Introducing Pleated Pneumatic Artificial Muscles for the Actuation of Legged Robots : a One-dimensional Set-up

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Abstract

This paper reports on the use of a new actuator, called Pleated Pneumatic Artificial Muscle, in a one dimensional set-up, it is build as a footless leg with only the knee powered by a pair of Pleated Pneumatic Artificial Muscles. The main goal of this study is the evaluation of the adaptable passive behaviour of these Artificial Muscles in a leg, which can be exploited for an energy efficient way of walking for legged robots.

The new actuator and its specific advantages for the use in legged robots will be discussed as well as the concept of the one dimensional set-up. It will be shown that a large amount of energy during a jump can be recuperated and continuous jumping can easily be achieved with low gauge pressures.

1 INTRODUCTION

From biology we know that humans, like all animals, try to move in an energy efficient way. One of the important tools available are tendons which make energy recuperation possible. For example, the Achilles tendon in a human leg can store up to one third of the motion's energy during running. The muscular system is capable of adapting stiffness characteristics in order to move in a wide range of different walking and running patterns and still exploit the passive behaviour of the actuation system.

Contrary to this kind of motion most, existing bipedal walking machines are not making use of such properties. Most of them are statically balanced which means that the vertical projection of the machine's global center of mass is situated at all times within the polygon of support. Because of this restriction, statically balanced robots are bound to move slowly in order to minimize inertia effects. This results in the incapability of storing energy of motion in compliance elements. Recently, more attention has been drawn to build machines that are balanced in a dynamical way, which means that the inertia effects are taken into account in the development of control algorithms in order to move faster and smoother. Hopping and running robots can only be dynamically balanced. The best-known examples are those of the

MIT developed by R. Raibert et al.(5). Examples of dynamically balanced walking robots come from Furusho(2), and Takanishi(7).

Energy consumption is not an issue until the autonomous character becomes important. In this case special attention has to be drawn to passive behaviour of the models, which means that control algorithms exploit natural behaviour of mechanisms. At one extreme are the so called “Passive Walkers” (Garcia, Ruina et al. (3))which have no active control at all, since only gravity leads them down a sloped surface.

In order to walk on a horizontal plane, minimum actuation should be provided to compensate energy losses due to collision and friction. This concept gets more and more attention. A recent example is the two legged “Flamingo Spring”(4) developed in the Leg Laboratory at MIT. This model uses standard passive elements which fix the eigenfrequency of the system by construction. To have more flexibility, by means of changing this frequency, one has to implement passive elements of which compliance is variable. In this context the group of Takanishi developed the two legged walker WL-14(9), where a complex non linear spring mechanism makes changes in stiffness possible.

A more elegant way to implement variable compliance, makes use of pneumatic artificial muscles, for which applied pressure determines stiffness. Research on this topic is exerted by Van der Linde in Holland(8) with implementation of Mc Kibben muscles, while at our department a new type of such pneumatic artificial muscles, the Pleated Pneumatic Artificial Muscle, will be implemented.

2 PLEATED PNEUMATIC ARTIFICIAL MUSCLES (1)

A pneumatic artificial muscle is essentially a membrane that will expand radially when inflated, while generating high pulling forces along the longitudinal axis. Different designs have been developed. The best known is the so called McKibben muscle(). This muscle contains a rubber tube which will expand when inflated, while a surrounding netting transfers tension. Hysteresis, due to dry friction between the netting and the rubber tube, makes control of such a device more complicated. Inherent to this type of muscles is a treshold level of pressure before any action can take place. The main goal of the new design was to avoid friction together with hysteresis and make control easier while avoiding the threshold. This could be achieved by arranging the membrane into radially laid out foldes that can be unfolded free of radial stress when inflated. The membrane's stiff longitudinal fibres transfer tension. The inflated and deflated state of the Pleated Pneumatic Artificial Muscle (PPAM) are illustrated in figure 1.

If we omit the influence of elasticity of the high tensile strength material used for the membrane, the characteristic for the generated force is given by :

$$F_t = pl^2 f_t\left(\varepsilon, \frac{l}{R}\right)$$

where p is the pressure, l the muscle’s full length, R its unloaded radius and ε the contraction. The dimensionless function f_t, which depends only on contraction and geometry, is given for different values of broadness R/l in the graph on the left of figure 2.

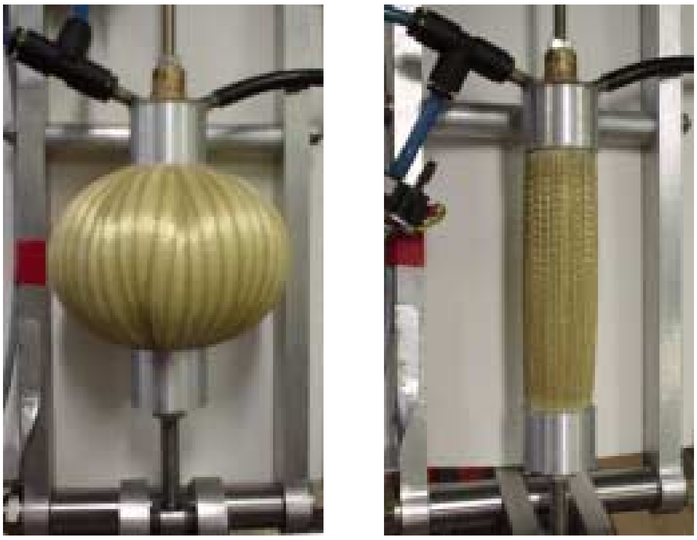


Figure 1 : Inflated and deflated state of the PPAM

The thicker the muscle, the less it contracts and the higher the forces it generates. Contraction can reach up to 54% in a theoretical case with *R/l=0*, which is bounded to about 0.1, in practise, because of the minimum space needed to fold the membrane.

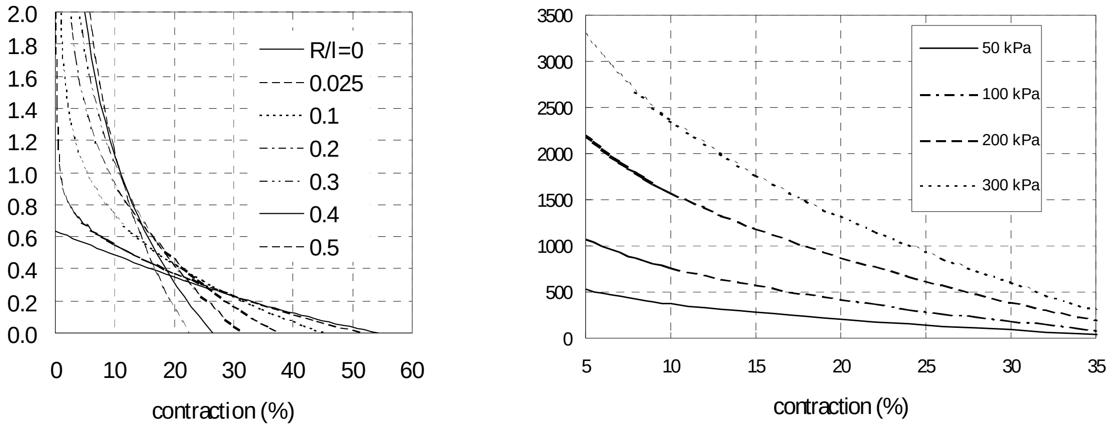


Figure 2 : Dimensionless force function f_t (left), muscle force (N) (right)

Low contraction forces are extremely high, causing excessive material loading, and generated forces drop too low for large contraction. Thus contraction will be bounded between two limits, 5 and 35%, in practise.

The graph on the right of figure 2 gives the generated force for different pressures of a muscle with initial length 10cm and unloaded diameter 2.5cm. Forces up to 3000N can be generated with gauge pressure of only 300kPa while the device weighs about 100g.

The graphs shown above are derived from a mathematical model which fits experimental results with deviations less than a few percent. This accurate mathematical model will be of great importance for developing control algorithms and performing simulations in later applications.

3 ONE-DIMENSIONAL SET-UP

3.1 General Description

In order to have a more profound understanding of the energy recuperation with the PPAM, a one-dimensional set-up has been build. This set-up consists of three parts (figure 3): lower leg, upper leg and body. Upper leg and body are connected with a one degree of freedom rotative joint which can be seen as a knee. Upper leg and body are connected in the same way at the hip. Both body and lowest part of the lower leg, the touch-down point, are connected to a vertical slider to restrict the movement of these parts to one dimension and avoid balance control.

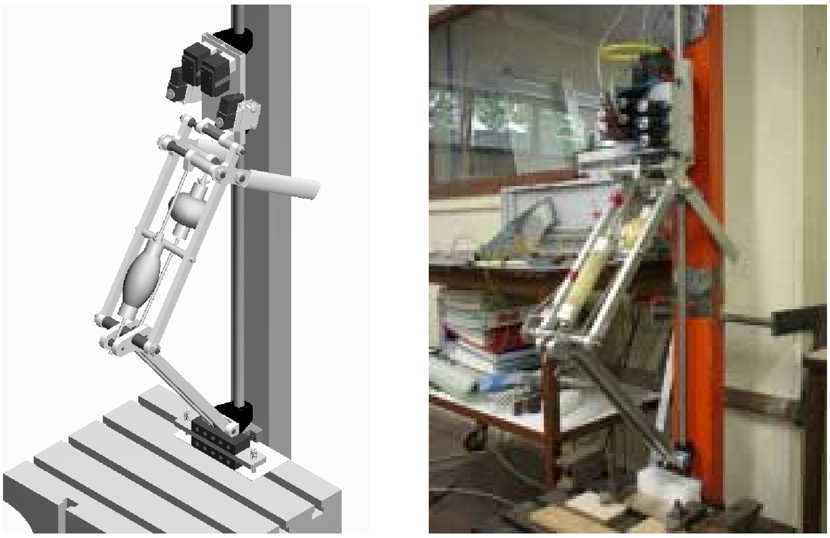


Figure 3 : Draft and picture of the set-up

Two PPAMs are spanned over the structure of the upper leg and provide the actuation of the knee. For each of these muscles, one proportional valve and one on/off valve is supplied to control air flows to and fro the muscle. The leg weighs 3kg and was designed to carry a load that can reach up to 10kg. Both upper and lower leg have a length of about 400mm.

3.2 Connection of the Muscles

Pneumatic artificial muscles only generate forces when they bulge and not, in the opposite direction, when they stretch. To have a bi-directional working joint one has to couple two muscles antagonistically. In addition, to transfer forces into torques, the muscles are attached with a leverage mechanism at the knee side and pulling rods at the hip side. The position of the points of attachment are essential in the design. In this context, different parameters (eccentricity, length of leverage arms,…) can be altered to determine the characteristics of the generated torques.

For the set-up, the following prepositions have been made for the design of the powering system:

- The flexor/extensor system is asymmetrical since the extensor needs to deliver the largest forces and the flexor has only a stabilising effect.

- Contraction of both muscles should be kept between 5 and 35% while the knee's working area is situated between 10 and 70 degrees (angle between vertical and lower leg)
- Linearity of both torque to angle relation with constant pressure should be pursued. As such, the highly non-linear force characteristic will transform to a linear torque to angle relation.

Once these demands are taken into account, one can alter the various parameters, which will result in a design with two different muscles of length 110mm for the extensor and 90mm for the flexor with R/l=0.125. The characteristics of the two generated torques can be approximated as a linear function, which is illustrated in the graph below. The values on the ordinate have to be multiplied with the gauge pressure (Pa) to know the actual torques generated by the respective muscles. The working limit of gauge pressures for the PPAM is set at 300kPa which sets the maximum generated torques for the extensor(m_1) at 120Nm for an angle of 70° and 45Nm at 10° for the flexor(m_2).

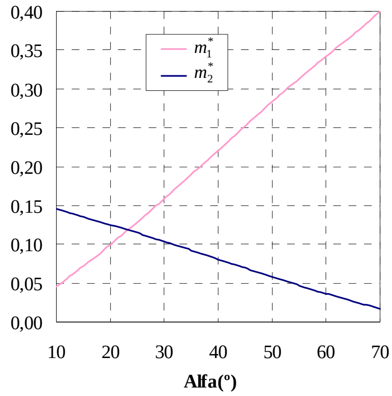


Figure 4 : Values of generated torques (Nm) divided by gauge pressures (Pa) for both muscles extensor (m^*_1) and flexor (m^*_2).

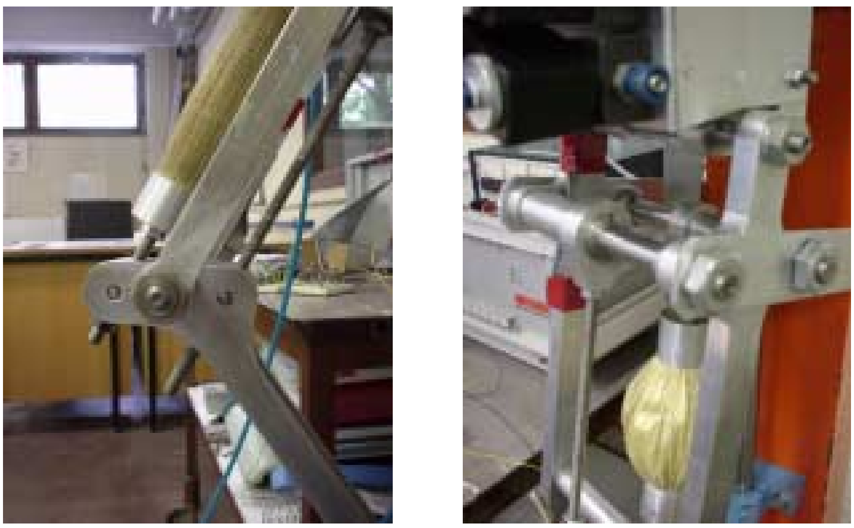


Figure 5 : Implementation of the PPAM in the structure of the upper leg

The pictures above show the connections of the muscles to the structure of the upper leg. In the left most picture, one can see the leverage mechanism where the position of the points of attachment are specified as stated above. The picture on the right shows the connection by means of a pulling rod at the hip side. With this system it is very easy to replace the muscles at all times, no complex transmission mechanism has be dismantled as is often the case when electrical drives are used.

3.3 Position Control and Compliance

3.3.1 Position Control

Figure 4 shows torques per unit pressure: if gauge pressures are increased in one muscle the linear line (m_1 or m_2) will shift parallel to a higher position. The generated torques can thus be represented by :

$$M_1 = p_1 m_1^* = p_1(k_1\alpha + m_1) \qquad\qquad M_2 = p_2 m_2^* = p_2(k_2\alpha + m_2)$$

Where p_i represents the gauge pressure in muscle i, k_i and m_i the respective linear approximation coefficients for m^*_i. The equilibrium position can be calculated with the condition $M_1 = M_2$ which results in :

$$\alpha = (m_2 - m_1\beta) \,/\, (k_1\beta - k_2).$$

With $\beta = p_1 / p_2$, which shows that position depends on gauge pressure ratios. This in contrast to pneumatic cylinders where, for a double acting cylinder position, will depend on pressure differences. The expression above can be used in an open-loop control, in (1) a closed loop control on position with standard PI-techniques were used for a symmetric unloaded rotative drive. A full range step of 60° could be achieved within 40ms with overshoot less then 1° and end error within 0.1°.

3.3.2 Compliance

The inverse of compliance; stiffness, can be obtained by deriving torque characteristic with respect to position:

$$K(=C^{-1}) = \frac{dM}{d\alpha} = \frac{d(M_2 - M_1)}{d\alpha} = \frac{dp_2}{d\alpha} m_2^* + p_2 \frac{dm_2^*}{d\alpha} - \frac{dp_1}{d\alpha} m_1^* - p_1 \frac{dm_1^*}{d\alpha}$$

This expression shows that stiffness is influenced not only by pressure changes but also by the fact that forces drop with contraction even in isobaric conditions. The latter effect is typical for pneumatic artificial muscles while the former effect is similar to pneumatic cylinders. One can see that stiffness will depend on pressure levels for closed muscles, once valve actions control pressure in the muscles, the dynamic responses of these valves will also determine compliance.

3.4 EXPERIMENTS

3.4.1 Passive Behaviour

In this experiment, the leg was dropped from a fixed height while both muscles were kept closed with the on/off valves so no valve action could influence stiffness. During stance, the leg will bend and thus stretch the extensor muscle. In the latter muscle, pressure and forces will increase as contraction lowers, which implies that the extensor muscle stores motion's energy that will be released again from the point where the leg straightens again. The leg will leave the ground again when the amount of stored energy is sufficient and will reach a certain height. This height is measured and compared with the initial height to have an idea of the ability to recuperate. The measured height is taken at the lowest part of the leg, touch-down point.

Bvecause of heavy fluttering during touch-down, a damping material was used to avoid these oscillations in the best possible way. This material consumes motion's energy and thus results in a lower percentage of recuperation.

Different parameters; like knee angle with touch-down, stiffness determined by sum of initial pressures, and load will influence the amount of recuperation. A larger knee angle results in a bigger amount of recuperation. When angles are too small, the leg will not make a second jump because the losses due to fluttering are too high. If the initial pressures are increased in the muscles, making the actuator less compliant, recuperation will be better. The same happens when the mass of the body, is increased. The figure below illustrates height evolution of the 'foot' for an initial knee angle of 50° and initial sum of pressures of 300kPa.

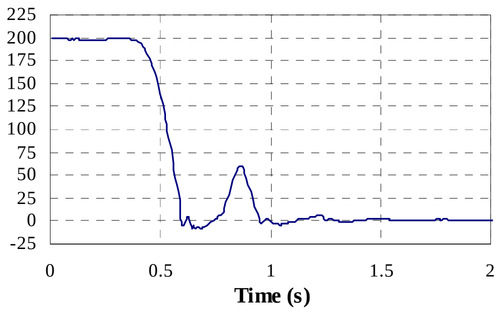
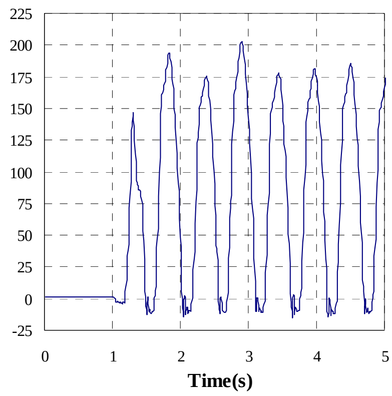


Figure 6 : Height (mm) for initial knee angle of 50° and sum of pressures 300kPa

The leg falls down from a height of 200mm and jumps a second time up to 59mm which is about 30% of its initial height. One can see on the graph that fluttering occurs after touch-down which strongly lowers the recuperation. In order to avoid fluttering disrupting energy recuperation a foot has to precede the movement during a touch-down.

3.4.2 Up and down jump-movement

To compensate losses, energy has to be added to the system, which can be done in the second half of the stance time where the leg stretches again while the actuator releases the stored energy of a former jump. The valves of the extensor muscle will be opened to increase temporary the pressure. Continuously jump movements are illustrated in the following graphs:



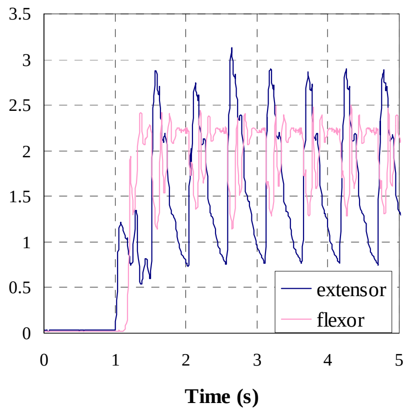


Figure 7 : (left) jumping height (mm) ; (right) pressure values in both muscles (bar)

Figure 7 shows that maximum pressure values are about 300kPa, while the leg jumps up to 200mm. The jump heights will also be influenced by the parameters mentioned in the former paragraph since this jump movement uses energy recuperation.

These experiments are not optimised and not controlled in order to have a fine tuned maximum jump height but are just an example of the possibilities. In this first set-up the great losses due to flutter will make control, based on the mathematical modelling of the muscles, difficult.

4 CONCLUSIONS

This paper introduces a new actuator suited for the actuation of legged robots because of its specific characteristics :

- A light structure able to generate high forces, up to 3000N with gauge pressures of only 300kPa and a weight of 100g.
- Can directly be coupled and easily implemented.
- Has an adaptable passive behaviour suited for energy storage.
- A very accurate mathematical model exists for the actuator.
- Precise position control is possible due to the absence of hysteresis.

Fundamentals of energy recuperation by means of the adaptable passive character of the actuator have been illustrated. Preliminary results show a promising exploitation of this behaviour for the actuation of legged robots in order to lower energy consumption. The next set-up to-be-build will incorporate a foot to avoid flutter which will strongly increase energy recuperation.

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