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Variable Recruitment Inelastic Bladder Hydraulic Artificial Muscles for High Efficiency Robotics

Michael Meller[1*], Jordan Chipka[1], Ephrahim Garcia[1]

[1] Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, USA

Abstract

McKibben muscles are an attractive choice of actuation for legged robots due to their light weight, high force capability, and inherent compliance. Additionally, these actuators have force-stroke profiles more similar to skeletal muscle than traditional hydraulic cylinders. These characteristics are a result of their construction, which is typically comprised of an inner elastomeric bladder surrounded by a helically braided mesh. Despite extensive modeling and characterization efforts, little is known about the energetics of McKibben muscle actuators. For actuation of mobile platforms, such as bipedal robots, efficiency is a large concern. Hence, this paper first discusses the effectiveness of traditional pneumatic McKibben muscles at converting the fluid energy delivered to mechanical output work. It was chosen to use the McKibben muscles hydraulically for the efficiency gains associated with using a higher bulk modulus fluid. To obtain further efficiency improvements in single McKibben muscles, an inelastic bladder is used to replace the typical latex bladder. Utilizing an inelastic bladder significantly reduces the energy lost due to elastic energy storage in latex bladder McKibben muscles. A 190% improvement in transduction efficiency was obtained when using a hydraulically powered, inelastic bladder McKibben muscle compared to traditional operation. The inelastic bladder muscle also exhibits increased free contraction and blocked force capability, and requires very little pressure to become activated. To further increase the actuation efficiency, throttling losses that occur in the hydraulic control valves must be drastically reduced as it is common for over 50% of the hydraulic power to be lost as heat in traditional hydraulic systems. This paper proposes using variable recruitment artificial muscle bundles to better match the load to avoid these throttling losses. Instead of inducing a pressure drop in your control valve, you selectively activate a certain number of 'muscle fibers' in a 'muscle bundle' to meet the force requirements by effectively changing the area of your actuator. The 'muscle fibers' that comprise the 'muscle bundle' are the inelastic bladder, hydraulic McKibben artificial muscle actuators. This concept is similar to shifting gears in a car, and results in higher efficiencies over a much wider actuation range of the muscles. To test these techniques, we have constructed a linear dynamometer that will prescribe specified force-stroke profiles. These profiles are the walking requirements for each joint of a six degree of freedom bipedal robot we have assembled. This humanoid robot currently uses hydraulic cylinder actuation. These 'muscle' bundles will be integrated into the robot in the future to demonstrate the power savings of this approach compared to traditional hydraulic control systems.

* Corresponding author, mam627@cornell.edu

1. INTRODUCTION

The main goal of the work presented in this paper is to improve actuation efficiency for bipedal robots. However, improving actuation efficiency in the manner demonstrated can be applied to almost any mobile platform. The benefits of improving efficiency include decreasing the size of the central power plant, which will in turn help increase the range of the robot. To begin addressing the issue of actuation efficiency, one must first choose an actuation area. Our chosen actuation area of focus is hydraulic control systems. Hydraulics has been gaining popularity among the robotics community, but for it to be truly useful in these mobile applications, the manner in which the actuators are recruited must be done far more efficiently.

Firstly, we chose McKibben artificial muscles as the actuators because they are light weight, have high force capability, and exhibit force-stroke profiles much more similar to skeletal muscle than hydraulic cylinders [1]. McKibben muscles are typically constructed of an inner elastomeric bladder that is encompassed by a helically interwoven mesh. These parts are energized via a fluid port on one end of the actuator. The other end is plugged, and both ends attach mechanically to the structure being actuated.

Fluidic artificial muscles (FAMs) are usually operated pneumatically, however there are a handful of research groups using them hydraulically [2, 3]. Using FAMs pneumatically is convenient because it allows venting the working fluid directly to the atmosphere, and bleeding the transmission lines is not an issue. There are downsides to pneumatics, as valve-controlled pneumatic systems are seldom over 30% efficient, while valve-controlled hydraulic systems can have efficiencies of approximately twice this due to its higher fluid bulk modulus [4]. To determine the transduction efficiency benefits of utilizing the McKibben muscles hydraulically rather than pneumatically, a brief series of experiments were performed at typical FAM operating pressures.

To avoid the losses associated with the elastic energy storage in the latex bladders of typical McKibben muscles, an inelastic low density polyethylene (LDPE) bag is used as the bladder instead. A series of transduction efficiency experiments were performed to demonstrate the gains related to employing this type of bladder material. These tests were based on previous experiments performed in the LIMS lab [5].

We address one of hydraulics' largest inefficiencies, valve throttling, by drawing inspiration from biology. Differential cylinder-driven hydraulic control systems induce a pressure drop in the valves to match the actuator loads. This is simple for control, but is very inefficient, oftentimes resulting in over 50% of the input power being lost as heat [6]. Nature on the other hand recruits different numbers of motor units to match the load by increasing the number of motor neurons firing, resulting in extremely efficient motion. In this paper, we use inelastic bladder hydraulic artificial muscle actuators as the muscle fibers of a variable recruitment artificial muscle bundle. To match the instantaneous loading requirements, different numbers of these muscle fibers can be selectively activated. An example loading scenario with the accompanying reduction in fluid energy consumption is presented.

Lastly, we show a linear dynamometer we have constructed, that will be used for our variable recruitment muscle bundles. We will first characterize recruitment efficiency gains for various loading scenarios. Then we will perform controller development, optimizing for efficiency offline of the robot. Then we will prescribe the loading requirements of each joint of our bipedal robot on the linear dynamometer. The last step involves integrating these muscle bundles on to the robot, demonstrating the required control authority and significant reduction in fluid power consumption compared to traditional hydraulic systems.

2. McKIBBEN 'MUSCLE FIBER' DEVELOPMENT

2.1 McKibben 'muscle fiber' working fluid

Since the chief goal is to increase actuation efficiency, before packaging these McKibben muscles in a bundle, each individual muscle should be improved upon in these terms as well. Traditional McKibben muscles were built with a helically braided mesh and latex tube, and run pneumatically and hydraulically. Full isobaric tension-stroke contraction tests were performed while measuring the force, length, pressure, and volume. With these four quantities, it was possible to experimentally determine the difference in transduction efficiency for hydraulic and pneumatic operation. Fig. 1 shows the efficiency benefits of using hydraulic fluid over air as the working fluid over a range of normal operating pressures for McKibben muscles. At 75psi, using a latex bladder McKibben muscle hydraulically results in an efficiency of just over 60%, while pneumatic operation results in an efficiency of just under 30%.

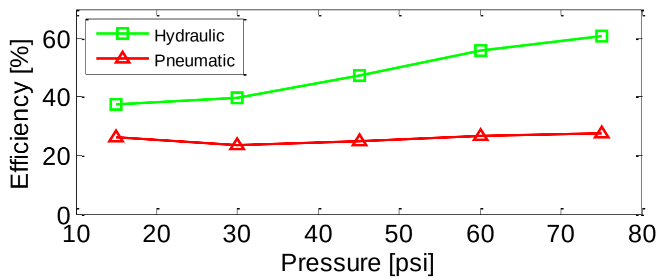


Figure 1. Transduction efficiency as a function of pressure for a latex FAM being operated both pneumatically and hydraulically

2.2 McKibben 'muscle fiber' bladder material

It is often reported that the latex bladders, or other elastomeric tubes that make up traditional McKibben muscles will store energy [1, 7]. This is one of the reasons the ideal virtual work models largely over predict the attainable strain values of the actuators. As a result of this elastic energy storage that cannot be recovered, significant losses occur [5]. This is why the LIMS lab opted to employ an LDPE inelastic bag as the McKibben muscle bladder, which can be seen in Fig. 2 (a). A picture of the constructed muscle in its resting and pressurized states is shown in the top and bottom of Fig. 2 (b) respectively. The bottom portion of Fig. 2 (b) is the muscle's free contraction at 50 psi.

The fact that the bladder is inelastic does pose other complications as well. The bladder can no longer bear any load since this may lead to bursting. Therefore in the construction process, the diameter of the LDPE bladder must be greater than that of the mesh in its most expanded state. This means that the bladder must fold and unfold when lengthening and contracting respectively. While this does mean additional friction exists inside of the actuator, the LDPE bladder McKibben muscle is still far more efficient than the latex bladder McKibben muscle. Full actuation cycle transduction efficiency tests, like described in the previous section, were performed for latex and LDPE bladder muscles hydraulically as a function of pressure, and the results are shown below in Fig. 3.

(a) (b)

Figure 2. (a) Components that make up the LDPE bladder FAM, and **(b)** this LDPE bladder FAM in the unpressurized (top) and pressurized (bottom) states

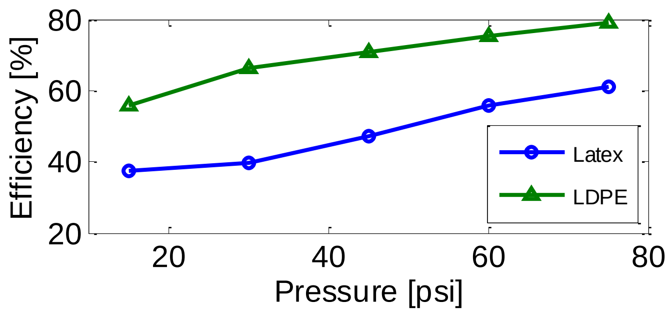


Figure 3. Transduction efficiency as a function of pressure for a latex bladder FAM and an LDPE bladder FAM being operated hydraulically

2.3 Characterization and modeling

It was desired to know how the tension-strain relationships of these inelastic bladder McKibben muscles evolve over a range of different pressures. It is important to know this accurately for one of these McKibben muscles since they will be bundled together for the purposes of variable recruitment. Hence, these characteristics were obtained on an Instron 5566 tensile testing machine for a number of isobaric experiments over the full stroke range of the actuator at various pressures. Since it is well known that the ideal virtual work models tend to over-predict the strain of the muscles, the free contraction and blocked force of the muscle was determined as a function of pressure. A curve fit was then applied to this data, as it will be used in a semi-empirical model presented below. The free contraction data and curve fit is presented in Fig. 4 (a), and the blocked force data and curve fit are shown in Fig. 4 (b).

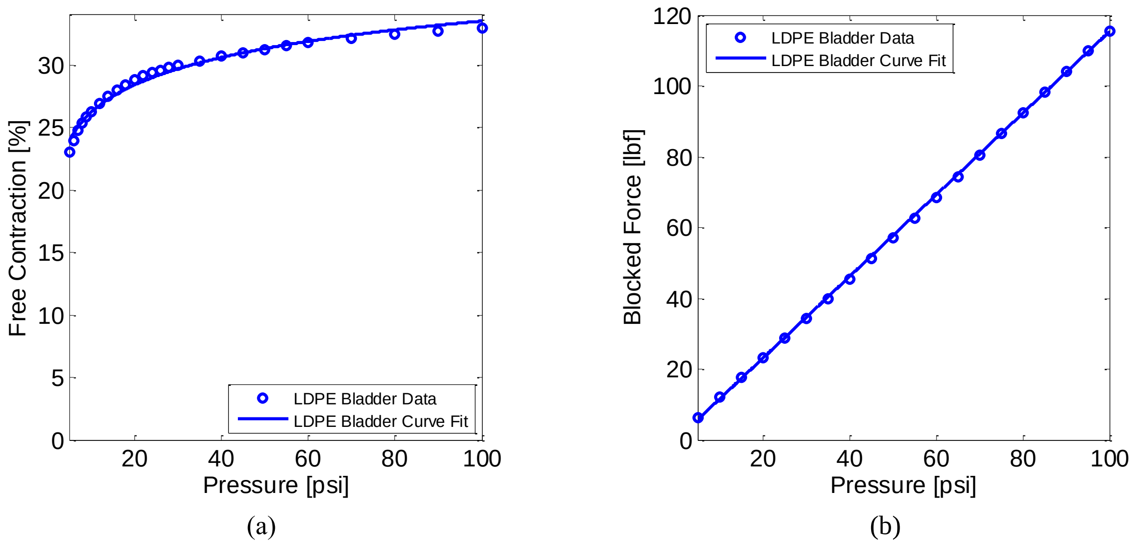


Figure 4. (a) Free contraction as a function of pressure, and **(b)** blocked force as a function of pressure

The isobaric characterization tests performed are shown in Fig. 5. These were done at 15, 45, and 75 psi. To model the quasi-static force-strain behavior shown, FAMs are often modeled using the principle of virtual work. This is done by equating the mechanical work output and fluid energy input as seen in Eqn. (1) [1]

$$F = P\frac{dV}{dl} = P\frac{dV/d\varepsilon}{dl/d\varepsilon} \tag{1}$$

where F is the tension, P is the pressure, V is the volume, l is the length, and ε is the strain.

Next, the muscle is assumed to have inextensible mesh fibers that obey the pantograph opening principle, and remain cylindrical throughout operation. This yields Eqn. (2) and (3) respectively

$$\frac{l}{l_0} = \frac{\cos\alpha}{\cos\alpha_0}\,,\quad \frac{r}{r_0} = \frac{\sin\alpha}{\sin\alpha_0} \tag{2}$$

$$V = \pi r^2 l \tag{3}$$

where α is the angle between the muscle's axis and the fibers of the mesh, r is the radius of the muscle, and $(\ )_0$ denotes the full length initial condition. Substituting and rearranging Eqns. (1)-(3) for the force output of the muscle as a function of initial geometry, the current pressure, and the current strain gives

$$F = (\pi r_0^2)P[a(1-\varepsilon)^2 - b] \tag{4}$$

where a and b are geometrical constants based on the initial position of braided mesh, and are given by Eqn. (5). Eqns. (4) and (5) make up the ideal force model with which many models in the literature begin [1].

$$a = \frac{3}{\tan^2\alpha_0}, \quad \text{and} \quad b = \frac{1}{\sin^2\alpha_0} \tag{5}$$

Since we know this model over-predicts the strain values of the McKibben muscle, we wanted to include blocked force and free strain data as a function of pressure seen in Fig. 4 to get better agreement between model and data. There are many existing models that go about doing this by including things such as friction and elastic energy storage, but we wanted a quick model that was good enough for predicting efficiency gains of variable recruitment, and control [1, 7]. Our modified force equation is

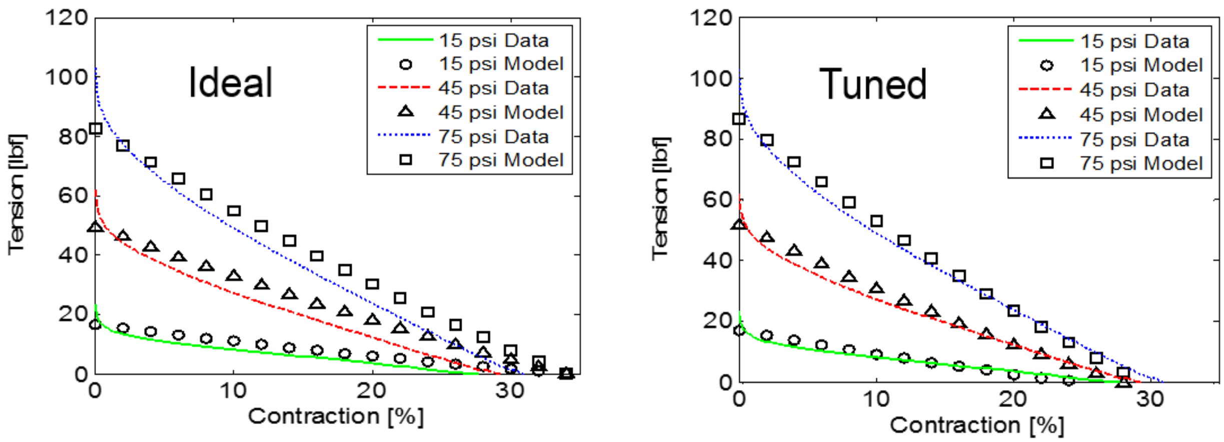
$$F_{mod} = \kappa_F(\pi r_0^2)P[a(1-\kappa_\varepsilon \varepsilon)^2 - b] \tag{6}$$

where κ_F and κ_ε and the force and strain tuning parameters defined as

$$\kappa_F = \frac{F_{meas,max}(P)}{(\pi r_0^2)P(a-b)}, \text{ and } \kappa_\varepsilon = \frac{1}{\varepsilon_{meas,max}(P)}\left(1 - \frac{1}{\sqrt{3}\cos(\alpha_0)}\right) \tag{7}$$

where $F_{meas,max}(P)$ is the force curve fit in Fig. 4 (a) and $\varepsilon_{meas,max}(P)$ is strain curve fit in Fig. 4 (b).

Fig. 5 (a) plots both the experimental data of the muscle as well as the ideal model from Eqn. (4). It is clear that the model over-predicts the strain values as expected, but not nearly as much as it normally does for elastomeric bladder FAMs, as the LDPE bladder FAM has a 2 mil thick bladder which is much closer to the zero thickness bladder assumption in the ideal model. Fig. 5 (b) plots the same experimental data, except now with the improved tuned model using Eqn. (6). It is clear that this new model better represents the data, and will be used in future sections.



(a) (b)

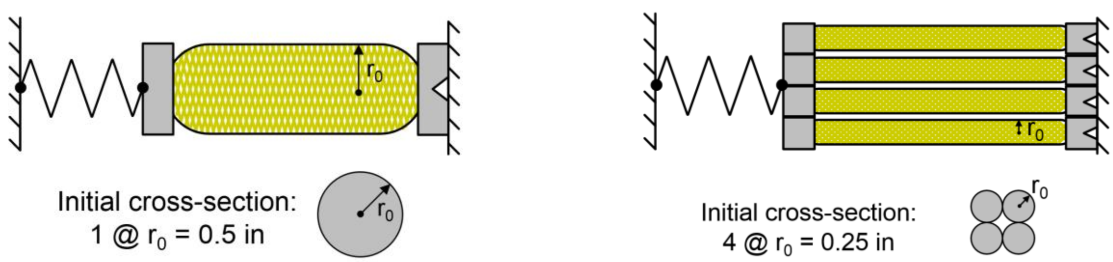
Figure 5. (a) Tension-contraction plot of LDPE bladder FAM with ideal virtual work model, and **(b)** tension-contraction plot of LDPE bladder FAM with empirically tuned virtual work model

3. VARIABLE RECRUITMENT INELASTIC BLADDER HYDRAULIC McKIBBEN MUSCLES

A variable recruitment actuation scheme positively affects efficiency. By using fewer of the muscle fibers to match smaller loads, less power is consumed from the hydraulic pump because instead of inducing a pressure drop in the valves, the volume of fluid delivered is reduced. The LIMS lab has performed some previous work with bundling latex bladder McKibben muscles [8]. In this paper, we will demonstrate how variable recruitment can save energy with an example load profile – that of a simple linear spring.

3.1 Variable recruitment example load profile

The example shown below utilizes the developed semi-empirical LDPE bladder muscle model from Eqn. (6) to simulate the benefits of variable recruitment for a given load profile of actuating against a linear spring. Actuators are sized to produce some maximum load (point C in Fig. 7 (a) and 8 (a)), but will spend much of the actuation cycle far beneath this operating point (traveling from point A to point in B Fig. 7 (a) and 8 (a)). The traditional approach would be to induce a pressure drop in the valve to match the load when below this maximum scenario, which results in low efficiencies. This example includes first a single LDPE bladder hydraulic McKibben muscle with a blocked force of 450 lbf and free stroke of 4.3 in, depicted in Fig. 6 (a). This actuator achieves force control to match the spring load by throttling in the valves, as there is no recruitment. This is then compared to a variable recruitment actuator with four levels of recruitment, seen in Fig. 6 (b), having equivalent maximum capabilities to the single muscle if all four muscles are simultaneously activated. It is important to note that actuating against a spring is one of the most inefficient configurations for McKibben muscles. However, actuating against this type of load clearly shows why changing recruitment state in a variable recruitment actuator is advantageous when compared to the traditional throttling approach.



(a) (b)

Figure 6. (a) Single equivalent area LDPE bladder FAM actuating against a linear spring, and **(b)** four LDPE bladder FAM muscle bundle with equivalent area to (a) and actuating against the same linear spring

3.2 Single equivalent actuator with throttling

The tension-stroke output of the single McKibben muscle, along with the example spring load, can be seen in Fig. 7 (a). The max operating pressure is 100 psi, and it is noted on the plot that to achieve force levels lower than point C, one must induce a pressure drop in the valves since the operating pressure is fixed. The energy consumed and efficiency plots are shown in Fig. 7 (b) and (c) respectively. It can be seen that the lowest efficiencies correspond to the lowest load regions (between points A and B), and this is because the actuator is sized to the maximum loading requirements (point C), and a significant amount of throttling is required when below this maximum operating point.

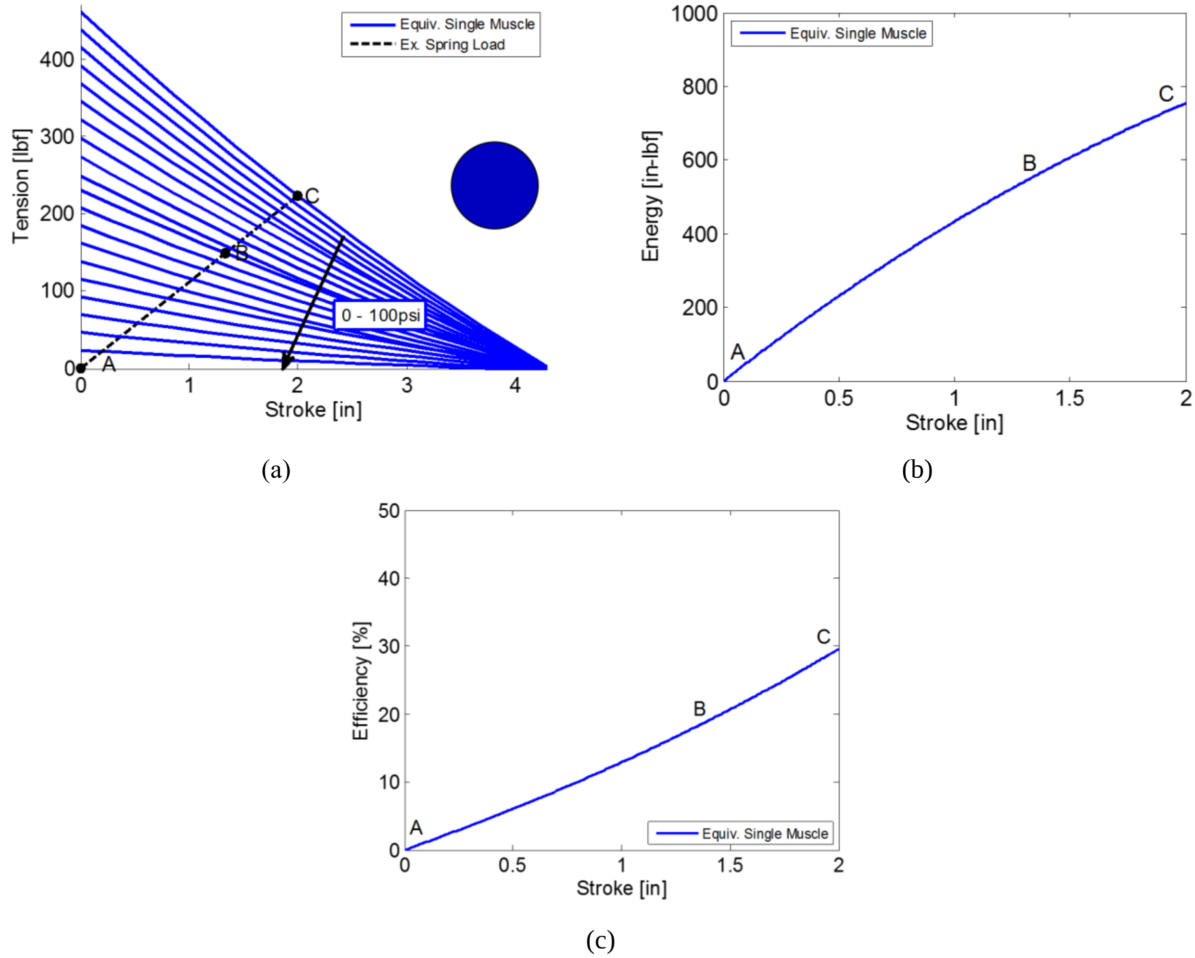


Figure 7. (a) Tension-stroke plot of single equivalent LDPE bladder FAM with no recruitment actuating against the linear spring load, **(b)** the fluid energy required of the FAM to produce the mechanical work to actuate the spring load, and **(c)** the associated efficiency

3.3 Variable recruitment four muscle fiber bundle

The tension-stroke output of the variable recruitment four McKibben muscle fiber bundle, along with the same example spring load, can be seen in Fig. 8 (a). The maximum operating pressure is also 100 psi, and the different colors on the plot denote changes in levels of recruitment. To achieve force levels lower than point C, one can change the number of active muscle fibers. To smooth the discrete transitions, throttling is used, but far less than in the single muscle example. The energy consumed and efficiency plots are shown in Fig. 8 (b) and (c) respectively. It can be seen in the efficiency plot that the slope is increased initially allowing higher efficiencies at the same stroke levels when compared to Fig. 7 (c). Then the force output of one muscle fiber saturates, and additional muscle fibers need to be recruited. This is seen as that instantaneous drop in efficiency. As the force requirements of that recruitment level increase, the efficiency also increases. This process is repeated, and is what gives the efficiency plot in Fig. 8 (c) its sawtooth-like appearance. Looking at going from point A to B again, variable recruitment has now caused the efficiency to double when compared to the single equivalent muscle, because half the actuator area is required to perform this action.

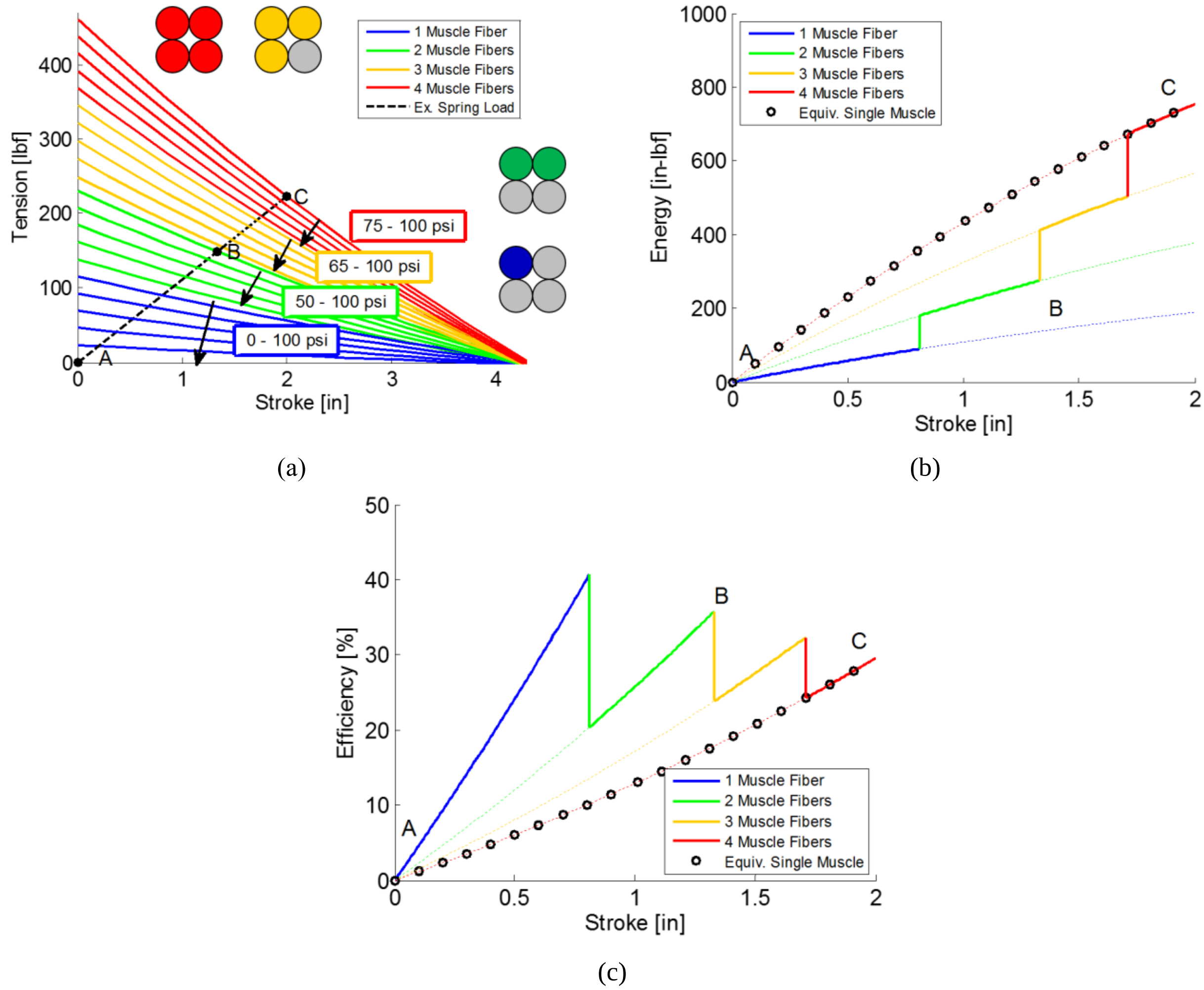


Figure 8. (a) Tension-stroke plot of the four LDPE bladder FAM bundle with recruitment actuating against the linear spring load, **(b)** the fluid energy required of the muscle bundle to produce the mechanical work to actuate the spring load, and **(c)** the associated efficiency (with equivalent single muscle with no recruitment included for comparison)

4. DYNAMOMETER TESTING

As we develop our McKibben actuators to be used in muscle bundles with variable recruitment capabilities, we must first understand how these actuators will behave when implemented on a system such as our walking machine, which can be seen in Fig. 10 (c). It is necessary to perform dynamics tests on our artificial muscles before implementation onto our robot.

To dynamically characterize our McKibben muscles, a test platform needed to be constructed. This platform needed to be adaptable so that muscle bundles of various sizes can be tested. Additionally, this test bed must allow for closed-loop control of both the pressure and displacement of the artificial muscle bundle. To meet all of these requirements, we constructed a linear dynamometer to test these actuators.

4.1 Testing approach

One of the goals of the dynamic testing is to characterize the performance of the artificial muscle bundles for use on our walking robot. Therefore, during dynamics testing, we wished to prescribe force-stroke requirements similar to what they would experience on the walking robot. In order to prescribe the appropriate forces and displacements to the muscle bundle, we first needed to determine these force and displacement trajectories. To obtain the force curves that the actuators would experience on the robot, we instrumented load cells in line with the current traditional hydraulic cylinders on our robot. From these load cells, we obtained the force requirements for our muscle bundles. An example of a force trajectory of the ankle actuator can be seen in Fig. 9 (a). To obtain the appropriate displacement trajectories for the muscle bundles to track, we recorded data from our rotary encoders on our robot to log joint angles. Then, given the geometry of the robot, we were able to convert these joint angles into linear displacements for our actuators. An example of a displacement trajectory of the ankle actuator can be seen in Fig. 9 (b).

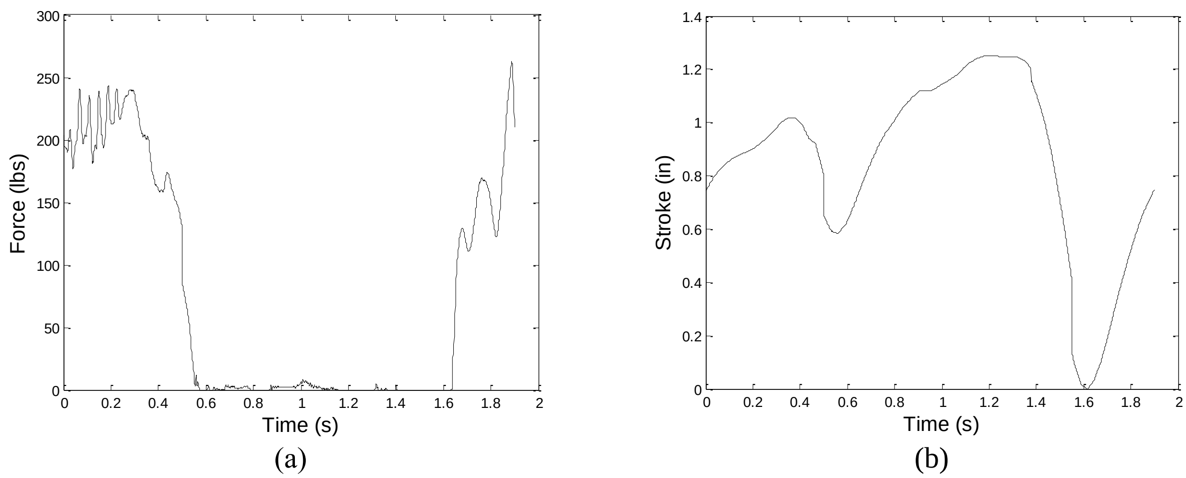
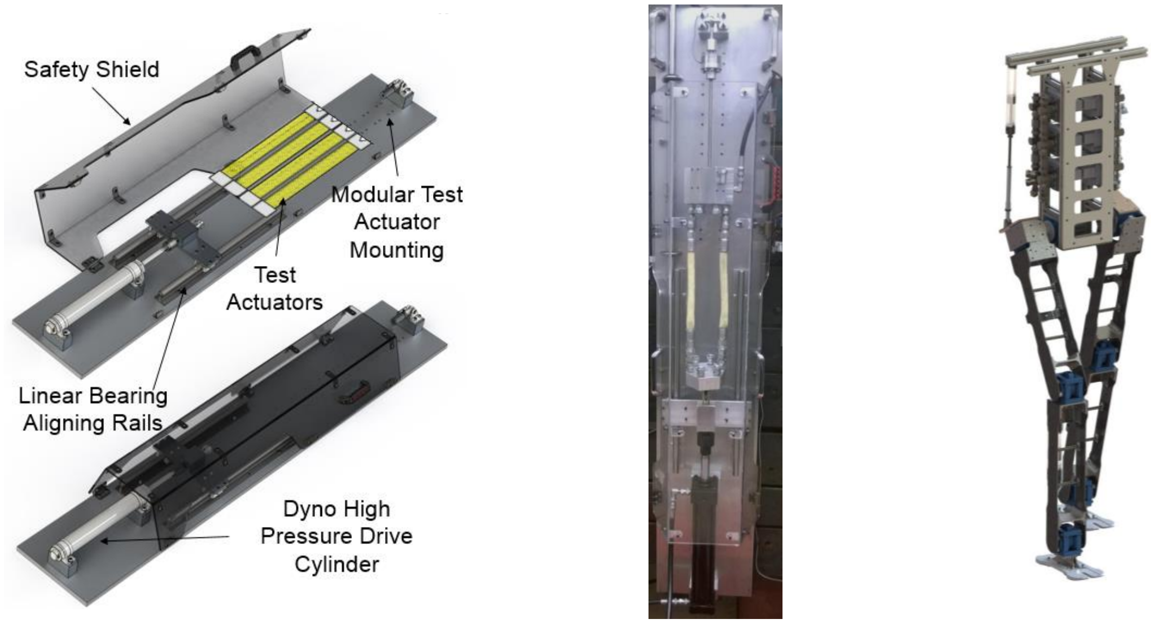


Figure 9. (a) Force profile to be prescribed to muscle bundle to simulate rear ankle actuator, and **(b)** displacement trajectory to be prescribed to drive cylinder to simulate rear ankle actuator

4.2 Test setup

A CAD rendering of the linear dynamometer can be seen in Fig. 10 (a). Also, a picture of the current experimental setup can be seen in Fig. 10 (b). As seen in these two figures, a high-pressure drive cylinder in connected to the test actuators through a sliding coupler. The coupler slides along linear bearing aligning rails. A load cell is instrumented in-line with the test actuators. Also, an LVDT is used to record the position of the sliding coupler. Additionally, a flow meter and pressure transducer are connected to monitor the flow of hydraulic oil to the test actuators. The flow will be controlled by four electrohydraulic servovalves. One of these valves will be used to control the flow to the drive cylinder. Then the other three valves will control the flow to the artificial muscle bundle. For our current setup, six McKibben muscles are connected to our variable recruitment manifold, which allows us to control these muscles in three pairs. Hence, we need three valves to control these three pairs of actuators. Finally, we will run closed-loop control using Simulink and QUARC.



(a) (b) (c)

Figure 10. (a) Rendering of linear dynamometer, **(b)** current state of linear dynamometer, and **(c)** rendering of bipedal robot

In order to ensure that our muscle bundle will be able to meet the force-stroke requirements of our walking robot, we must be able to test these actuators under similar conditions. The method we will use involves controlling the position of the high-pressure drive cylinder, while controlling the force of the test actuators. By using the measurements from the LVDT to provide feedback, we will use PID control to prescribe the appropriate displacement of the drive actuator, and thus, the test actuators as well (since they are rigidly connected). Similarly, by using the measurements from the load cell to provide feedback, we will use PID control to prescribe the appropriate force curve to the artificial muscles.

4.3 Current state of testing and future directions

We have recently completed the static testing phase of our newly designed artificial muscles. This testing was important so that we could ensure that our actuators were strong enough to handle high pressure and loads without tearing. Our artificial muscles can now endure more than 550 psi while unloaded, and more than 400 psi while loaded at 800 lbs. This is sufficient for our purposes as we will only be pressurizing our muscles to 250 psi and loading them to no more than 300 lbs.

Although the ultimate aim is to implement our variable recruitment artificial muscle bundles on our walking robot, the current goal is to show the benefits of hydraulic artificial muscle bundles with variable recruitment. Therefore, the immediate goal of the dynamometer testing is twofold. First, we want to ensure that our artificial muscles can meet the force-stroke requirements for our walking robot. This will be done by prescribing the appropriate force and displacement trajectories, and confirming that the artificial muscles can meet these specifications. Second, we will show the power savings of variable recruitment. We will then compare the cost of transport of a hydraulic system with variable recruitment as opposed to a traditional throttling scheme without variable recruitment.

5. CONCLUSIONS

First, this paper presented an efficient type of individual McKibben muscle that functions as a 'muscle fiber' in a muscle bundle. This McKibben muscle has an inelastic LDPE bladder rather than a latex tube, and is operated hydraulically instead of pneumatically. These two changes cause an improvement in transduction efficiency of 190% at 75 psi. Isobaric tension-strain characterization tests were performed on this McKibben muscle to determine the relationship between force, pressure, volume, and position.

For the purposes of predicting the benefits of variable recruitment as well as control, a semi-empirical model based on the principle of virtual work was developed for the individual 'muscle fiber.' Four of these actuators were bundled together, and each McKibben muscle fiber can be selectively activated to better match the load, thereby improving system efficiency. The energy savings offered by variable recruitment, as opposed to the traditional throttling approach, were simulated.

There are a number of challenges a variable recruitment actuation scheme poses. One issue is determining the number of muscle fibers in the muscle bundle. More muscle fibers result in smoother transitions between recruitment thresholds and lessens pressure drops. However, this adds system complexity and weight mostly due to the valving. Future research efforts will involve developing an effective hybrid controller to smoothly shift between levels of recruitment to produce efficient motion and force control of our bipedal robot. This controller will be developed offline of the robot through use of the linear dynamometer. Verifying that our actuators and controllers can produce the robot requirements will also occur on this test platform.

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