Fatigue Life and Frequency Response of Braided Pneumatic Actuators

Daniel A. Kingsley and Roger D. Quinn
Case Western Reserve University
Cleveland, OH 44106

Abstract

Although braided pneumatic actuators are capable of producing phenomenal forces compared to their weight, they have yet to see mainstream use due to their relatively short fatigue lives. By improving manufacturing techniques, actuator lifetime was extended by nearly an order of magnitude. Another concern is that their response times may be too long for control of legged robots. In addition, the frequency response of these actuators was found to be similar to that of human muscle.

1. Introduction

Braided pneumatic actuators, also known as McKibben artificial muscles [xx], or rubbertuators [xx] consist of an inflatable core surrounded by a fiber mesh. When the core is inflated, it tends to increase in volume; however, the mesh constrains it to contract axially and expand radialy. The result is a powerful actuator with many muscle-like properties. This paper has two purposes: first it details means by which the fatigue life of these actuators may be extended, and second, it quantifies the frequency response of these devices—an important but often overlooked property.

Braided pneumatic actuators are known for their phenomenal force to weight output; an actuator weighing less than a quarter of a pound is capable of lifting over two hundred pounds. The great drawback of these devices however is their relatively short fatigue life. Whereas electric motors and air cylinders are produced using well characterized materials and exacting quality control, McKibben muscles are made of much weaker materials (latex and spandex vs. the steel and aluminum of motors and fluid devices) that by nature are more failure prone. A theoretical analysis by Klute and Hannaford pointedly demonstrates this critical weakness [xx]. A thorough crack propagation model of latex, taking into account both the radial and axial deformations present in these actuators, was used to produce a fatigue limit ratio between a McKibben actuator and latex in uniaxial tension of:

$$\frac{N_{McK}}{N_{UT}} = \frac{\left(\frac{1}{(\lambda_{1\,UT})^{1/2}}\right)^{\beta}}{(9.6-8.6\lambda^{2}_{1,Mck})^{\beta/2}}$$

where β is an experimentally determined material property, and λ is material strain. Using published material data, an estimated lifespan of approximately 3000 cycles was determined for actuators operating at 50 psi and constructed using natural rubber latex. Obviously this is far too short a fatigue life for most practical applications, especially when one takes into account other damaging factors that may occur during manufacture and operation of the actuator.

Not only is it important to extend the lifetimes of McKibben muscles to effectively implement them in a robotic system, it is also necessary to characterize the performance of these actuators while operating over a range of frequencies. The speed at which such a device can effectively operate will of course directly affect the performance of the system in which it serves as an actuator. For example, a robot cannot be expected to take five steps a second if the actuators that drive it are incapable of operating any faster than three cycles per second.

2.1 Actuator Fatigue Life

Because robustness is of critical importance to robotics in general, and to the ultimate goal of autonomy in specific, a study of actuator fatigue life was performed with the goal of extending this characteristic as much as possible. To complete this task, a test rig was built to cycle actuators against a load. This consisted simply of a pinned arm upon which the actuator was mounted opposite a cluster of springs. A 1:6 moment arm caused the springs to extend enough to provide a reasonable opposing force while still allowing the actuator to fully contract. The valve driving the actuator was fed a square wave input, causing the actuator to contract and release at a frequency of one hertz across a pressure range of zero to ninety-five psi (Figure 1).

All actuators were produced in the same basic manner; all changes discussed were modifications of this process. Each end consisted of a rubber core with a diameter of 3/8 of an inch; one end was solid and the other had a through hole for the air inlet tube. A small amount of latex was applied around the edge of the inlet tube that would ultimately exist inside the actuator to reduce leakage (Figure 2A). The latex tube was stretched around these stoppers and a thin piece of rubber tube was stretched over this assembly (Figure 2B). Both ends were sealed by applying a high-strength water-based glue between the layers of rubber and latex. This core was then placed inside the mesh, both ends of which were folded over to create loops for mounting, and a clamp was used to tighten and seal each end of the actuator. A line of glue was applied around the clamp to prevent slipping (Figure 2.2C).

Figure 1: Actuator fatigue testing rig

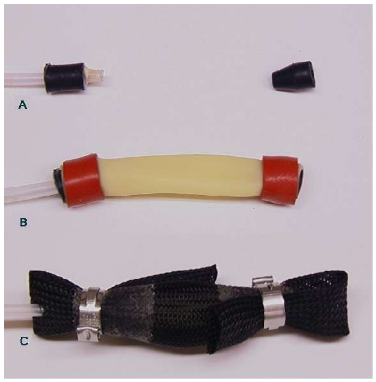


Figure 2: Stages of actuator construction

The first actuators to be tested were the simplest possible, consisting of a latex tube wrapped in a PET monofilament mesh. The latex had a 3/8 inch inner diameter and a wall thickness of 1/32 inch; with a nominal length of three inches, these dimensions are typical for actuators to be used on Robot IV and its successors. Two such actuators were built and cycled at a pressure of 95 psi. The first failed after approximately 90 cycles, the second failed after 150 cycles. The next two actuators to be tested were modified by adding a spandex sheath between the latex and the mesh. The spandex sheath was made by wrapping spandex around a half-inch Aluminum rod and bonding the seam with a layer of painted-on latex (Figure 3). This was done to prevent the fibers of the mesh from pinching the latex bladder during operation; damage that was evident in the previous actuators. These actuators lasted approximately 720 and 900 cycles. All four of these actuators failed through similar mechanisms: they began to deform at the ends, eventually leading to a hole forming in the mesh. The latex bladder then pushed through this hole and expanded until it ruptured (Figure 4). In both cases of the second set of actuators, the spandex sleeve did not fail along its seam, suggesting that the manufacturing method of this element was sound.

The next actuator tested was one produced by the Shadow Robot company, and although it did not have a spandex sleeve, the latex was prestressed; as a result, when the actuator was relaxed the latex caused the mesh to expand slightly, helping to separate the two and thereby reducing the amount of abrasive wear. This failed after 1,320 cycles at 95 psi through a "pinhole" failure—effectively some small irregularity in the latex caused a stress concentration, which led after many cycles to a small hole being formed in the bladder.

B

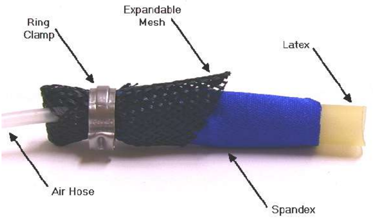


Figure 3: Actuator with spandex sleeve

An actuator was then made integrating the Shadow technique of prestressing the latex while retaining the spandex sleeve. In addition, the ends of the mesh were painted with a coat of latex in an attempt to prevent the mesh from separating as it had in the earlier samples. This was tested at 95 psi and failed after 1,800 cycles through a pinhole break.

In an attempt to reduce the occurrence and effects of the pinhole failures, a new actuator was made using two layers of latex, each half the thickness of the tubing previously used. This was done in the hope that if one layer developed a failure, the other would remain functional and allow the actuator to continue operating. This actuator lasted 1650 cycles at 95 psi, and again suffered a pinhole failure of both layers in the same location.

Figure 4: Catastrophic mesh integrity failure

Analysis of the above actuator showed that failure occurred immediately below the location of the folded-over mesh (Figure 5A), suggesting that the loose polymer strands had been forced through the spandex (which in this region exhibited significantly more wear than other portions did) and eventually both layers of latex. To alleviate this problem, all subsequent actuators were constructed with an additional fold in the mesh and a weld to keep the ends well away from the bladder (Figure 5B). The first such actuator lasted 4150 cycles at 95 psi, but again suffered a double pinhole failure. This failure occurred along the seam-line of the spandex sheath, and was realized to be the result of the latex tubing adhering to the latex used to seal the spandex. This bonding had resulted in a significant stress increase that had caused the failure.

In the hopes of finding a less abrasive mesh, a variety of samples were procured from TechFlex of Sparta New Jersey, including a Kevlar mesh, one using single strands of PET (most meshes use groups of three strands) and one with the brand name Clean Cut®, which used a tighter weave of thinner strands. Although very smooth, the Kevlar did not offer much contraction, and was thus deemed unusable. The single strand mesh was too widely spaced, and the large spaces in between fibers would result in mesh failure. The Clean Cut® mesh however provided many attractive properties. The tighter braiding used resulted in a much more stable mesh with smaller openings that would lead to less abrasion of the latex core. Furthermore, the tighter mesh resulted in a more even pressure distribution around the latex, which would reduce the occurrence of failures due to stress concentrations. Although this mesh did not offer quite as large an expansion ratio (and thus it could not contract quite as far) as a standard one did, it was actually able to extend further when stressed. The result was an actuator capable of nearly the same stroke length of previous actuators.

The first Clean Cut® lasted 3000 cycles. Although not a significant improvement by any means, there were two important findings on the cadaver. First, failure was once again along the seam of the spandex sleeve. Second, both the spandex and the latex showed significantly less wear than previous actuators had.

Figure 5: A potentially damaging mesh end (A) and a much less abrasive one (B)

A

The next series of actuators produced did not have a spandex sleeve, but instead allowed the latex to contact the mesh directly. The first two of these actuators failed after 4700 and 2500 cycles respectively; in both cases, failure was due to an end plug separating from the clamp holding it in place. This failure was a result of the thinner braiding material used in the mesh coupled with the removal of the spandex. This produced an actuator with a smaller radius at its solid ends, and because the clamping force was a direct result of the compression of the ends, they were easier to blow out. However, in both cases the latex core showed very little abrasive damage. To increase the clamping force, a layer of latex was wrapped around the plugs, and the latex layer on the ends of the mesh was extended to cover the plugs (this provided significantly more friction under the clamping force, but had not previously been done because the clamps would not fit over the old mesh with an additional latex layer.) The actuator thus produced lasted 14700 cycles at ninety-five psi. Failure was a result of abrasion between the latex on the mesh and the bladder. The rest of the latex core still exhibited very little wear. Another actuator was produced without the latex layer at the ends, this one lasted 4200 cycles with a pinhole fracture forming at the end. This early failure was anticipated, as the ends are subjected to not only radial forces but axial as well, which increased the amount of wear significantly, but it did confirm the need for keeping latex on the actuator ends.

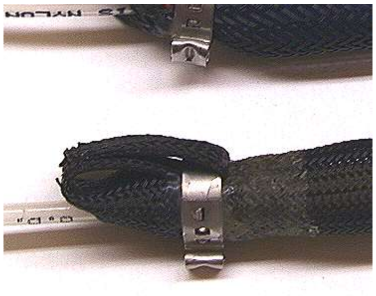
2.2 Results

The changes made to actuator design and manufacture throughout the course of this study have lead to a significant extension of actuator life, exceeding that predicted by theoretical models. Although a few specific changes served to produce the greatest increases, almost every modification attempted had some impact on the fatigue life of these devices. A summary of actuator types and lifetimes clearly demonstrates the effectiveness of each change made (Figure 6).

The success of the actuators constructed using the Clean Cut® mesh lead to a more in depth fatigue analysis of these devices. A total of four actuators were tested in an attempt to better characterize their lifetime and associated standard deviation. These actuators lasted an average of 14,000 cycles, and exhibited a standard deviation from this value of 1,400.

B

Figure 6: Fatigue life and cause of actuator failure.



This testing process did not carry a great deal of statistical backing, but was intended to serve as a benchmarking process for extending the life of these actuators. It is within reasonable limits to expect that material and manufacturing characteristics did not change significantly between actuators, and that the resulting data can be used as a rough mean. This leads to many conclusions. First, the spandex sleeve does seem to benefit the actuator's fatigue life to a limited extent—as long as there are other failure mechanisms present, the spandex does protect the latex from some damage. This is because the spandex not only bears some of the load that the latex would otherwise experience, but it also prevents the latex from being pinched between the fibers of the mesh. For any actuator that is expected to last a significant time however, either the spandex must be removed or a seamless protective sheath must be developed. Second, prestressing the actuator increases the actuators' robustness. Prestressing allows the mesh to wholly reform between cycles, adding to its integrity and once again preventing the latex from being pinched by the mesh fibers. It should be noted however that too much prestressing also leads to mesh failures, as the mesh is compressed too far, and it once again looses its integrity. Third, and probably most important, is the significant role that the mesh itself plays in the fatigue of the actuators. There can be little doubt that the change to the more tightly woven Clean Cut® mesh has to this point been the most critical element in extending actuator life. The tighter weave of this mesh produces significantly less wear on the latex core, ultimately extending the lifetime of the actuator by nearly an order of magnitude.

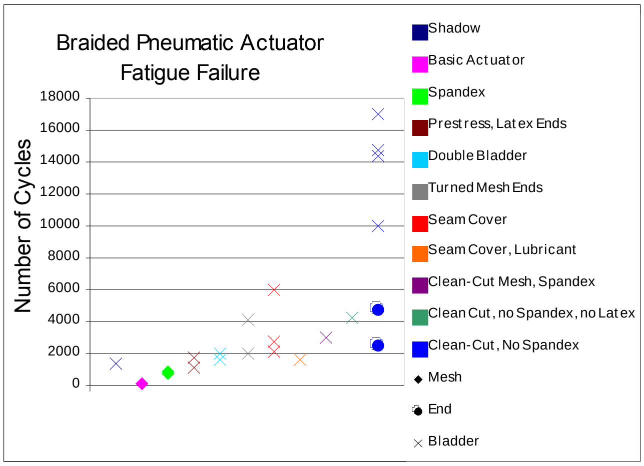
On a final note, it should be said that the fatigue tests to which these actuators were exposed are in the extreme of any conditions that would be seen in normal operation. Not only do the rapid changes between pressure extremes cause severe dynamic loading, but the use of a square wave instead of a gentler sinusoid or even sawtooth wave undoubtedly had a detrimental effect on the actuators. It should be understood that in normal operation much smaller pressure differentials as well as smoother loading conditions should be anticipated, which can be expected to result in extended fatigue lives.

3.1 Frequency Response

To test the frequency response of these actuators, a simple rig was constructed to allow measurement of stroke length. This consisted of a low friction slider that an actuator could pull along an extruded Aluminum track. A pen that marked the actuator's stroke on a stationary piece of paper was attached to the slider (Figure 7). The total weight of the slider was 5.01 pounds. This test could have been performed without the slider, but it would have resulted in motion in directions other than that in which the actuator was pulling; the directional constraint provided by the slider was deemed far more advantageous than any frictional losses incurred.

Figure 7: Frequency response rig

For these tests an actuator manufactured as described above was used. This actuator had a working length (length capable of expansion, measured from clamp edge to clamp edge) of 2.67 inches when statically supporting the slider at atmospheric pressure (this is effectively the rest length of the actuator) and a length of 2.01 inches at 95 psi while supporting the slider. The valve controlling the actuator was given an input of square waves with frequencies ranging from one tenth of a Hertz to five Hertz. Although a different type of signal could have been used, such as a sinusoid, the results would have been the same, as the solenoid valve controlling air flow has a binary state of either open or closed; a sinusoid would have caused the valve to open when it surpassed the threshold voltage for activation, and close when the signal again dropped below that voltage. To actually achieve a sinusoidal activation, a



controller implementing either pulse width or pulse frequency modulation would have been required. Tests were performed at a supply pressure of 95 psi. Transients were allowed to settle out of the system before data were taken.

Traces of the stroke length were measured using a pair of calipers; in most cases the maximum length was well defined, but a level of noise was present at minimum length as the slider bounced slightly. However, in this situation, the vast majority of deviation seemed to be perpendicular to the direction of actuator force, and as a result a consistent minimum length could still be determined.

The previous test was then repeated with an additional five pound weight attached to the slider, for a total weight of 10.01 pounds. This caused the actuator to extend to a rest length of 2.77 inches, while contracting to 2.03 inches when fully pressurized.

Because braided pneumatic actuators must be used in opposing pairs, a third test was performed in which another actuator was mounted below the rig. This actuator was activated opposite the first, forcing the slider down when the pressure in the upper actuator was released. This test was more reflective of normal operation of a braided pneumatic actuator driven joint. The lifting actuator, which was the only one used in the previous tests, had a length of 2.07 inches when fully activated and 2.78 inches when the opposing actuator was fully activated. Note that this greater length when fully activated was due to the opposing force generated by the second actuator, which at this point was being stretched to its limit.

3.2 Results

The position data from the stylus were used to produce plots of actuator strain versus frequency. In the case of the third test, in which two actuators were used, strain was measured relative to the lifting actuator, which had been used exclusively in the other two tests. In all cases, at high frequencies the actuators were capable of fully inflating, and incapable of fully deflating. As can be seen from the plots (Figures 8-10) a larger opposing force—either a weight or opposing actuator—increases the frequency range over which an actuator can produce useful contractions. In large part this is due to the opposing force causing the actuator to extend, which in turn forces air out through the release valve. It is this valve that limits the speed of the actuator, for although it has an activation time of a few milliseconds its orifices are small and impede the flow of the exhausting air. This is not as evident during activation of the actuator because of the large reservoir of pressurized air available. The exhaust phase, however, depends solely on the pressurized air contained in the actuator, and as the pressure begins to drop so does the force motivating the exhaust.

Use of opposing pairs of braided pneumatic actuators provides the added benefit that these devices are capable of slightly higher frequency operation in this configuration. Although the amplitude drop-off of all tests began at about two Hertz, the slope of the opposing pair configuration was significantly less, allowing operation over a limited range of motion at higher frequencies. However, even in this case, operation above roughly three Hertz will still significantly reduce the range of motion available. This is not foreseen to be a major impediment to the use of these actuators in robotics, as most walking speeds will likely remain within this viable range.

Perhaps not surprisingly, this performance characteristic of the braided pneumatic actuators is fairly consistent with actual muscle. Research points to a cut-off frequency of human muscle in the range of 1.7 to 3 Hz (Brerton and McGill, 1998). Given the variation in muscle properties due to muscle specialization and between individuals, a tighter range would probably only be discernable for specific muscles. Regardless, and although the mechanisms responsible for this frequency response are quite different, the result is that braided pneumatic actuators can be expected to operate effectively across a range of frequencies very close to that of human muscle. Although insects are capable of much higher frequency motion, simple scaling laws tell us that a robot, such as Robot III, which is seventeen times larger than the insect on which it is based, should only be able to move at a frequency one fourth that of its biological counterpart. Likewise, smaller actuators

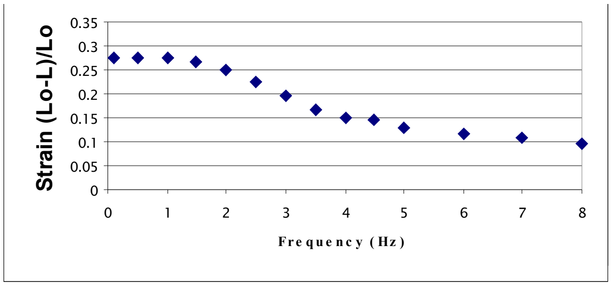
Figure 9: Frequency response of a single actuator lifting a 10.01 lb. slider and weight.

should be able to operate faster, as they contain less air than larger ones (White, 1994).

4. Conclusions

This work explored the viability of the use of braided pneumatic actuators in the design of what will eventually be mission capable robots. The first, and most important, goal of this work was to develop a manufacturing process by which the fatigue life of these actuators could be extended to a useful limit. The order of magnitude increase that was accomplished, and the fact that the failure mechanism is known, strongly indicate that these devices can be used as a practical means of locomotion. The frequency response of the McKibben muscles is already within a range suitable for many robotics applications, and a reduction in actuator core volume, could not only produce actuators capable of faster cycle times by reducing the amount of air that must be exhausted, but ones that use less air during operation as well. This in turn will improve overall robot efficiency and extend mission time.

Figure 10: Frequency response of an opposing pair of actuators.



References

Bachmann, R.J. (2000) A Cockroach-Like Hexapod Robot for Running and Climbing. M.S. Thesis, CWRU.

Bachmann, R. J., Nelson, G. M., Quinn, R. D., Watson, J., Ritzmann, R. E. "Design of a Cockroach-like Robot, Proceedings of the 11th VPI&SU Symposium on Structural Dynamics and Control, May 12-14, 1997.

Binnard, M.B. (1995) Design of a Small Pneumatic Walking Robot. M.S. Thesis, M.I.T.

Brerton, L.C. and McGill, S.M (1998). Frequency Response of Spine Extensors During Rapid Isometric Contractions: Effect of Muscle Length and Tension. Proceedings of the 1998 North American Congress on Biomechanics.

Caldwell, D.G, Medrano-Cerda, G.A., and Bowler C.J. “Investigation of Bipedal Robot Locomotion Using Pneumatic Muscle Actuators” . IEEE International Conference on Robotics and Automation (ICRA'97), Albuquerque, NM.

Chou, C.P., B. Hannaford, “Measurement and Modeling of McKibben Pneumatic Artificial Muscles,” *“IEEE Transactions on Robotics and Automatio*n,” Vol. 12, No. 1, pp. 90-102, Feb 1996.

Colbrunn, R.W. (2000) Design and Control of a Robotic Leg with Braided Pneumatic Actuators M.S. Thesis, CWRU.

Klute, G.K., B. Hannaford, (1998). Fatigue Characteristics of McKibben Artificial Muscle Actuators. Proc. Of IROS 1998, Victoria B.C. Canada, pp. 1776-82.

Klute, G.K., B. Hannaford, “Modeling Pneumatic McKibben Artificial Muscle Actuators: Approaches and Experimental Results,” Submitted to the ASME Journal of Dynamic Systems, Measurements, and Control, November 1998, revised March 1999.

White, F.M. *Fluid Mechanics* McGraw Hill, New York, 1994.