Pleated Pneumatic Artificial Muscles: Compliant Robotic Actuators

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Abstract

Pleated pneumatic artificial muscles (PPAMs), which have recently been developed at the Vrije Universiteit Brussel, Department of Mechanical Engineering are brought forward as robotic actuators in this paper. Their distinguishing feature is their pleated design, as a result of which their contraction forces and maximum displacement are very high compared to other pneumatic artificial muscles. The PPAM design, operation and characteristics are presented. To show how well they are suited for robotics, a rotative joint actuator, made of two antagonistically coupled PPAMs, is discussed. It has several properties that are similar to those of skeletal joint actuators. Positioning tasks are seen to be performed very accurately using simple PI control. Furthermore, the antagonistic actuator can easily be made to have a soft or careful touch, contributing greatly to a safe robot operation. In view of all characteristics PPAMs are very well suited for automation and robotic applications.

1 Introduction

One of the major difficulties in robotics is finding suitable actuators. Many types of electric, hydraulic and pneumatic drives are currently used in robotics. Nevertheless, there is no such thing as the perfect actuator and for several applications, such as biped robots, there are no appropriate actuators as yet. This paper discusses a kind of pneumatic artificial muscle (PAM), namely pleated pneumatic artificial muscles (PPAMs) as robotic actuators. Basically these are inflatable devices that generate a linear and one-way motion and that are characterized by

- power to weight ratios in excess of $1\,\mathrm{kW/kg}$ ([1–3]), by way of comparison, electric drives typically have some $100\,\mathrm{W/kg}$ [4];
- a varying force-displacement relation at constant gas pressure, contrary to pneumatic cylinders, which results in a muscle-like behavior;
- an adjustable compliance, due to gas compressibility and the dropping force-displacement characteristics;
- a maximum displacement or stroke of up to 50% of initial length;
- the absence of friction and hysteresis, as opposed to other types of PAMs;
- the ability to operate at a wide range of gas pressures, and thus to develop both very low and very high pulling forces;
- the possibility of direct connection to a robotic joint, i. e. without having to use any gears, because of their high output forces at all speeds.

Moreover, PAMs are easy to install and replace because they can be connected directly to a robotic joint without having to use any gears. No hazards like fire, explosion or pollution are caused by these actuators.

As will be shown in this paper, PPAMs can be used to achieve an accurate and fast joint position control without having to use complex control strategies. They are equally suited to drive a robot that has to work in a fragile environment because it is easy to make the robot have a soft touch. In view of the cited characteristics, PPAMs are also inherently suited to power legged robots. Indeed, high power to weight ratios, direct joint connection and compliance are essential features for such an application. Other possible applications are powering lightweight robots that carry a heavy payload, and powering grippers with an easily adjustable firmness.

2 Pleated Pneumatic Artificial Muscles

2.1 Design

PAMs are contractile devices whose core element is an inflatable membrane. When they are inflated they shorten and thereby generate a contraction force. Inflation can happen either by membrane strain or by membrane rearranging, meaning unfurling of some sort. The so-called McKibben muscle [5], which is most frequently used today, is of the straining kind. It is basically a rubber tube surrounded by a braided sleeve. Expansion and contraction happen by the change of braid angle. Although such a PAM is easy to make and use, it has some important drawbacks:

- its total displacement is only about 20% to 30% of its initial length [5,6];
- friction between the netting and the tube leads to a substantial hysteresis in the force-length characteristics, this obviously has an adverse effect on actuator behavior [7] and necessitates using complex models [8,9] and control algorithms [3];
- tough rubber is often needed to avoid the tube from bursting, this comes at the cost of a high threshold pressure—typically about 90 kPa [5]—that has to be overcome in order to start deforming the rubber material and below which the actuator will simply not operate;
- rubber deformation, like any material deformation, needs energy, this will lower the force output of this type of muscle up to 60% [3].

Because of these, a membrane unfurling muscle was developed at our department [1]. What was aimed for was a PAM having a high maximum contraction, low friction and hysteresis, a low threshold pressure and a high allowable pressure and negligible material deformation. This led to the design pictured by Fig. 1, showing the muscle in its uninflated and in its inflated state. The 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 packed together in folds along the long axis, quite like a car engine air filter. The folds thus hold the extra membrane material needed to expand. 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 starts to bulge and shorten. The expansion is highest in the middle of the membrane and gradually goes down toward both ends where no expansion at all can occur. 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.

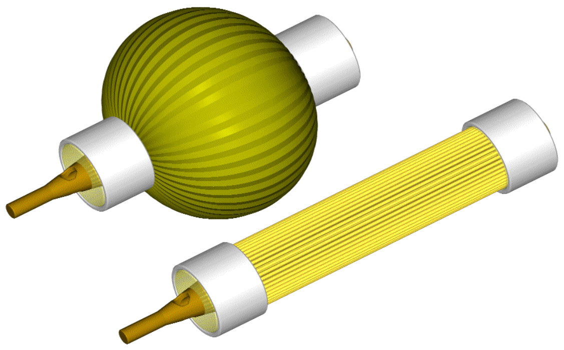

Figure 1: Pleated muscle concept.

An extra objective was to have no membrane stress in the direction perpendicular to the long axis, because such stress was considered to hold back the expansion and, thus, to limit contraction. This is only possible if the membrane is orthotropic with a high tensile stiffness in one direction and a zero E–modulus in the other. Folding the membrane is an attempt to approximate this mode of inflation: the higher the number of folds and the shallower they are, the better the approximation will be.

2.2 Characteristics

All PPAM characteristics, such as shape, volume, diameter, force, maximum contraction can be determined accurately from a mathematical model [1]. The model is that of a closed axisymmetric membrane subjected to a uniform internal pressure and axially applied forces at both membrane ends. The membrane is considered orthotropic, as explained in the previous section. The shape of such a membrane gradually moves from its original cylindrical form at zero contraction toward an oblate spheroid or pumpkin-like form at maximum contraction, cf. Fig. 2. Besides the degree of contraction the ratio of the muscle's initial length to diameter, l/D, or slenderness, determines the shape.

The characteristics regarding geometry, membrane tensile stress and contraction force depend on the membrane's initial length l, its initial diameter D, the degree of contraction ϵ, the applied pressure p and a parameter a that takes into account the longitudinal elasticity of the membrane. Force, maximum diameter and volume can respectively be expressed as

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

$$\tilde{D} = l\, d(\epsilon, \frac{l}{D}, a) \tag{2}$$

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

with f, d and v non-dimensional functions of contraction, slenderness and elasticity. These functions are found by solving a set of equations that involve elliptic integrals of the first and second kind [1]. The above expressions imply

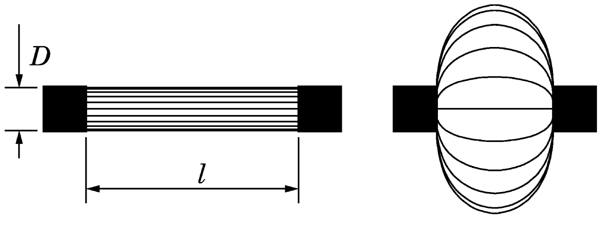

Figure 2: PPAM shape at full length (left) and full contraction (right), $l/D = 5$.

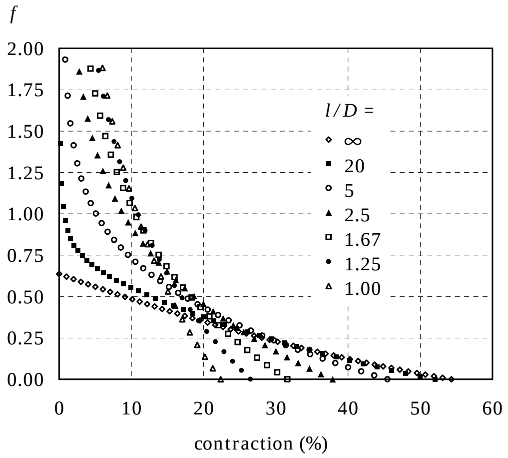

Figure 3: Non-dimensional force function f.

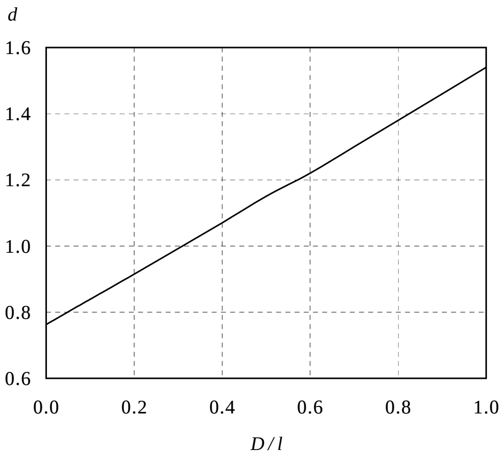

Figure 4: Non-dimensional diameter function d.

that the behavior of the pleated muscle is basically determined by the value of slenderness and the membrane elasticity. Using a high tensile stiffness material, the influence of elasticity becomes negligible and can accordingly be omitted. All characteristics are then only dependent on a non-dimensional function of slenderness and contraction and on a proper scaling factor.

Fig. 3 diagrams the calculated force function f for various values of slenderness. Unlike pneumatic cylinders, the PAM output force changes with displacement at constant pressure. Applying an internal pressure at full muscle length causes an extremely high pulling force to be generated. With contraction increasing, 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. The maximum contraction or stroke depends on slenderness, typical values of this are 40% to 50% for slenderness ranging from 4 to 10.

Fig. 4 shows a diagram of the calculated diameter function d for various values of slenderness. From this the maximum actuator diameter, which has to be taken into account when deciding to use this type of actuator, can be determined. As an example, a muscle of $l = 10\,\text{cm}$ and $D = 2.5\,\text{cm}$ will grow to a diameter of $9.5\,\text{cm}$ at full contraction.

The calculated and measured characteristics agree very well. A muscle of $l = 10\,\text{cm}$ and $D = 2.5\,\text{cm}$, having a total of 44 folds each $2.5\,\text{mm}$ deep and weighing as little as $60\,\text{gr}$ can be cited as an example. Noticeable deviations were only found in the lower and upper regions of contraction and for low values of pressure. For contractions ranging from 5% to about 30%, the measured values of force and diameter were seen to be within 1–2 percents of the values predicted by the mathematical model. Stroke was predicted to be 43.5% and experimentally found to be 41.5%. The isobaric force diagrams of this muscle are plotted in Fig. 5. Force was limited to some $3500\,\text{N}$ at low values of contraction in order to limit the steeply growing membrane stress. Besides the ability to develop very high traction forces and to contract substantially, the diagram also proves the possibility to operate at a wide range of pressure levels—$10\,\text{kPa}$ to more than $300\,\text{kPa}$. Both very low and very high forces can accordingly be developed.

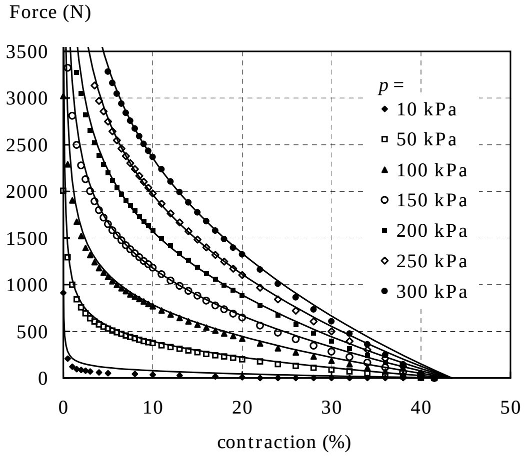

Figure 5: Measured (dots) and calculated (solid lines) values of force-contraction at various levels of pressure ($l = 10\,\text{cm}$, $D = 2.5\,\text{cm}$).

3 Antagonistic Actuator

As PAMs are contractile devices they generate motion in only one direction. Just as with skeletal muscles, it takes a pair of actuators to generate bidirectional motion, one for each direction. This opposite connection of the muscles to a joint is generally referred to as an antagonistic setup. A rota-

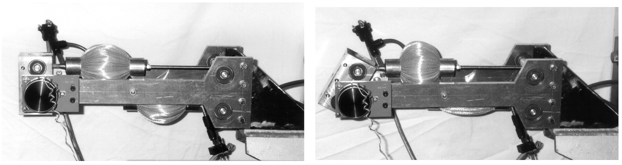

Figure 6: Joint driven by two pleated PAMs, central position (left) and rotated by 30° (right).

tive joint actuator was built according to this principle. Two identical PPAMs, with $l = 10\,\mathrm{cm}$ and $D = 2.5\,\mathrm{cm}$ drive the joint. When both muscles are put at the same pressure, the joint is in its central position. Inflating one muscle causes a rotation toward that muscle. Fig. 6 shows the joint in two different positions. The muscles are connected to the joint using a lever arm mechanism and rigid pull rods. The lever mechanism is designed to have a range of motion of 60° coinciding with a muscle contraction range of 5% to 35%. At the central position both muscles are contracted by 19%.

The torque–angle relationships of this joint can be expressed as

$$M_1 = p_1 l^3 m_1 \approx p_1 l^3 (m_0 - k\alpha) \tag{4}$$

$$M_2 = p_2 l^3 m_2 \approx p_2 l^3 (m_0 + k\alpha) \tag{5}$$

with m_i non-dimensional torque functions, α the angle of rotation, p_i the individual muscle pressures, $m_0 = 0.138$ and $k = 0.207\,\mathrm{rad}^{-1}$. The torque-angle characteristics of the joint are shown in Fig. 7 for various values of muscle pressure. The two groups of curves represent the torques exerted by each muscle in the direction of that muscle. Features similar to that of skeletal muscles are apparent: as the joint moves toward one muscle the torque generated by that muscle, the flexor muscle, gradually drops, while the extensor muscle's restoring torque grows. The diagram also shows how in the absence of an external load, the equilibrium joint position is located at the point of intersection of two opposite torque curves and determined by the ratio of the muscle pressures. In skeletal systems this is similar: every position can be held with various levels of flexor and extensor activation.

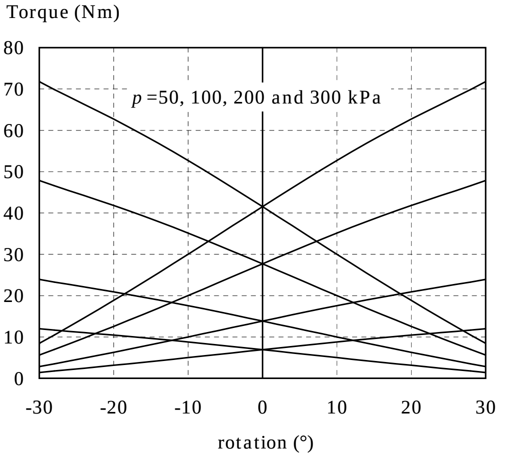

Figure 7: Torques exerted by the individual PPAMs on a rotational antagonistically driven joint.

Like all pneumatic actuators, PAMs have an elastic behavior due to air compressibility. In addition to this, PAMs have a varying force-displacement characteristic at constant pressure and this is a second source of elasticity. This can be seen by expressing the joint compliance, or inversely, stiffness K mathematically:

$$\begin{aligned} K &= -\frac{dM_1}{d\alpha} + \frac{dM_2}{d\alpha} \\ &= l^3\left(-\frac{dp_1}{d\alpha}\, m_1 - p_1\,\frac{dm_1}{d\alpha} + \frac{dp_2}{d\alpha}\, m_2 + p_2\,\frac{dm_2}{d\alpha}\right) \\ &\approx l^3\left(\underbrace{-\frac{dp_1}{d\alpha}\, m_1 + \frac{dp_2}{d\alpha}\, m_2 +}_{} \underbrace{kp_1 + kp_2}_{}\right) \\ &= \qquad\quad K_p \qquad\quad + \qquad K_m \end{aligned} \tag{6}$$

Part of the expression, K_p, comes from the change of pressure with angle and, hence, muscle volume and is related to gas compressibility. Its value is determined by the thermodynamic processes going on inside each muscle and by the gas flow into and out of them. The other part, K_m, is typical for PAMs and describes joint stiffness or compliance at constant muscle pressures. It is proportional to the sum or mean value of both pressure levels. Fig. 8 shows values of stiffness in case of tightly closed PPAMs and assuming polytropic processes (PV^n = constant, with P the absolute muscle pressure and V muscle volume). Although the joint position does not change by doubling both pressure levels, its stiffness does and the position is held firmer. The same phenomenon is observed in skeletal systems, e. g. when grasping an object the level of activation of both ex-

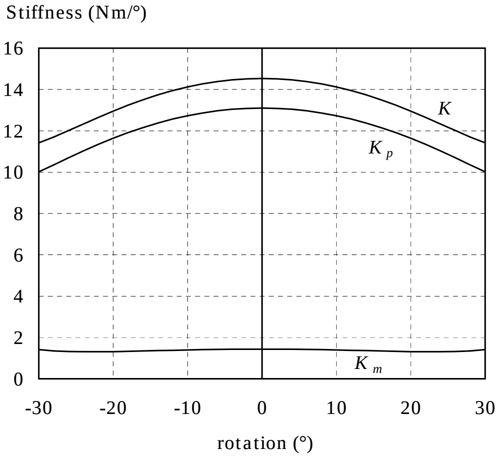

Figure 8: Joint stiffness ($p_1 = p_2 = 200\,\mathrm{kPa}$ and $n = 1.2$).

tensor and flexor muscle groups determines the firmness of the grip.

4 Antagonistic Actuator Control

As was seen before, both position and compliance of the joint are determined by the muscle pressures. Controlling the antagonistic joint actuator is therefore done by controlling pressure. Pressure feedback controlled valves—proportionally or on-off operated—can be used for this purpose. The results presented here were obtained with a pressure regulating servo-valve, the KPS 3/4 by Kolvenbach AG, Germany. These are very fast acting valves (time delay $= 5\,\text{ms}$) that set the pressure at a level proportional to the valve signal input voltage. The complete system comprised of two PPAMs, two servo-valves and the joint, was seen to act as a first order system with time delay if the mean muscle pressure $p_m = (p_1 + p_2)/2$ was kept fixed. Its time constant was thus found to depend on p_m, ranging from $50\,\text{ms}$ for $p_m = 300\,\text{kPa}$ to $200\,\text{ms}$ for $p_m = 50\,\text{kPa}$.

With this information in mind an angular feedback proportional-integral control law was used for position control. The mean muscle pressure is not affected by this law, a change in position is brought about by changing only the difference of the pressures:

$$p_1 = p_m + \Delta p \tag{7}$$

$$p_2 = p_m - \Delta p \tag{8}$$

Because a permanent change of position requires a permanent change of pressure, the integral controller part is essential. Fig. 9 illustrates the performance of such a controller, it shows the responses for a $10°$ and a $60°$ step input. Although the first order approximation is only valid 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 $40\,\text{ms}$ for a small amplitude of $3°$ to about $500\,\text{ms}$ for the full range step. The end error is within $0.1°$or $1/600$th of the full motion range, overshoot is within $1°$. At larger values of mean gas pressure, the step responses are faster because of smaller values of the time constant.

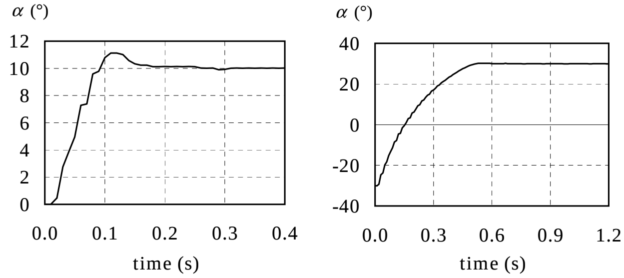

Figure 9: PI controlled step input responses, $p_m = 150\,\text{kPa}$.

The joint stiffness is influenced by this way of controlling position. In fact, the control system actively uses stiffness in order to set and maintain position. This can be seen by substituting Eqs. (4), (5), (7) and (8) into Eq. (6) leading to

$$K \approx 2kl^3 p_m - 2m_0 l^3 \frac{d(\Delta p)}{d\alpha} \tag{9}$$

The last term of this expression is influenced 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.

Instead of a feedback control system an open-loop control system can be used as well. The pressures are then set to fixed values that are calculated from the desired equilibrium position α_s using Eqs. (4), (5) and from the desired joint stiffness, which is now expressed as

$$K \approx 2kl^3 p_m \tag{10}$$

If an obstacle of some sort is encountered the joint will exert a torque onto it that is equal to

$$\begin{aligned} M_e &= -M_1 + M_2 \\ &= K(\alpha - \alpha_s) \end{aligned} \tag{11}$$

This torque will increase as the deviation from the set angle grows. From the readings of actual angle and pressures M_e can be calculated. This is interesting if it has to be limited, e. g. for reasons of safety. This can be done by decreasing the set angle value while leaving stiffness unaltered. In other words $p_1 - p_2$ is lowered and $p_1 + p_2$ kept constant. A moving obstacle will then eventually be able to make the joint yield. This feature allows a safe interaction with a delicate environment or between man and machine to be ensured. Moreover, it does so in an extremely simple and straightforward manner.

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 $p_m = 150\,\text{kPa}$ 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. (4) and (5). 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

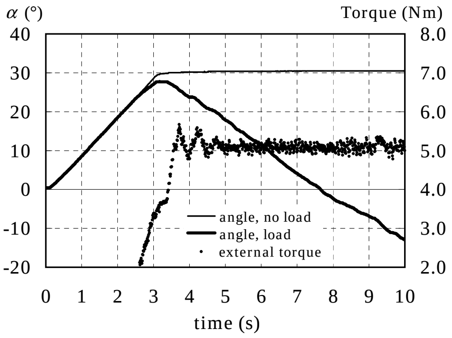

Figure 10: Open-loop compliance control experiments, $p_m = 150\,\mathrm{kPa}$.

is calculated at each sampling period, is lower than $5\,\mathrm{Nm}$. As soon as this value is reached, the individual muscle pressures are adjusted as explained above and the joint will back, as can be seen on the diagram.

5 Walking/Running Machines

PPAMs also look promising to power walking and running machines. Weight, power, compliance and direct connection to the joints are the dominating considerations here. Compliance is a prerequisite for several reasons. First of all, impacts need to be absorbed and softened, because they 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. Thirdly, compliance can be used effectively to store and release energy during the phases of bending and stretching. 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. As can be concluded from previous sections PPAMs comply to these requirement.

A one dimensionally hopping leg was built at our department in order to test the PPAM's suitability to power walking and running machines. The leg's knee is driven by an antagonistic actuator similar to the one discussed in this paper. By using the same control techniques, the leg could be made to move slowly and to hop. Continuous jumping was made possible by using the PPAM elastic behavior. After each touchdown a small pressure boost was applied to the extensor muscle to compensate for energy loss. Jumping height was controlled by the level of this boost pressure. A more detailed report of this can be found in [10].

6 Conclusion

Pleated pneumatic artificial muscles are strong and lightweight actuators that perform very good in position control and other automation and robotic tasks. They are easy to use, require no gearing and are easy to connect and replace. Because of the absence of friction they do not show any stick-slip effect. In order to have a two-way motion an antagonistic setup is needed. A high degree of positioning accuracy is accomplished with them and this just by using off-the-shelf pressure regulating servo-valves together with simple PI control techniques. Furthermore, they can easily be made to have a soft touch so as not to damage fragile objects or to effect a safe man-machine interaction. Because of their inherent characteristics PPAMs are suitable for powering walking and running machines. Autonomous machine operation can then be guaranteed in a number of ways, e. g. by using on-board small size internal combustion engines and compressors.

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