewhat stronger than predicted due to the finite fold depth. A muscle of $l = 10\,\text{cm}$ and $D = 2.5\,\text{cm}$, having a total of 44 pleats each 2.5 mm deep and weighing as little as 60 gr can be cited as an example. For contractions ranging from 5% to about 30%, the measured values of force and diameter were seen to be within a few percents of the values predicted by the mathematical model [6]. The muscle diameter grows nearly fourfold during contraction, from 2.5 cm to 9.35 cm. Travel was predicted to be 43.5% and experimentally found to be 41.5%. The isobaric force diagrams of this muscle are plotted in Fig. 4. The applied pressure was limited to 300 kPa, although short bursts of up to double that value were found not to harm the muscles. Force was limited to some 3500 N at low values of contraction in order to limit the steeply growing membrane stress. Fig. 5 shows two photographs of this pleated PAM, one in its extended state and one at a contraction of 35%.

Besides the ability of developing very high traction forces and contracting substantially, Fig. 4 also proves the possibility to operate at a fairly wide range of pressure levels—10 kPa to more than 300 kPa. Both very low and very high forces can accordingly be created. This is not so for McKibben muscles: if soft rubber is used they only operate at low pressures because high pressures would then burst the tube, if tough rubber is used they have a substantial threshold pressure, e.g. 90 kPa [1], below which the rubber will not extend and the muscle will not operate. The reason for the low threshold pressure of pleated PAMs is to be found in their design. The membrane of the muscle of Fig. 4 is made of a Kevlar®49 quasi–unidirectional fabric lined with a polypropylene film. It has a total thickness of only 0.28 mm, guaranteeing it to be quite flexible. Flexibility is very important because of the structural stability or stiffness a muscle gains from its pleated configuration. The less flexible the membrane is, the harder it will be to

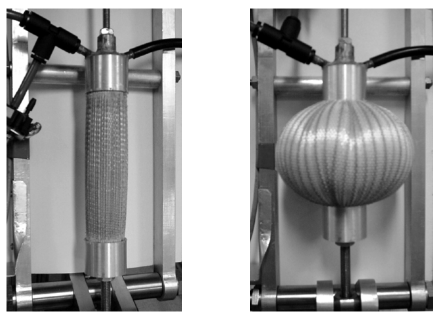


Fig. 5. Pleated PAM, extended and partially contracted.

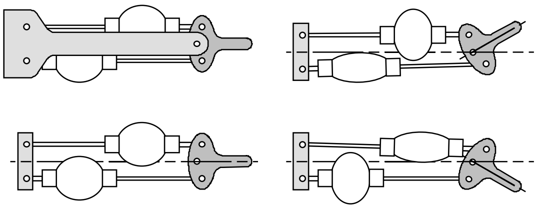


Fig. 6. Revolute PAM powered joint.

inflate it and the higher the threshold pressure will be.

IV. Antagonistic revolute joint actuator

Because PAMs can only pull, two are needed to get bidirectional motion, one for each direction. Such a paired setup is often referred to as an antagonistic coupling. Using two identical muscles of $l = 10\,\mathrm{cm}$ and $R = 2.5\,\mathrm{cm}$ we built a revolute joint actuator as outlined in Fig. 6. The muscles are connected to the joint by a leverage mechanism and rigid pull rods. The leverage is designed to have a linear torque to angle relation and to have a rotation range of $\pm 30°$ coinciding with a muscle contraction range of 5% to 35%. At lower contractions the muscle force risks becoming too high and at higher contractions forces are considered too low to be of very useful, cf. Fig. 4. Because of the asymmetrical operation the lever gets larger on the shortening muscle's side and smaller on the other side, as can be seen on Fig. 6. This way, compared to a pulley system, torques generated by a short muscle are somewhat raised and those generated by an extended muscle reduced. At center position both muscles are contracted by 19%. Moving from 0° to 30° is done by contracting the upper muscle from 19% to 35%, while elongating the lower muscle from 19% to 5%.

Fig. 7 shows the torques exerted by each muscle at varying values of muscle pressure. At 100 kPa and center position both muscles produce a torque of 14 Nm. The maximum obtainable torque is about 73 Nm. From Eq. (2) and from the lever mechanism geometry, the torques M_i can be expressed using dimensionless functions m_i. Furthermore, they can be approximated by lines, as can be seen

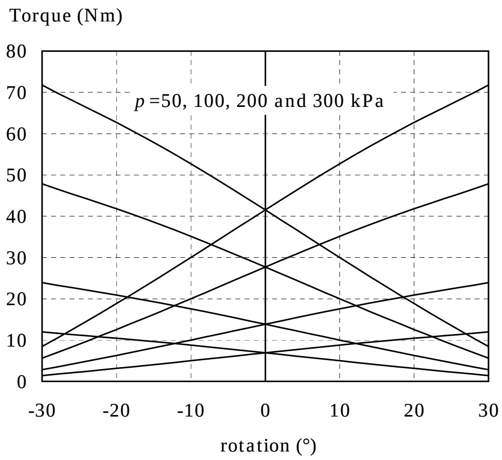


Fig. 7. Torques exerted by the pleated muscles.

from Fig. 7:

$$M_1 = p_1 l^3 m_1 \approx p_1 l^3 (m_0 - k\alpha) \tag{5}$$

$$M_2 = p_2 l^3 m_2 \approx p_2 l^3 (m_0 + k\alpha) \tag{6}$$

with α the angle of rotation, p_i the individual muscle pressures, $m_0 = 0.138$ and $k = 0.207\,\mathrm{rad}^{-1}$.

A. Position control

In the absence of external loads, the motion governing equation of the joint can be written as

$$J\ddot{\alpha} + kl^3(p_1 + p_2)\alpha = m_0 l^3 (p_1 - p_2) \tag{7}$$

with J the moment of inertia of all moving parts. At equilibrium this results to

$$\alpha = \frac{m_0}{k}\frac{p_1 - p_2}{p_1 + p_2} \tag{8}$$

showing the importance of pressure control in controlling the position of this revolute actuator. This can be done by off–the–shelf pressure regulating servo–valves. These usually set a pressure that is proportional to the applied input voltage. The position control presented here was performed using KPS 3/4 servo–valves manufactured by Kolvenbach AG, Germany.

If the sum of both muscles can be kept fixed, Eq. (7) describes a linear system with input Δp, defined as

$$p_1 = p_m + \Delta p \tag{9}$$

$$p_2 = p_m - \Delta p \tag{10}$$

These are in turn set by the servo–valves reacting to their input voltages, making the voltage difference signal, ΔU, the actual system input. The dynamic behavior of the system—muscles, valves and the joint—was characterized by open–loop step input response tests: a small step in valve command signal was imposed and the resulting angular displacement was measured. This led to the following model

$$\alpha(s) = \frac{m_0}{U_m k}\frac{e^{-t_d s}}{(1+\tau s)(1+(s/\omega_n)^2)}\Delta U(s) = H(s)\Delta U(s) \tag{11}$$

with the natural frequency defined as

$$\omega_n = \sqrt{\frac{2p_m k l^3}{J}} \tag{12}$$

and $t_d = 5\,\mathrm{ms}$ the valve delay time and τ the pressure setting time constant. The latter was found to be dependent on the mean pressure level and, to a lesser extent, on the angular position. Its values range from 50 ms for $p_m = 300\,\mathrm{kPa}$ to 200 ms for $p_m = 50\,\mathrm{kPa}$.

Position control of the joint was done in conditions of negligible load. An angular feedback proportional–integral control law was used for this purpose. The integral term is indispensable because a permanent change of pressures is necessary in order to have a permanent displacement. The

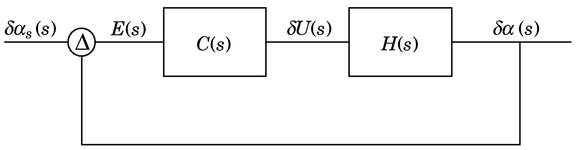


Fig. 8. Controlled system blockdiagram.

complete system blockdiagram is given in Fig. 8. As an illustration, Fig. 9 shows responses for a 10° and a 60° step input, with in both cases p_m set at 150 kPa. Although the system is only linear for small motion amplitudes, the linear PI control is effective for large amplitudes as well. The rise time depends on the step amplitude and ranges from some 40 ms for a small amplitude of 3° to about 500 ms for the full range step. The end error is within 0.1°or 1/600th of the full motion range, overshoot is within 1°. At larger values of mean gas pressure, the step responses are faster because of smaller pressure setting time constants. Although the controller uses a fixed value of mean muscle pressure, it is possible to change this value during control. If this is done at a set position it leads to a small disturbance of position, within 1°, lasting for about 200 ms. If it is done when moving toward a target position it will speed up the response in case of an increase in mean pressure and slow it down in case of a decrease in mean pressure.

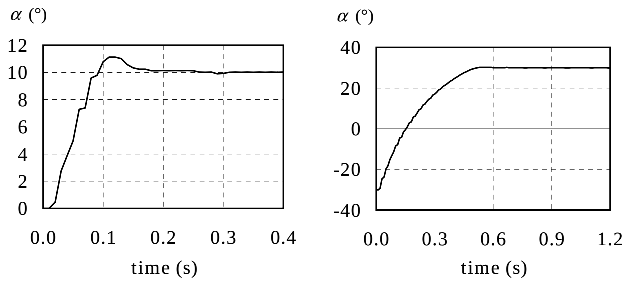


Fig. 9. PI controlled step input responses.

B. Joint stiffness

A pleated PAM basically has two causes of compliance: gas compressibility and the dropping force–contraction curve. Even if the gas pressures can be kept fixed at all times, the generated force changes with displacement, implying compliance. Joint stiffness of the considered revolute actuator, can be deduced from Eqs. (5) and (6):

$$\begin{aligned} K &= -\frac{dM_1}{d\alpha} + \frac{dM_2}{d\alpha} \\ &= l^3(-\frac{dp_1}{d\alpha}\, m_1 - p_1\, \frac{dm_1}{d\alpha} + \frac{dp_2}{d\alpha}\, m_2 + p_2\, \frac{dm_2}{d\alpha}) \end{aligned} \quad (13)$$

Part of this—$dp_i/d\alpha$—is caused by the change in gas pressure with rotation, which is determined by the action of the servo–valves and by the thermodynamic processes occurring in this system. The other part is related to the change of force at isobaric conditions and can be directly understood from the diagram of developed joint torques, cf. Fig. 7. Membrane elasticity has a negligible influence on joint stiffness or compliance because of the high value of its tensile stiffness, therefore it is not included in the expression above.

The position control system of the previous section actively uses stiffness in order to set and maintain position. This can be seen by combining Eqs. (5), (6), (9), (10) and (13), which leads to

$$K \approx 2kl^3 p_m - 2m_0 l^3\, \frac{\delta p}{\delta\alpha} \quad (14)$$

where $\delta p/\delta\alpha$ represents the controller action. If the angular position is suddenly changed the controller will react by instructing the valves to change the muscle pressures in order to restore the position. The proportional controller action will add a constant value to the stiffness and the integral action a progressively growing value as the deviation persists. The restoring torque and stiffness will increase until the desired position has been reestablished.

Compliance can be controlled by an open–loop control system that sets the position by regulating the muscle pressures at fixed values. In that case Eq. (13) is reduced to

$$K \approx 2kl^3 p_m \quad (15)$$

This implies the joint stiffness or compliance can be controlled by setting the muscle mean pressure. The values of the individual pressures can be determined from the desired compliance and position using Eqs. (15) and Eq. (8). Such a controller focusses on compliance rather than on position and, therefore, it can only set the desired position in the absence of external loads. When an external torque is applied, (quasi–)static torque equilibrium is expressed as

$$M_e = -M_1 + M_2 = k\, l^3(p_1 + p_2)\alpha - m_0 l^3(p_1 - p_2) \quad (16)$$

This shows how the position will change with this open–loop controller when a load is applied. Conversely, measuring the angle and the muscle pressures allows to determine the load. Eq. (16) can then be used to limit M_e by lowering $p_1 - p_2$ at a constant $p_1 + p_2$. This goes at the cost of position, which is allowed to move further away from the target. The joint is consequently made to yield to the external torque.

Fig. 10 plots the results of two experiments of such an open–loop controller. In a first run, marked as 'angle, no load', the angle was changed from 0° to 30° with p_m = 150 kPa without applying external loads. The end error of the angle is higher compared to the PI controlled case—up to 1° compared to less than 0.1°—which is only normal since the angular displacement feedback is suppressed and the accuracy now depends on the accuracy of the linear approximations of Eqs. (5) and (6). In a second run, marked 'angle, load' and 'external torque', a torque was applied by hand as the joint reached its end position. The diagram shows how the joint starts moving away from the desired position as the applied torque increases. The controller keeps the values of the muscle gauge pressure constant irrespective of the disturbance as long as the external load, which is calculated at each sampling period,

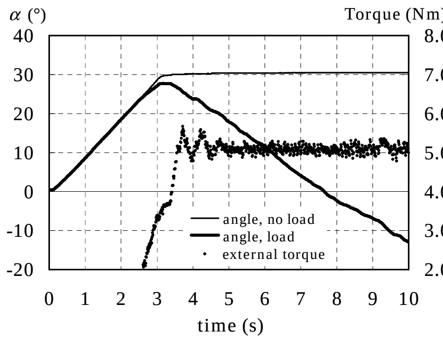


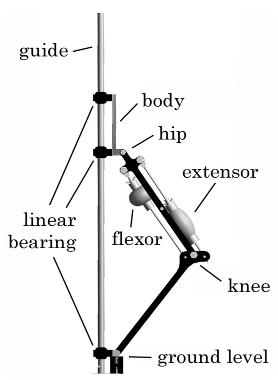
Fig. 10. Open–loop compliance control experiments.

is lower than 5 Nm. As soon as this value is reached, the individual muscle pressures are adjusted and the joint will then back, as can be seen on the diagram.

V. Hopping leg

As stated in the introduction, PAMs are inherently suited to power walking and running machines. As a first step toward such a machine we built a hopping mechanism [7], composed of a lower leg, upper leg, hip and body and sliding along a guide shaft as shown in Fig. 11. A pair of pleated PAMs was used to drive the knee joint of this mechanism. The muscles were attached to the hip and to the knee joint using a similar rod and lever transmission as in the previous section. As in biological systems, the muscles are called extensor and flexor. The flexor is needed to stretch the leg and to make it jump, while the flexor will mainly serve to prevent the leg from overstretching and to help set the knee joint compliance. Because of this the extensor has to be stronger than the flexor and was accordingly longer: $l = 11\,\text{cm}$ for the extensor and $9\,\text{cm}$ for the flexor, while both muscles have a slenderness value of 4. The pressure of each muscle was controlled by the KPS 3/4 pressure regulating servo–valves.

Moving this mechanism up and down is simply done by applying the position control discussed in the previous section. Because of the extensor power and the speed of the servo–valves the leg is also able to jump. This is done by boosting the extensor pressure when the knee is maximally bent. By choosing this boost pressure, it is possible to control the jumping height anywhere between 8 cm and 20 cm. It is equally possible to have the mechanism jump continuously. In this case both muscles are closed off during touchdown and bending. Because of this the pressure in the extensor muscle will steeply increase and a high extension torque will thus be generated. This will slow down the bending motion in a first instance and then reverse it to a strong extension, able to thrust the leg of the ground. The actuator thus acts partly as a spring, storing potential and kinetic energy on impact and releasing this energy to power the next jump. Due to all kinds of energy losses—shocks, heat loss, bearing and joint friction—the boost pressure is reset during each jumping phase. Again, the jumping height can be controlled effectively by choosing the right boost pressure, the fluctuation of jumping heights can easily be kept within a few cm.



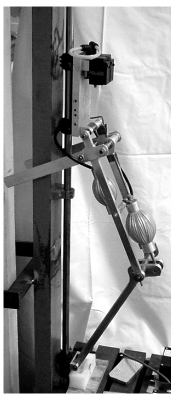


Fig. 11. Hopping leg.

VI. Conclusion

This paper summarized the design and characteristics of pleated PAMs. These muscles perform very well in position control: they are easy to use, they require no gearing, they are easy to connect or replace and a high degree of accuracy is accomplished with them. Furthermore, they do not require the use of elaborate control hardware and algorithms for this, only off–the–shelf pressure regulating servo–valves together with a plain PI control law are necessary. An extra advantage of pleated muscles is their failure mechanism: failure starts as a small membrane rupture and, hence, gas leak which only lowers the muscle efficiency, the muscle will continue to operate as long as the rupture is not exceedingly large. Other automation tasks, e.g. generating a one–way motion at high force levels and controllable speed, can just as successfully be done by them. Due to their adjustable compliance, they are ideal drives for walking and running machines and robotic applications that require force control or a soft touch.

References

[1] C.–P. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscle", *IEEE Transactions on Robotics and Automation*, vol. 12, nr. 1, pp. 90–102, 1996.

[2] B. Tondu, V. Boitier and P. Lopez, "Natural compliance of robot–arms based on McKibben artificial muscle actuators", *European Robotics and Intelligent Systems Conference*, Malaga, Spain, pp. 783–797, 1994.

[3] C.-P. Chou and B. Hannaford, "Static and dynamic characteristics of McKibben pneumatic artificial muscles", *IEEE International Conference on Robotics and Automation*, San Diego, California, pp. 281–286, 1994.

[4] B. Tondu, "Analysis and modeling of the dynamic behaviour of the McKibben artificial muscle", *5th IFAC Symposium on Robot Control*, Nantes, France, pp. 315–319, 1997.

[5] D. G. Caldwell, G. A. Medrano–Cerda and M. J. Goodwin, "Control of pneumatic muscle actuators", *IEEE Control Systems Magazine*, vol. 15, nr. 1, pp. 40–48, 1995.

[6] F. Daerden, *Conception and Realization of Pleated Pneumatic Artificial Muscles and their Use as Compliant Actuation Elements,* PhD thesis, Vrije Universiteit Brussel, Belgium, 1999.

[7] B. Verrelst, F. Daerden, D. Lefeber, R. Van Ham and T. Fabri, "Introducing pleated pneumatic artificial muscles for the actuation of legged robots: a one–dimensional setup", *CLAWAR 2000: Third International Conference*, Madrid, Spain, pp. 583–590, 2000.