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Pneumatic Spring for Legged Walker

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ABSTRACT

Over the years, scientists and artists alike have imagined walking mechanisms that mimic the natural gait of humans and animals. Only recently have engineers begun to unravel the mystery of animal locomotion. Several walking robots have been built in the past few years [1]. An ongoing research problem with these robots is their inefficiency. Whereas animal locomotion is quite efficient, our efforts to mimic it have not been, with a few notable exceptions [2]. In this paper, we present a design for efficient legged locomotion, and we show the initial concept demonstration.

Key words: Robotics, mobility, legged locomotion

INTRODUCTION

Mechanisms for storing and returning energy are necessary for legged systems. During walking and other maneuvers it is necessary to delay the energy return, thus a simple spring will not do. This type of timed energy return can be traced back to the mechanical escapement. From the first verge and foliot escapements to Christian Huygens' invention of the pendulum clock in 1657 these mechanical devices allowed clocks to become more and accurate. To achieve this type of timed energy return in a legged mechanism is a design challenge, because although there are many similarities in concept, in practice our design will be much different from a traditional escapement.

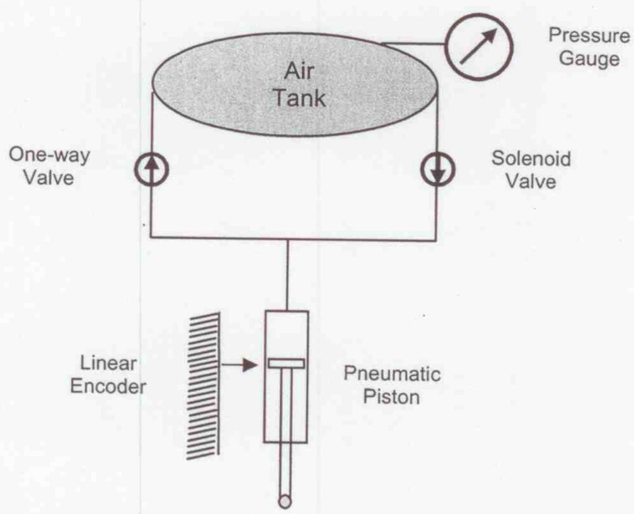

Figure 1: Pneumatic Spring Design

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DESIGN FOR EFFICIENCY

Legged Walkers can be very inefficient. Theoretically, these inefficiencies are due to the loss of kinetic energy at heel strike. We seek to mitigate these collision losses by slowing the foot down before ground contact, storing that energy in an air-spring and returning the energy at toe-off.

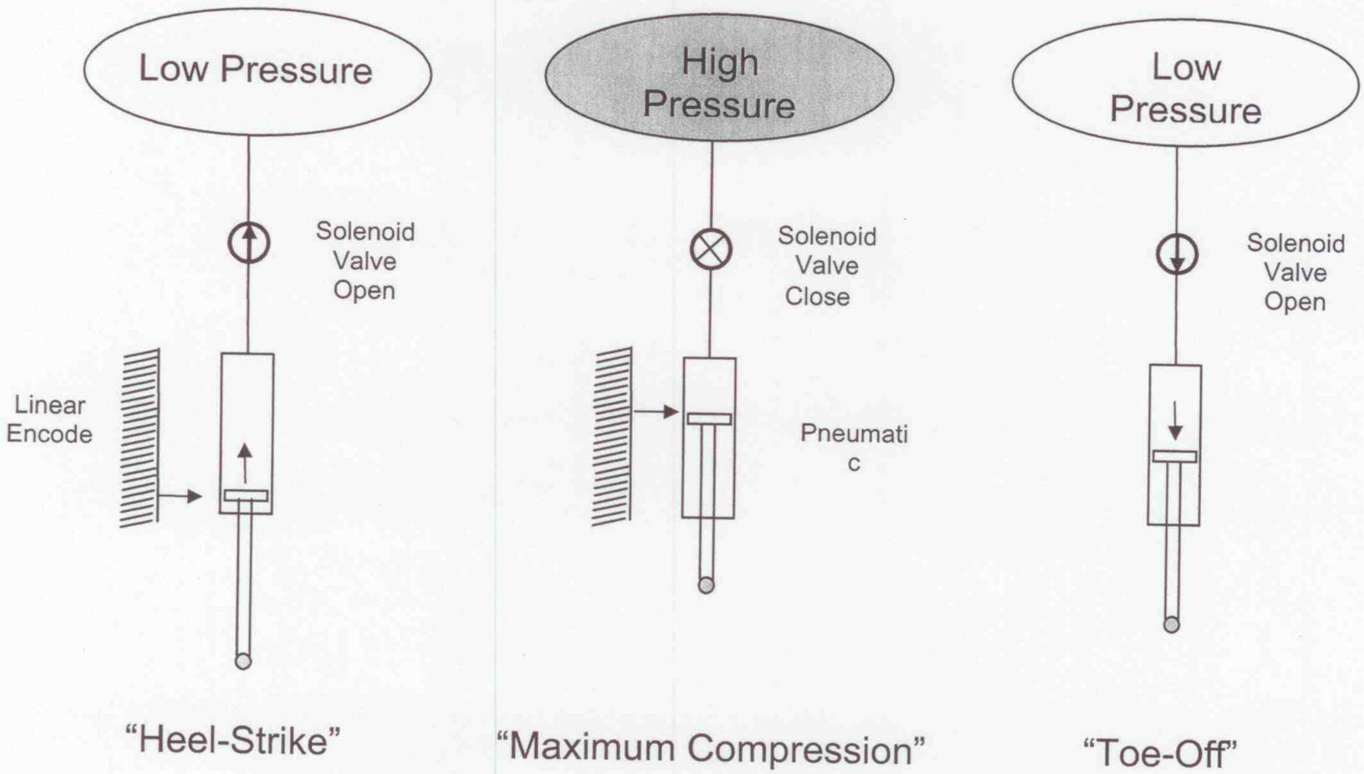

Figure 2: Pneumatic Spring Operation

The Basic Operating Sequence of our design is as follows:

1. At "Heel Strike" the Solenoid Valve is opened to allow high pressure air into the reservoir to be stowed for later use.

2. At "Maximum compression" the valve is closed to trap the compressed air

3. At "Toe-off" the solenoid valve is opened to actuate the pneumatic piston

Conceptually, this design is quite simple. In practice, however, further modifications may be required.

DESIGN MODIFICATIONS

Modification A: Depending on what spring stiffness is required, the reservoir may have to be pre-pressurized from an external source. Modification A adds a high pressure external source. We can also use this high pressure air to actuate the cylinder as well as tune the spring rate. Actuation would require the addition of an exhaust valve to lower the air pressure at the end of the cycle. The addition of a high pressure source also allows you to self-level or tune the stiffness of the air spring. This modification will most likely be required for practicality.

Modification B: The design shown in Figure 2 has only one solenoid valve. This valve would be opened by computer control depending on the walking gait of the robot. While reducing the part count, this design must precisely predict when heel strike occurs to allow a smooth (albeit nonlinear) spring rate. Otherwise there will be a discontinuity in the spring rate. Having a one-way valve in parallel like that shown in Figure 1 could allow heel strike to be "detected" passively by a pressure spike in the system, thus allowing the control system some robustness for heel strike.

Modification C: Having a variable air reservoir volume would change the profile of the nonlinear spring rate. This could be achieved with a (presumably) larger piston.

MCKIBBEN ACTUATOR MODIFICATION

Figure 3: McKibben Actuator

The braided pneumatic actuator [4], also called a McKibben actuator, consists of an inflatable bladder with a fiber mesh. When the actuator is filled with air (Figure 3B), the fiber mesh expands, allowing the volume to increase. However, the fiber lengths are basically inextensible, so as the actuator expands radially, it must simultaneously shorten [5], resulting in a muscle-like contraction as shown in Figure 4.

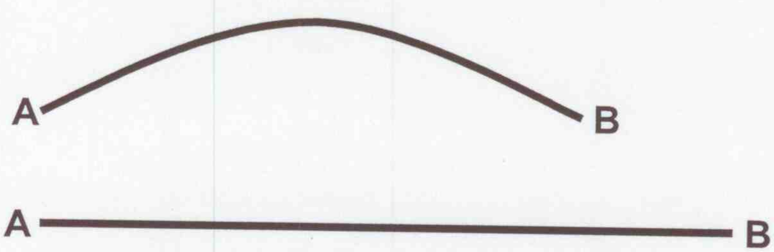

Figure 4: Contraction of the McKibben fiber

To accommodate a McKibben actuator, we need to modify the existing design for the air spring. Basically, we replace the pneumatic piston with a McKibben actuator, as shown in Figure 5.

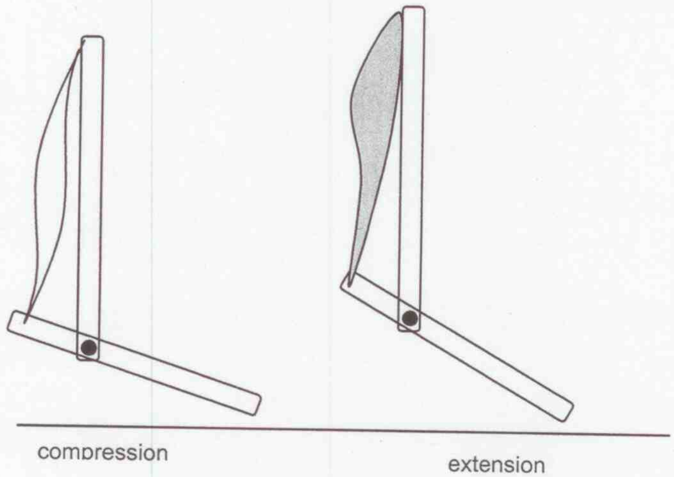

Figure 5: McKibben Air Spring

To analyze the mechanism, consider the gait sequence shown in Figure 6. At heelstrike, on the left side of the picture, the device is in extension to allow maximum compression of the air spring. (Recall from Figure 5 that the muscle is in *contraction* when the leg is *extension.*) As the leg progresses through the stance phase, the "ankle" changes angle with respect to the leg, and McKibben actuator is compressed. (Again looking at Figure 5, the muscle is *elongated* while the leg goes through compression) As the leg leaves the ground during toe-off, the energy that was stored during the compression phase is now released.

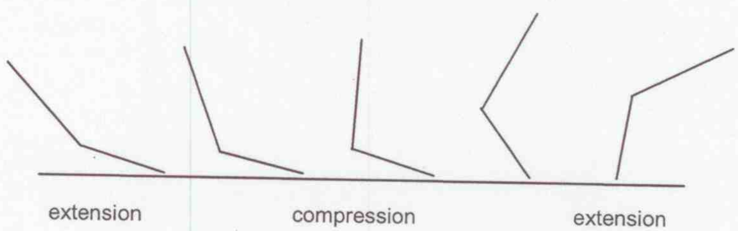

Figure 6: Gait Sequence

An initial mockup of the design is shown in Figure 7.

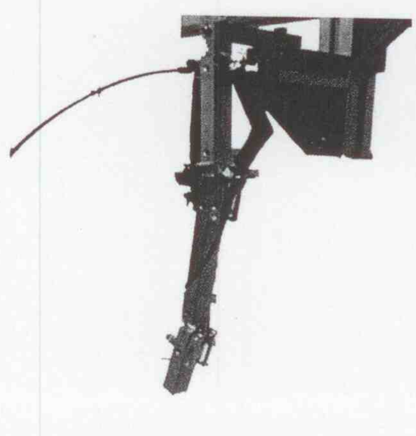

Figure 7: Construction of the Design

This is a proof of concept of the design. Not shown as of yet is the air spring portion of the design. We expect to complete the full working prototype of the design by the time of the conference. Results will be presented in the poster. We do know that most Mathematical Models of the McKibben actuator assume that there is a large volume of air connected to the device such that pressure stays relatively constant over the stroke of the actuator [6]. This will not be the case here because we are only using the McKibben actuator volume as an air spring.

THEORETICAL MODEL OF THE DESIGN

A mathematical model would help the development and design of this concept. However a complete model considering the non-linear functions of this system is presently outside the scope of this paper. We therefore consider the most ideal of conditions and will attempt to capture and identify the variables that may have an effect on the system. [3]

First we will assume *isothermal* conditions where temperature is constant during actuator motion. In this case Boyle's law holds that the relationship between pressure and volume are inversely proportional (again if the temperature remains constant).

$$P_1V_1 = P_2V_2$$

The variables with the 1 subscript mean initial values before the manipulation and the variables with the 2 subscript mean final values after the manipulation. The simplest demonstration of Boyle's Law is a hand bicycle pump. By pushing down on the piston, the reduced volume increases the pressure of the air inside so that it is forced into the tire. Because pressure changes will have an affect on temperature (feel the pump after a few seconds of pumping), temperature must be allowed to return to its prior value for Boyle's Law to hold true. In reality, we know that the temperature will vary in the actuator, so we will also consider operation in an *adiabatic* environment. This assumes that the locomotion process is occurring in a thermally insulated environment where there is no flow of heat to or from the surroundings. In this case, Boyle's law becomes:

$$p_1V_1^\gamma = p_2V_2^\gamma$$

where $\gamma = \frac{C_p}{C_v}$ and C_P and C_V are the specific heat of air at constant pressure and volume, respectively.

We can model the spring rate of our air spring using Boyle's law. The simplest analysis involves looking at a pneumatic piston in isothermal conditions.

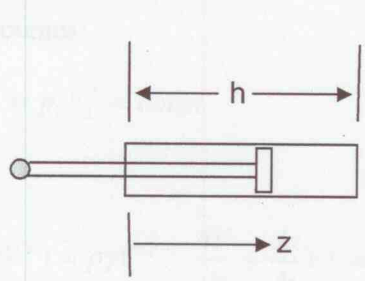

Figure 9: Model of a Pneumatic Piston

For isothermal conditions, $p_0V_0 = p(z)V(z)$. Noting that the volume of the cylinder is simply the effective area times the length, we find that $p_0A_eh = p(z)A_e(h-z)$. Solving for *p(z)*, we see that: $p(z) = \frac{p_0h}{h-z}$.