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Modelling of a novel rotary pneumatic muscle

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Abstract

This paper describes a mathematical model for a novel rotary pneumatic rotary actuator with potential applications in revolute direct robotic mechanisms. The analytical model describes the behaviour of the rotary pneumatic actuator and simulated results using this model are generated. Potential applications of this model are discussed in the context of soft model based controllers used in prosthetic devices.

1 Introduction

The actuation system is an essential feature of a robotic mechanism. This provides the force, torque and mechanical motions needed to move the joints, limbs, or body. Whatever actuator is used there are certain general requirements. The actuator should have a high ratio of power to weight. In addition it should provide flexible control of movement.

It is important in robotic applications that the weights of all components should be minimised. These components of an actuator system include the actuator and the energy store [McDonald, 1988]. A desirable feature of such a system is that it should be as quiet as possible if it is to be used as a general purpose robot. Above all, safety must be considered if the robot is to be generally acceptable [Andeen, 1988].

When designing actuators, it is important to consider how the power is transmitted to the link/joint/drive mechanism. Systems where power is transmitted by belts, cables, straps and chains tend to suffer from friction, hysteresis, and backlash [McKerrow, 1991]. However use of direct drive actuators can overcome this problem [Young, 1973]. Current methods of intelligent actuation include arrays of devices based on thermal actuation, shape memory alloys, piezo electric actuators, and McKibben pneumatic muscles [Chow and Hannaford, 1996] [Dynalloy., 1989]. This paper proposes a McKibben based design

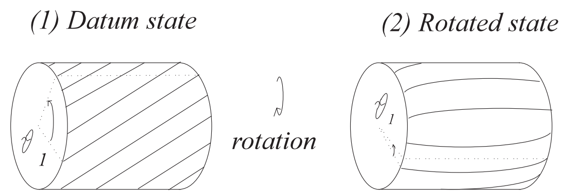

Figure 1: Rotary pneumatic muscle in uninflated$^{(1)}$ state and inflated$^{(2)}$ state.

delivering rotary actuation and describes a theoretical model of the muscles characteristics.

2 Rotary pneumatic muscle construction

The pneumatic muscle is constructed from two metal cylinders held together with a bearing in betweem. This forms a single cylinder where each end is able to rotate independently about the longitudinal axis, shown in figure 1. A rubber bladder is attached at each end of the composite cylinder. Nylon fibres at a predetermined angle to the longitudinal axis are bound at each end to the cylinder to form an outer sheath. The sheathing is located on the outside of the rubber bladder.

Actuation by inflation of the inner bladder causes the angle of the nylon fibres to the longitudinal axis to change axial orientation. The resulting motion is a rotation to the axial direction.

3 Model of the muscle's actuation

The rotary pneumatic muscle converts pneumatic energy into mechanical energy by transferring the pressure applied on the surface of the bladder to radial tension. In order to find the tension as a function of pressure and actuator rotation without considering the geometric structure, a theoretic approach using the principles of energy conservation is presented,

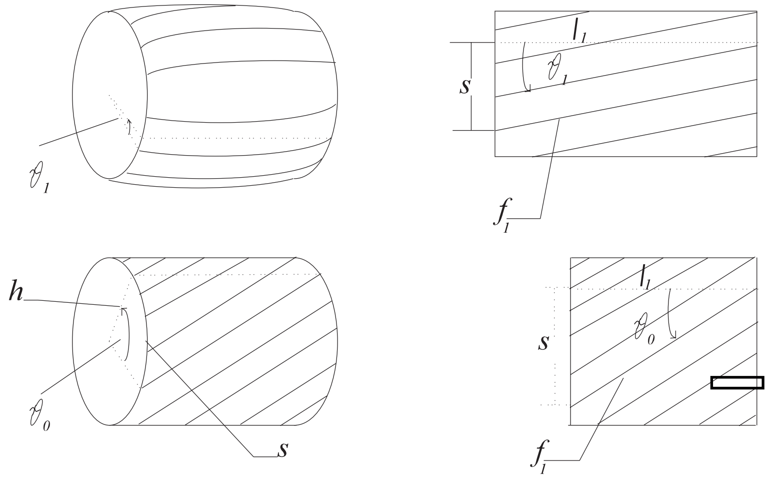

Figure 2: Rotary pneumatic muscle converted to a pseudo 2D plane; h is the radius of the muscle; θ_1 is the angle rotated by the muscle; s is the arc length of the rotation; f_1 is the muscle fibre length; l_1 is the effective length of the muscle.

1. Input work is done when the inner surface of the bladder is inflated by the gas.

$$
\begin{aligned}
dW_{in} &= \int_{in} (P - P_0) dI_i dS_i \\
&= (P - P_0) \int_{in} dI_i dS_i \\
&= P' dV \qquad (1)
\end{aligned}
$$

where $(P - P_0)$ is the relative pressure, S_i is the surface area, dI_i is the inner area change and dV is the volume change.

The output work (W_{out}) is done when the actuator rotates with changes in the volume where F is the axial tension and $d\theta$ is the axial displacement.

$$dW_{out} = F d\theta. \qquad (2)$$

From the view of energy conservation, the input work should equal the output work $dW_{out} = dW_{in}$ if a system is lossless and without energy storage. Assuming the ideal state the virtual work argument and equating equation 1 and 2 gives,

$$F = -P' \frac{dV}{d\theta}. \qquad (3)$$

The estimation of $\frac{dV}{d\theta}$, the change in volume to the bladder with respect to axial displacement requires some geometric assumptions.

It is assumed when there is no pressure in the muscle and the muscle is uninflated, and the fibres lie in a certain orientation θ_0. If the muscle were not constrained about its length and was lying in a flat two dimensional plane this would appear as figure 2.

Next an assumption is made about the two dimensional representation of the rotary pneumatic cylinder. Given that the length of the cylinder is fixed, then if an increase in pressure occurs, a change θ_0 occurs. The assumption is that if the change in shape of the three dimensional geometric structure were transformed to a two dimensional plane, where the length of the cylinder is not constrained; the change in θ it would increase the effective length of the two dimensional representation and cause a change in angle, θ_1, shown in figure 3.

A rotation about the longitudinal axis produces a change from θ_0 to θ_1. Using these geometrical approximations the effective length and angle of the fibre makes with the longitudinal axis can is given as,

$$S = h\theta_1. \qquad (4)$$

Assuming the fibre length and the angle to the datum θ_0 is known, by basic trigonometry,

$$\theta_1 = arcsin(s/f_1), \qquad (5)$$

subing equation 4 into 5 gives,

$$\theta_1 = arcsin(h\theta_0/f_1). \qquad (6)$$

We now make a geometric assumption about the cross sectional view for the muscle shown in figure 4.

If a cross sectional view of the rotary pneumatic muscle were taken, the muscle surface from one end of the cylinder to the other takes the shape of an arc, l. The assumption is made that the arc length, l, is approximated by the effective length, l_1 in the two dimensional representation.

The volume of the muscle is calculated by a volume of revolution about the x-axis.

The problem then reduces to finding the equations describing the curve of the arc.

We know the length, k, and the arc length, l, and the angle of rotation of the muscle θ, however this cannot be solved directly and requires an approximation. We assume that the radius is large and changes very little with l thus we treat R as a constant, shown in figure

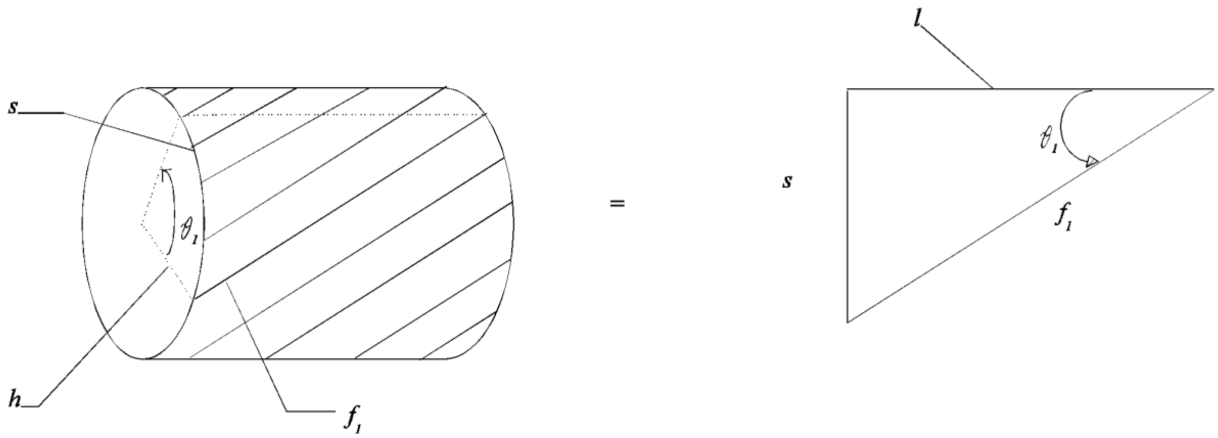

Figure 3: Fibre angle changes with rotation.

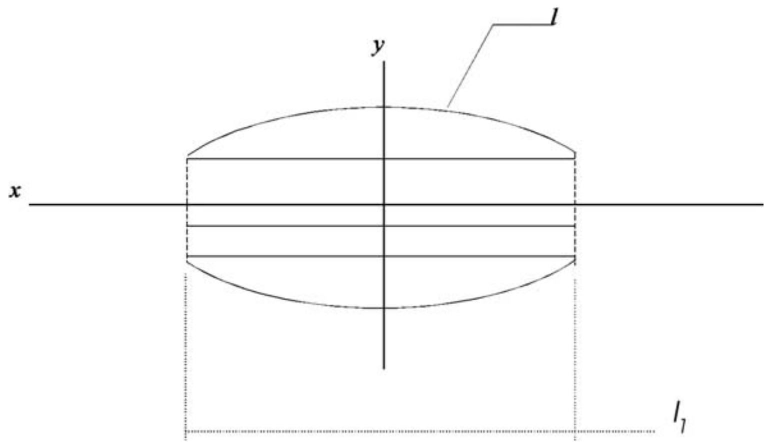

Figure 4: Cross sectional view of the rotary muscle.

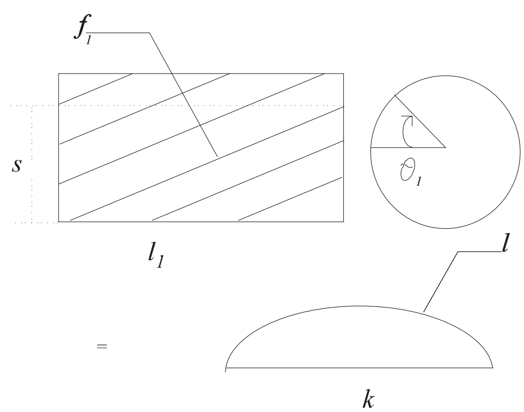

Figure 5: Muscle curvature changes with effective length, l.

6. We then obtain the volume by revolution of the arc around the x axis, given by

$$V = \pi \left\{ kR^2 - \frac{k^3}{12} - (Rl + kh)\left(Rl - \frac{k^2}{4}\right)^{0.5} + Rlh \right\}, \tag{7}$$

differentiation in respect to θ yeilds

$$\begin{aligned} \frac{dV}{d\theta} &= \frac{\pi R h^2 \theta_1 (h^2\theta_1^2 + f_1^2)^{0.5}}{l\sqrt{(R^2 - \frac{k^2}{4}} - kR} \{3kR\sqrt{R^2 - \frac{k^2}{4}} \\ &\quad + 2lh\sqrt{R^2 - \frac{k^2}{4}} - 3lR^2 + \frac{lk^2}{2} - 2khR\} \end{aligned} \tag{8}$$

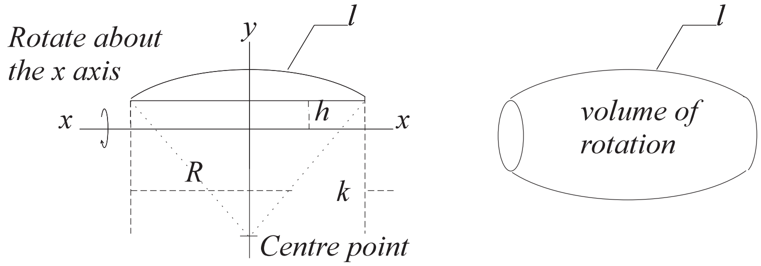

Figure 6: Volume of revolution of the rotary pneumatic muscle.

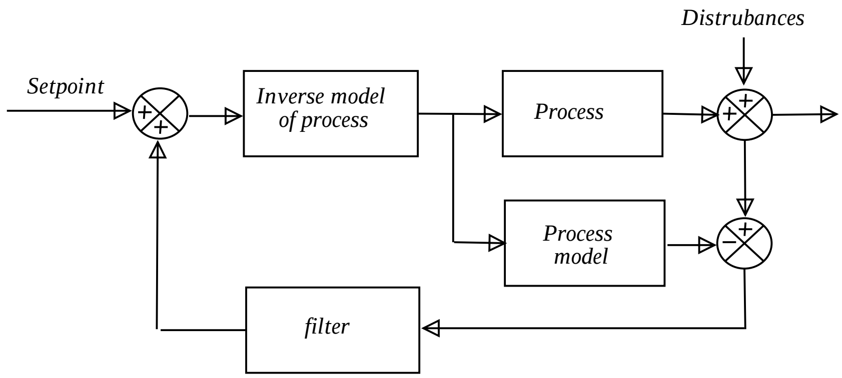

Figure 7: Proposed control schematic for rotary pneumatic muscle.

subing into equation 3 gives,

$$F = -P\frac{\pi R h^2 \theta_1 (h^2\theta_1^2 + f_1^2)^{0.5}}{l\sqrt{(R^2 - \frac{k^2}{4}} - kR}\{3kR\sqrt{R^2 - \frac{k^2}{4}} + 2lh\sqrt{R^2 - \frac{k^2}{4}} - 3lR^2 + \frac{lk^2}{2} - 2khR\}. \quad (9)$$

The resulting equation suggests linear relationships between force produced and angle turned; force produced and muscle pressure and a highly non-linear relationship between angle turned and muscle pressure. A direct inverse model producing the angle turned as a function of muscle force and pressure is of a highly non-linear nature and not readily obtainable analytically. Thus we propose the use of the model in the following control system shown in figure 7.

4 Results

A simulation of the model was implemented on Matlab. Simulated results of how the muscle behaves under certain conditions were produced. The results relate to a muscle with the dimensions *fibre length(f) =14cm, arc radius(R)=75cm, muscle length(l)=10cm* and *muscle radius(h)=1cm*. The conditions simulated were isobaric and isometric conditions. The simulated results are shown in figure's 8 and 9.

The isometric results were produced from a simulation of the rotary pneumatic actuator where the angle of rotation is constrained. These results indicate that the force produced by the muscle is linearly related to the pressure.

The isobaric results were produced from a simulation with the pressure constrained. These results indicate that the force produced by the muscle is nearly linearly related to the angle of rotation.

5 Summary and further work

An investigation into alternative robotic actuation systems resulted in the design and development of a novel pneumatic muscle. The rotary action may have potential advantages in the design of robotic devices with rotary and revolute joints, over linear actuators.

Models describing the behaviour of the rotary pneumatic muscle were developed and, presently, are the subject of further development. Currently we are in the early stages of this research and intend to test the models developed more extensively in the future. We also intend to develop a robot with the rotary pneumatic muscle design to prove the concept.

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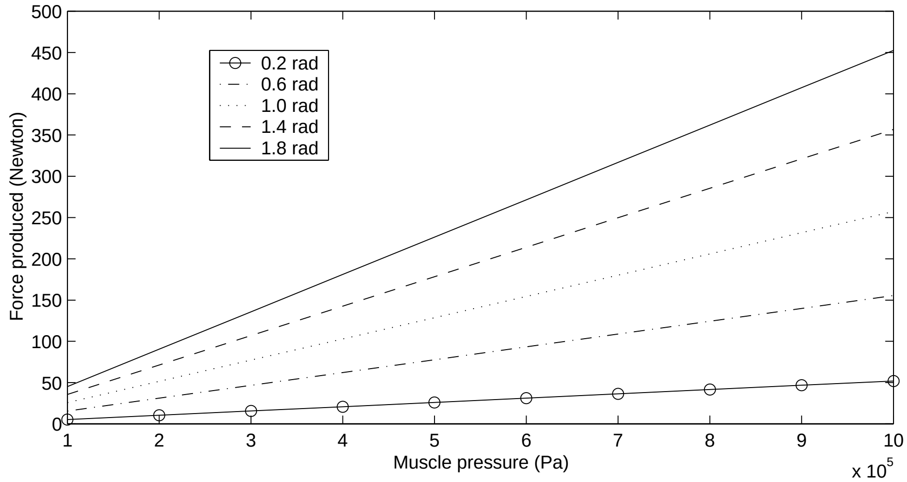

Figure 8: Isometric simulation results.

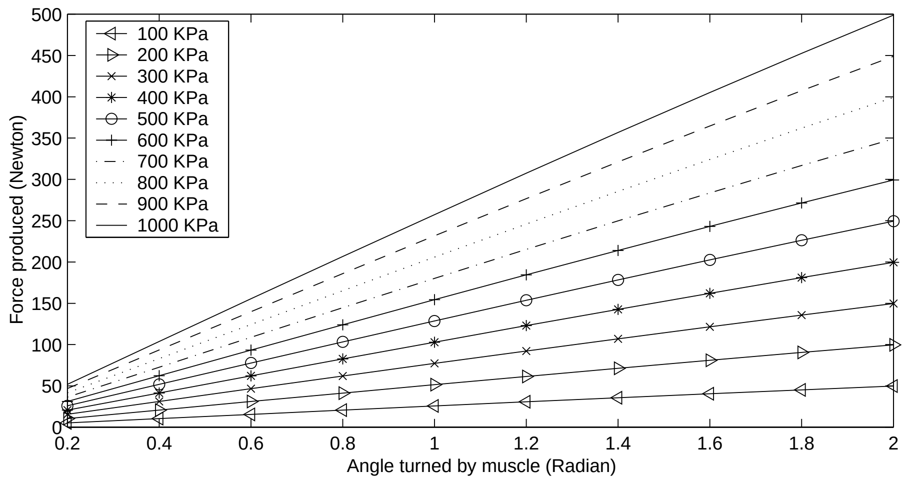

Figure 9: Isobaric simulation results.

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