Quantifying Viscoelastic Properties of Nylon-6,6 Actuators

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Abstract: Orthostatic Hypotension (OH) is a prevalent condition affecting 52.1% of stroke patients, characterized by a drop in atrial blood pressure upon standing. This is due to the pooling of blood in the abdomen and leg, and OH results in debilitating symptoms of nausea, lightheadedness, and dizziness. Current management techniques are limited and not very effective, so I propose an active, compression abdominal band that contracts when needed. This device should have a minimal design, so nylon-6,6 actuators, powerful artificial muscles created from fishing line and conductive thread, were chosen as the compressive element. Given that previous research focused on strength and force-excursion characteristics of these actuators, this study focuses on determining their viability for this application by conducting stress-relaxation and creep tests on single actuators (sample sizes of 10) and on a forty actuator band. Stress-relaxation results indicate that actuators will be able to maintain tension levels required effective compression 18 times as long as necessary. Creep testing is inconclusive due to oscillations found in the data as a result of low processing power of the Instron machine used to conduct tests. Despite the fact that more tests need to be conducted to resolve various limitations of this study, I conclude that I can move forward to create a prototype of the abdominal band.

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ACKNOWLEDGEMENTS

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Thanks to Javier, who approached Dr. Sulzer for this device, and to Sean Brocklehurst and Krista Niklaus who first had the idea of using fishing line actuators for this purpose. Finally, I would also like to thank ETC building manager Ricardo Palacios, ETC technical staff assistant Mark Phillips, and staff at UT Austin’s Longhorn Maker Studio for helping me with various equipment I needed to use. I appreciate all of your help; thank you!

BACKGROUND AND MOTIVATION

Orthostatic Hypotension

Orthostatic hypotension (OH) is diagnosed as a persistent systolic over diastolic blood pressure decrease of 20 over 10 mmHg, respectively, upon standing, and it occurs in more than thirty percent of people over the age of 70 [1]. Although small decreases in blood pressure after standing are common and largely asymptomatic, chronic OH can cause serious nausea, fatigue, lightheadedness, dizziness, visual blurring, and even syncope (fainting) [1]. This is especially true for immobilized or hemiparalyzed patients – 52.1% of stroke patients experience OH, according to a study conducted by researchers in Singapore [2]. Furthermore, OH increases the incidence of stroke, heart failure, atrial fibrillation, and myocardial infarction, while complicating treatment for these conditions and for hypertension [1].

OH is caused by the failure of autonomic cardiovascular adaptive mechanisms to compensate for the decrease in venous return (rate of blood flow back to the heart) that occurs when standing up after sitting or lying down for long periods of time [1]. Blood flow usually returns to normal after respiration, venous valves, and the contraction of lower limb muscles force blood back up to the right atrium. Because stroke patients with loss of lower limb function cannot effectively increase venous return automatically, their blood often pools in the veins of the abdomen and lower limbs, which are areas of low venous pressure [3]. As a result, they often suffer from long periods of lightheadedness and dizziness from decreased blood pressure. Another, more short-term, cause of OH is eating; blood often pools in abdominal arteries and veins to aid digestion after large meals [3]. This can also result in a significantly lower venous return and therefore lower atrial blood pressure.

Current management methods are limited and mainly include lifestyle changes and compression garments. Patients are usually warned to stand up slowly or carefully and to avoid bending at the waist [3]. Doctors also often prescribe various stretches to encourage blood flow to the heart and upper body [3]. Unfortunately, these methods are not always effective and are often not practical for patients with limited motor function. Another common management technique is compression stocking or abdominal binders. During application of these garments, the resulting pressure applied to the lower limbs and/or the abdomen forces blood back up to the heart [3]. However, studies published in the academic journal *Age and Ageing,* which is devoted to geriatric medicine research, indicate that the level of non-compliance for elastic compressive stockings is a significant problem that impedes effective OH management [4]. Out of 90 surveyed subjects with chronic OH, 51% reported difficulty when putting on compressive stockings, 31% reported discomfort while wearing them, and 43% never even used them, despite being prescribed by a physician to wear them daily [4].

Even if patients do comply and wear compression stockings often, recent research suggests that they are not as effective as previously thought. Out of 28 OH patients who had either calf or thigh compression, 18 (64%) reported no change, mildly worse, or moderately worse symptoms [5]. In fact, abdominal compression has been proven to be significantly better (p-value < 0.001) than calf, thigh, and calf + thigh compression at mitigating orthostatic hypotension, according to a team of researchers at the University of Pittsburgh [5]. This is because abdominal venous capacitance is much higher than that of lower limb veins. Significantly more blood pools in the abdomen, because abdominal venous and capillary volume is larger than that of the legs [5]. Smit et al. have shown that abdominal compression of 20 mmHg for five minutes increases standing systolic/diastolic pressure by 15/6 mmHg, significantly mitigating OH symptoms [6]. In fact, this applied pressure is very similar to those generated by antigravity suits (G-suits) worn by aviators and astronauts to prevent blacking out (due to blood pooling in the lower body at high levels of acceleration) [6]. Smit et al. actually used G-suits as the therapeutic device in their study.

Motivation for a Proposed Device

Although these suits are very effective at mitigating OH, they are not practical for daily wear. Most G-suits consist of five large air bladders: one around the abdomen, one on the front of each thigh, and one on the side of each calf [7]. There is a large valve and hose to inflate the suit, which can be done manually, though it is tedious. The suits are bulky, expensive, and difficult to use every day [7]. Of course, just an abdominal band with an air bladder would be sufficient to alleviate orthostatic hypotension, but it would have to be worn throughout the whole day, over the user's clothes. Slim, passive abdominal binders exist on the market already; they are rarely used because constant pressure around the stomach is not comfortable [4]. Furthermore, because passive garments do not apply pressure when symptoms are felt or atrial blood pressure starts to drop, they are poor methods to manage OH [4].

Javier Corona, an orthostatic hypotension patient, approached my supervising professor for a solution to this problem. He is hemiparalyzed, and suffers from lightheadedness, dizziness, and nausea for several hours throughout the day. To ameliorate these symptoms, he leans forward in his wheelchair, but this is not very effective. He asked for an easily applied compression garment that he can wear under his clothes. Thus, for my thesis, I focus on a minimal, active abdominal band that applies pressure only when the user is feeling symptoms of OH, the optimal solution to this problem. For a slim design, a small or thin compressive element is necessary.

Due to recent research advances in flexible, artificial muscles, I focus on polymer-based shape-memory alloy actuators, specifically nylon-6,6 actuators.

Nylon-6,6 Actuators and Other Alternatives

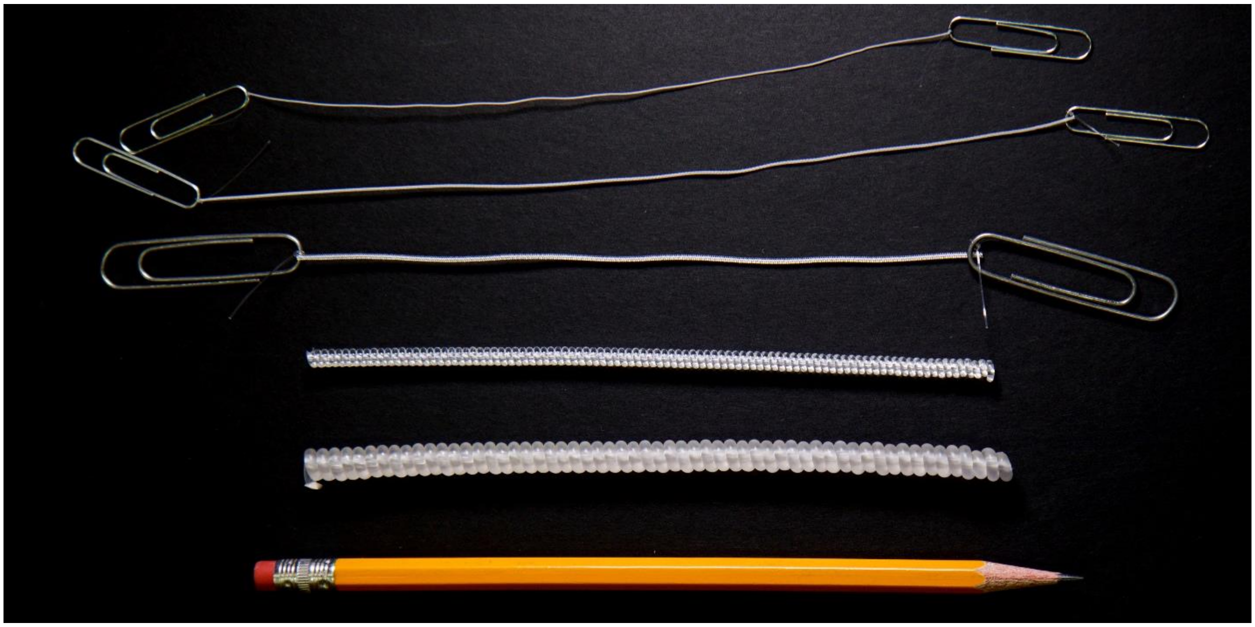

Figure 1 *Nylon-6,6 actuators made from fishing lines of different sizes. [8]*

Nylon-6,6 is a common polymer consisting of repeating segments with twelve carbon atoms and two amide groups [9]. It exhibits high tensile strength and is used as fishing line, rope, air bags, and carpets [9]. High levels of twist insertion followed by annealing transforms nylon-6,6 monofilament (e.g. fishing line) into coiled muscles (see ***Figure 1)*** [9]. Running conductive thread through the actuator results in an even distribution of electricity. Applied current heats the fiber, causing the coil to twist slightly and contract, allowing small amount of work in the form of tension to be extracted from very low voltages (approximately three volts) [9]. Dr. Ray Baughman and his research team at the University of Texas at Dallas have done considerable research quantifying nylon-6,6 actuators' strength and various material properties, describing their results in a paper published in *Science*:

> "Extreme twisting produces coiled muscles that can contract by 49%, lift loads over 100 times heavier than can human muscle of the same length and weight, and generate 5.3 kilowatts of mechanical work per kilogram of muscle weight, similar to that produced by a jet engine." [9]

Nylon itself provides several important material properties that contribute to the impressive strength of these actuators [9]. Its size and volume change significantly with a change in temperature, making it capable of reversible thermal contraction and high levels of volumetric thermal expansion [9]. This effect is magnified when polymer chains are aligned in the same direction, since conformational strains are minimized [9].

Other shape-memory materials, such as carbon nanotube fibers or nitinol, a nickel titanium alloy, could also be used as the compressive element of the device, but they have significant limitations. Carbon nanotube fibers are usually composed of a 'guest,' usually paraffin wax, added to twist-spun carbon nanotube yarn. When placed in an electrolyte and electrically stimulated, the muscles contract by less than 2% but exhibit stress up to 26 MPa, one hundred times that possible by natural muscles [10]. Although this strength is promising, they are expensive due to the high cost of carbon nanotube yarn [10]. Because this project requires large numbers of actuators to generate abdominal compression, using carbon nanotube actuators is simply not practical. Immersing actuators in electrolyte is also not possible. Another alternative, nitinol can undergo deformation at one temperature and return to its original shape after being heated above its transformation temperature [9]. Just above this temperature, nitinol is very elastic and can undergo high amounts of reversible deformation [9]. Despite having very useful properties, nitinol is rarely used, because of significant costs associated with production [9]. It is also not as strong as nylon -- nylon-6,6 coils actually provide levels of contraction against larger applied stresses than nitinol [9]. They exhibit little or no inherent hysteresis unlike nitinol coils, which make them well suited for this application [9].

Testing

Before building and testing a prototype of the active abdominal band, it is necessary to ensure that nylon-6,6 actuators are strong enough for this application. Previous research on nylon-6,6 actuators has focused on its strength and force-excursion characteristics (as shown above in the discussion of the UT Dallas research team's work), but not on its long-term material properties. Thus, we know that nylon-6,6 coils are capable of producing the tensions needed to produce 20-30 mmHg of compression, but not if they can deliver this load over long periods of time. This information is crucial to determine the appropriateness of nylon-6,6 actuators for this application, since users will wear the abdominal band throughout the day and activate compression several times. Thus, my thesis focusses on obtaining this data; I identify two key viscoelastic to determine nylon-6,6 actuators' suitability: stress-relaxation and creep.

Stress-relaxation is the exponential decrease in stress (tension exerted on an object) seen when a constant level of strain (deformation) is applied (see ***Figure 2a***). This is important to test because the coils need to be stretched around the abdomen and contract several times, so they must not lose their compressive ability over time. If the measured relationship between stress and time indicates that the stress decreases to below the threshold force required for the abdominal band, then nylon-6,6 actuators cannot be used and another compressive element must be found. The other side of the coin, creep is the exponential increase in strain when a constant level of stress is applied (see ***Figure 2b***). Lengthening of actuators over time will decrease the amount of force they can produce, so it is crucial to ensure sure that they do not stretch and unwind under tension. Often material sciences studies will also measure creep recovery, or how the material returns to its original length after force is removed. This information is not needed to determine suitability for this application, so creep recovery data is not collected for this study. Hysteresis was also not measured because the UT Dallas team has already determined that nylon-6,6 actuators exhibit very low hysteresis.

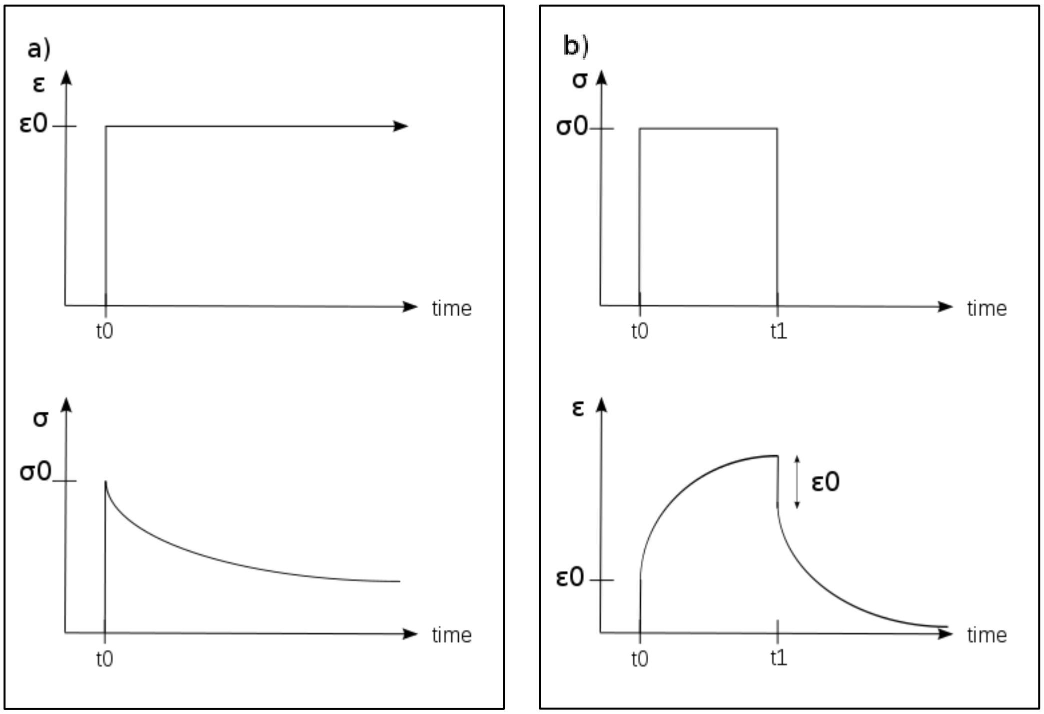

Figure 2a *depicts stress-relaxation characteristics: an exponential decrease in stress over time (bottom graph) due to a constant applied strain (top graph). [11]*
Figure 2b *depicts creep characteristics: an exponential increase in strain over time (bottom graph) due to a constant applied stress (top graph). Creep recovery data (decrease in strain after t1) was not important for this application, so this was not measured. [12]*

METHODS

Basic Device Design

Determining thresholds of stress and strain that need to be met during testing necessitates calculating the number of actuators needed for the abdominal band and force required per actuator. This can easily be done by finding various parameters, such as applied pressure, waist radius, thickness of actuators, etc. and plugging them into the thin-walled hoop stress formula.

Because waist diameter is more than twenty times the radius of the nylon coil, the thin-walled assumption is valid, simplifying calculations. The clinical standard for compression around the abdomen to mitigate the symptoms of OH is 20-30 mmHg, and the average waist circumference of an adult man is 100 cm [6]. Using the following thin-walled hoop stress formula,

$$F = \frac{PrA_c}{t}$$

where P is pressure (20-30mmHg), r is radius of the band, t is radial thickness of the band, and A_c is the cross-sectional area, the band needs to produce 38-55N of force. Given that one actuator can apply at least one newton, the abdominal band should comprise about forty meter-long actuators in parallel. Configurations of actuators other than in parallel could be used, but to simplify tension, stress, and strain calculations, only parallel actuators were considered.

Actuator Production

Actuator production involves two main steps: twist insertion (coiling) and annealing. Basic methods were given in a *Science Friday* article by the UT Dallas team. For this study, twist insertion and coil construction were originally conducted using a DEWALT 20-volt power drill, which was attached to one end of nylon-6,6 monofilament with a paper clip. The other end was connected to a weight that maintained tension in the line to prevent the formation of negative supercoils. Negative supercoils occur if the line is slack to compensate for applied stresses during twist insertion; they are often seen when DNA polymerase unwinds DNA. It is important to prevent negative supercoils because it is difficult to undo them without inducing so much tension in other parts of the line that it snaps. At a max rpm of 2500, it took 30 minutes to produce an actuator one meter long from 20ft (approximately 6m) of fishing line. But, meter-long actuators made using this method were uneven, full of kinks and varying diameters, so it would often take upwards of an hour to produce one even coil. Any kinks or uneven coiling significantly reduce the strength of the actuator and increase the probability of it unwinding under stress. Sample sizes of ten for both creep and stress-relaxation would require almost a whole day to just twist the actuators. Conducting tests on a band of 40 actuators would be near impossible.

Therefore, to have sample sizes large enough and samples even enough to conduct statistical analyses, automating actuator production was necessary. There were three important considerations when making this device: (1) the motor must move forward as the length of the filament decreases due to coiling, (2) the tension in the line must be maintained (high enough that no negative supercoils form, but low enough to prevent snapping or damage to the motor), and (3) the coil must not be able to unwind, so all parts need to be tightly attached or weighed down. The final product of this step is a 20ft x 1ft x 1ft wooden device that produces one high quality actuator every ten minutes or so, as shown as a simplified SOLIDWORKS model in ***Figure 3***.

Figure 3 *Automated Actuator Production Device*

The device consists of a 12V high-torque motor with a max speed of 12,000 rpm secured to a platform (see ***Figure 4a***). Paper clips were attached to both ends of twenty feet of fishing line, one paper clip hooked to the motor (see ***Figure 4b***), and the other to a hook screwed into a stationary headboard, as shown in ***Figure 4c***. As the motor spins, the twisted line gets shorter, pulling the platform toward the headboard, guided by the rails. The weight of the platform and friction prevent it from moving forward too quickly, which would cause unwanted supercoils to form. The rails and the platform serve to increase the evenness of the produced actuator and prevent unwinding, since twist insertion and coil formation always remain perfectly horizontal and level. Eventually, a coil starts to form on one or both sides of the line, as depicted in ***Figure 4c***, and grows to encompass the whole filament. The actuator can be easily removed with the paper clips, the platform reset to its original spot, and a new actuator can be created. Using this device, 80 actuators were produced for this study.

Figure 4a

Figure 4b

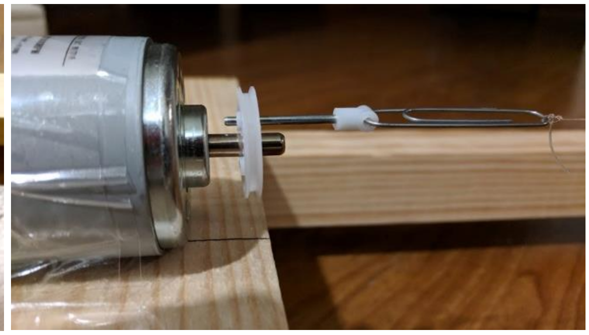

Figure 4c

Figure 4a *shows the platform with the motor and associated circuitry.*

Figure 4b *depicts fishing line attached to the motor with a paper clip.*

Figure 4c *shows the formation of a coil attached to the hook in the headboard with a paper clip.*

The next process in creating working actuators is annealing, or slow heating to a temperature below the melting temperature of the polymer (300°F for nylon-6,6) and slow cooling back to room temperature. After actuators are removed from the device discussed above, they twist rapidly in the opposite direction of the coiling for a couple hours, then more slowly for a week. Annealing prevents excessive unwinding of the actuator and keeps it stable at high temperatures and high loads. Actuators were annealed in an Electra dual chamber heat treat furnace in the mechanical engineering machine shop, one of the few ovens on campus that was at least a meter long. Three cycles of heating to 150°F for 30 minutes and cooling down to room temperature were conducted. Multiple cycles are necessary to 'train' the artificial muscle, making room between the coils and stabilizing the actuator. Actuators had to be held at a slight level of tension while annealing to prevent bends or kinks from forming during the heating process.

Testing

After producing working actuators, tests could be conducted. As mentioned above, two main tests were conducted: stress-relaxation and creep. An Instron 3345 machine, as shown in ***Figure 5a***, owned by the biomedical engineering department was used to conduct these tests, because it provides significant capabilities. It measures extension and load every 0.1 seconds, so even an experiment protocol lasting just five minutes yields about 3,000 data points. Furthermore, constant strain, constant stress, extension rate, and length of the hold condition can be easily

Figure 5a

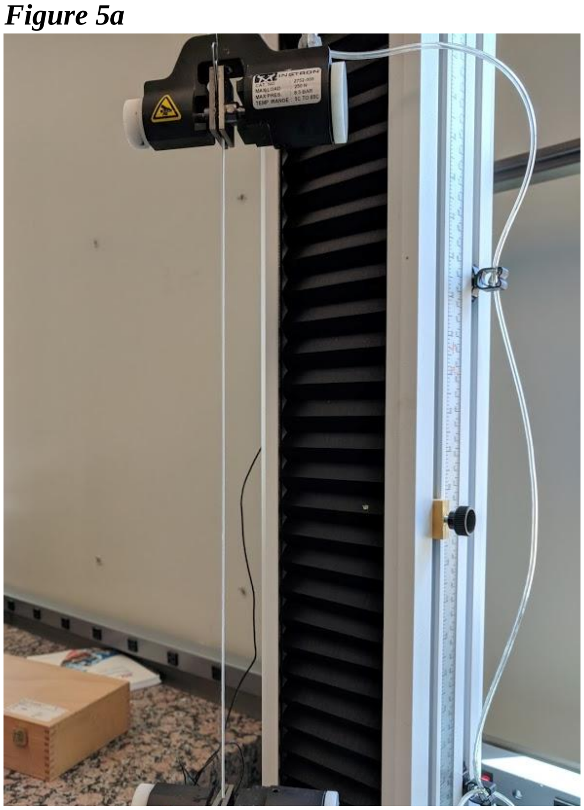

Figure 5b

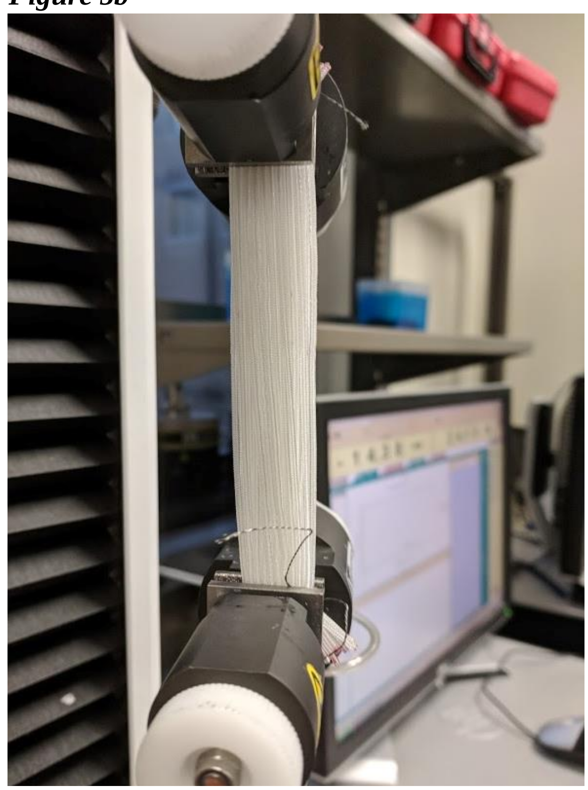

Figure 5a *shows a single actuator test conducted on the Instron 3345 machine.*
Figure 5b *shows a 40 actuator band test on the same machine.*

changed and saved. To determine extension and load hold conditions, pull-until-failure tests were conducted, and load and extension values in the middle of linear elastic regions were used.

For stress-relaxation tests, actuators were pulled in tension at a constant rate of 5 mm/sec until they reached strains of about 100%. They were held for five minutes, since Smit et al., who determined that abdominal compression returned blood pressure to normal levels after OH, applied pressures for five minutes. A sample size of ten was used for both tests. Creep tests were conducted with a hold condition of 4N, also for five minutes. Because the final device will consist of forty nylon-6,6 actuators, testing a band of 40 actuators (see ***Figure 5b***) was important. The band was stretched at a constant extension rate of 0.5 mm/sec and held at 23% extension for stress-relaxation testing and 40N for creep testing.

Statistical analysis was conducted in MATLAB using regression analysis, comparing creep and stress-relaxation behavior to the ideal generalized Maxwell model (also known as the Maxwell-Wiechert model) shown in ***Figure 6***. This model, like the standard linear model, the Kelvin-Voight model, and the Maxwell model, is comprised of springs, which represent elastic components in the material, and dashpots, which represent viscous components. Unlike the other

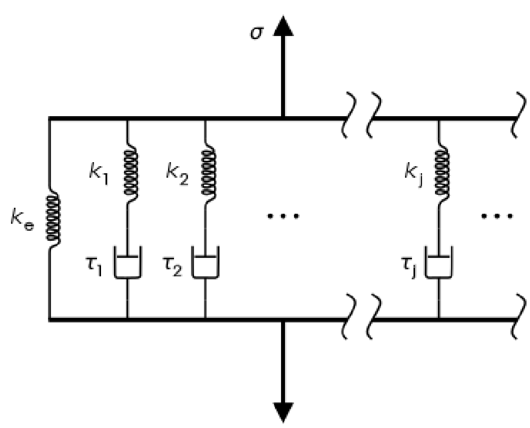

Figure 6 *The generalized Maxwell model has a spring in parallel with springs and dashpots in series. The total stress is the sum of the stresses of all parallel branches. The total strain is equal to the strain of each branch. [13]*

models, however, several dashpots and springs in series can be added in parallel, resulting in a more accurate prediction of short-term and long-term behaviors. Thus, the generalized Maxwell model takes into account that relaxation of both stress and strain occurs over varying time distributions.

Because the total stress is the sum of all of the branch stresses and total strain is equal to that of each branch, the differential equations relating stress, strain, and time can be solved to yield the following general solution:

$$\sigma(t)\ OR\ \varepsilon(t) = \sum_{k=1}^{n} C_k e^{-t/\tau_k}$$

The time constant τ_k for each term determines whether that term dominates short-term or long-term behavior. For example, if the time constant is a very large number, then the term approaches C_k very quickly as t approaches zero, so the other exponential terms must dominate short-term behavior.

RESULTS

Pull-until-failure Testing of Single Actuators

Although pull-until-failure is not one of the main tests conducted for this study, the data for this experiment provide useful information to characterize the strength of nylon-6,6 actuators. As shown in ***Figure** 7*, an actuator elastically deforms until very high levels of stress and strain. At 7N, the coil starts to pull apart and plastically deforms. This indicates that even when actuators are stretched to more than 2.6 times their original length, they can recover with minimal relaxation or damage done. This is a very promising result. Hold conditions of 4N for creep testing and 100% strain for stress-relaxation testing were chosen because they were in the middle of the linear elastic region of this graph.

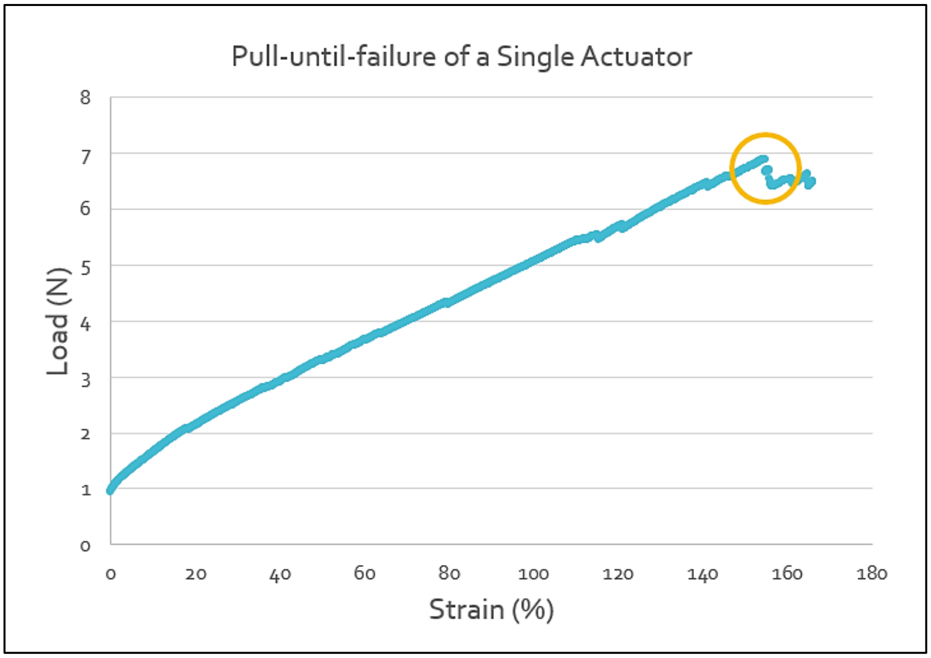

Figure 7 *depicts a pull-until-failure test of a single actuator. The coil unwound at 7N under 160% strain, shown with the orange circle in the figure.*

Stress-Relaxation Testing of Single Actuators

Stress-relaxation testing of single actuators yielded a linear increase in load or stress vs time during the constant extension rate phase to an average maximum of 4.8N, then an exponential decay of load or stress over time, as shown below in ***Figure 8a***. The average load at the end of the hold phase at 300 seconds is 3.7N. This is well above the 1N in compression that each actuator needs to be able to exert. Exponential regression analysis (***Figure 8b)*** conducted on these samples resulted in the following relationship between stress and time:

$$\sigma(t) \; = 1.978e^{-\frac{t}{18.9789}} + 12.61e^{-\frac{t}{4.1068\times 10^{3}}}$$

The time constant τ_c of the second term is relatively large, so this term tends toward 12.61 at small values of time. Therefore, the first term dominates short-term stress-relaxation behavior of nylon-6,6 actuators. The second term determines long-term behavior, or the relaxation at large values of *t*. The R^2 value of this relationship is 0.9869 – 98.69% of variance that exists in the data is explained by this regression equation. Based on this relationship, it would take more than

90 minutes of constant compression for actuators to become unable to produce one newton in tension. Practically, this should not occur.

Figure 8a

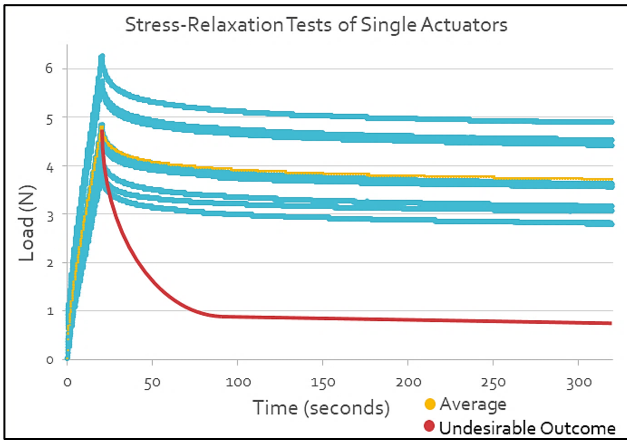

Figure 8b

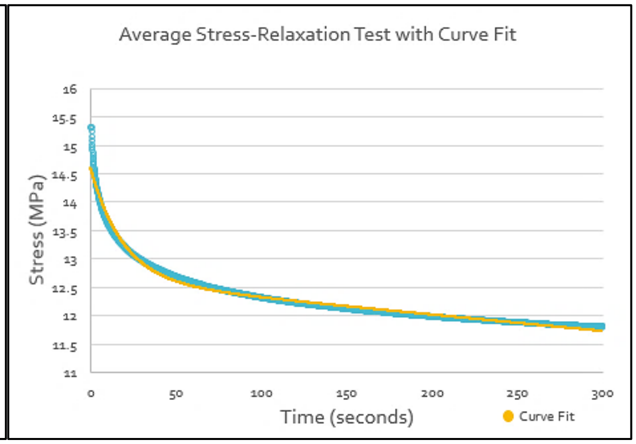

***Figure 8a** depicts the results of 10 stress-relaxation tests, with a linear region where actuators were stretched at a constant extension rate and an exponentially decreasing region. **Figure 8b** shows the curve fit of a two-term generalized Maxwell model.*

Creep Testing of Single Actuators

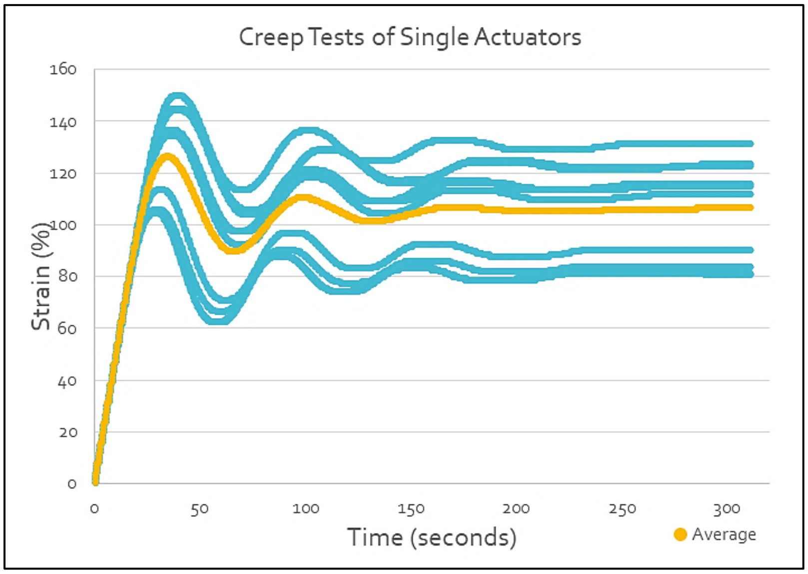

***Figure 9** depicts the results of creep testing on ten actuators. The orange line represents the average results. Clearly, the data oscillates over time, which is undesirable.*

Just like the stress-relaxation tests, the results of creep tests show a linear increase in strain as a function of time during the constant extension rate period. However, instead of exponentially increasing after load is held constant, strain oscillates for approximately 150 seconds before slightly increasing for the last 100 seconds of the hold condition (see ***Figure 9***). This is because the load is held perfectly constant – the data indicate that strain also oscillated over time, as shown in ***Figure 10***.

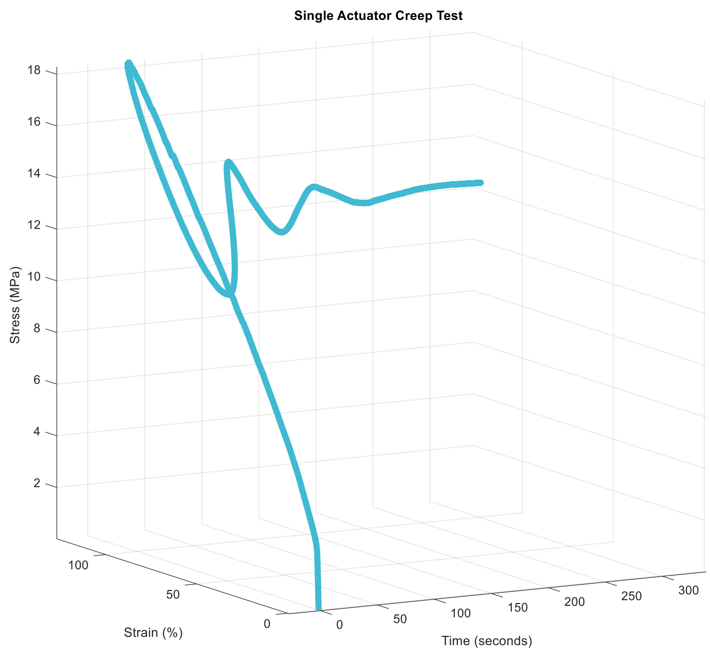

Figure 10 *depicts the oscillations in both stress and strain as a function of time. This is due to the limitation of the Instron machine.*

However, it is still useful to obtain a best-fit curve that provides some information about creep behavior of these actuators. Therefore, regression analysis (***Figure 11***) was conducted on the last one hundred seconds of data, after the oscillating decreased and the data seem to become stable, yielding the following equation for strain as a function of time:

$$\varepsilon(t) = 105.7e^{t/2.4576\times10^3} - 1.328e^{-t/38.8802}$$

This relationship is also defined by two terms; the second determines short-term creep behavior, and the first determines long-term behavior. Despite the low resolution of the data and selecting only the last one hundred seconds, this relationship is actually fairly strong. The R^2 value is 0.9971, even better than that of the stress-relaxation testing discussed above.

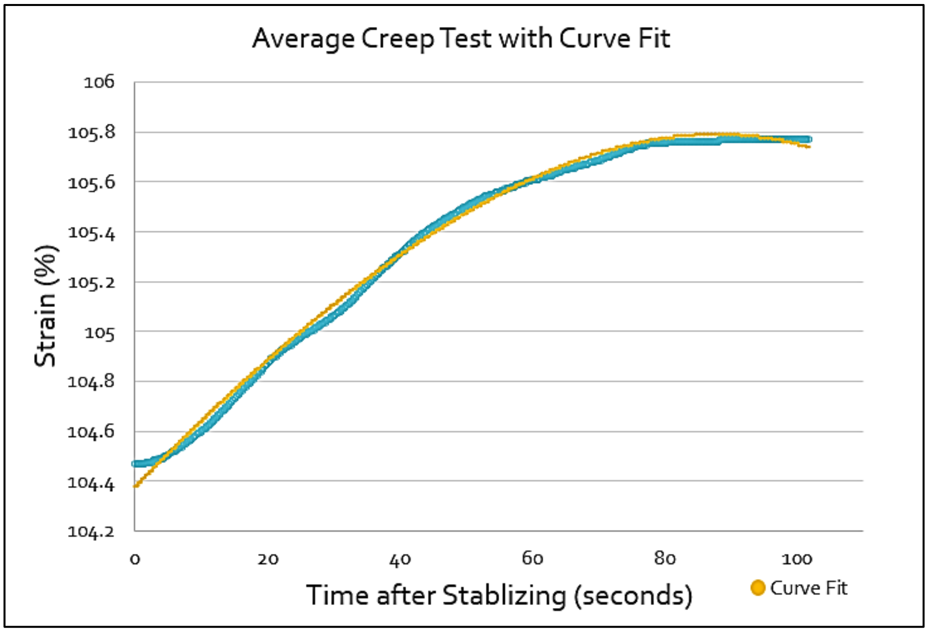

***Figure 11** depicts the last one hundred seconds of creep data with the generalized Maxwell model fit, using regression analysis.*

Normally, the generalized form of this equation for creep behavior is given by

$$\varepsilon(t) = 1 - \sum_{k=1}^{j} C_k e^{-t/\tau_k}$$

rather than the mere summation of two exponential terms. This is due to strain increasing very quickly at small values of *t*, but more slowly as time increases. Unfornately, the regression analysis solver in MATLAB could not converge on a solution of this form, resulting in the equation given above.

Pull-until-failure Testing of 40 Actuator Band

The strength of nylon-6,6 actuators connected in parallel was confirmed by the results of the pull-until-failure testing of a 40 actuator band. The band elastically deformed until 80N, at which point the test had to be stopped to protect the Instron machine's load cell, as depicted in ***Figure 12***. This indicates that the yield strength of the band is probably above 100N, confirming again that these actuators have enough compressive ability for this application.

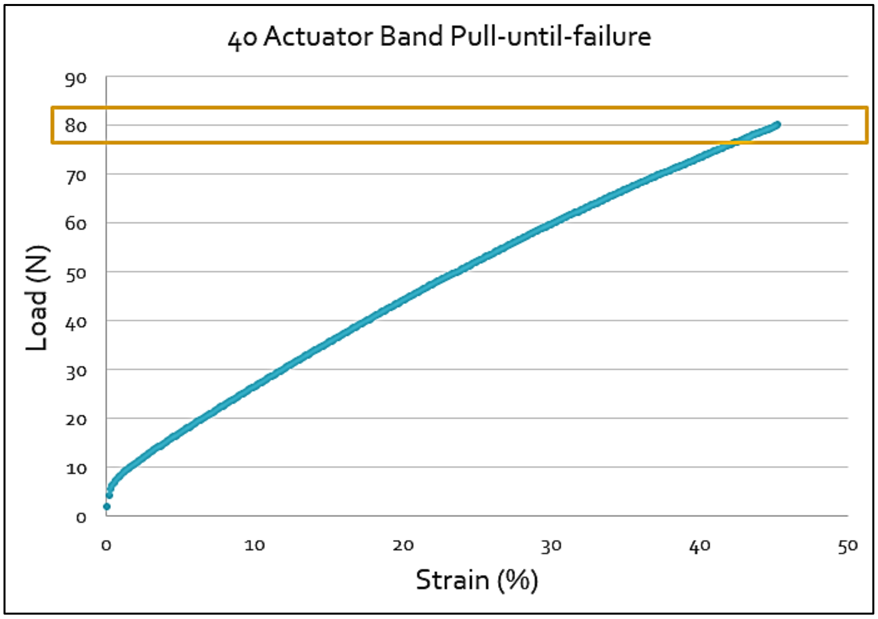

Figure 12 *depicts the pull-until-failure test of the 40 actuator band. The orange box represents the limit of the load cell.*

Stress-Relaxation Testing of 40 Actuator Band

The stress-relaxation characteristics of the 40 actuator band closely resemble that of single actuators, but the max stress is only 6.53MPa. This is because the strain hold condition was 23%, much lower than the 100% for the single actuator tests, to protect the load cell of the Instron. After five minutes of holding at that strain, the measured load was 43N, well above the minimum of 38N needed to apply 20mmHg of pressure around the abdomen. The regression curve for stress as a function of time is given by:

$$\sigma(t) = 0.9167e^{-t/21.7637} + 5.62e^{-t/3.8314\times10^3}$$

Just like the single actuator tests of both creep and stress-relaxation, this relationship has two terms that determine the short-term (term 1) and the long-term (term 2) stress-relaxation characteristics of the band. This regression analysis, shown in ***Figure 13***, is also fairly accurate, with a R^2 value of 0.9888. 98.88% of the variance in the data is explained by this function.

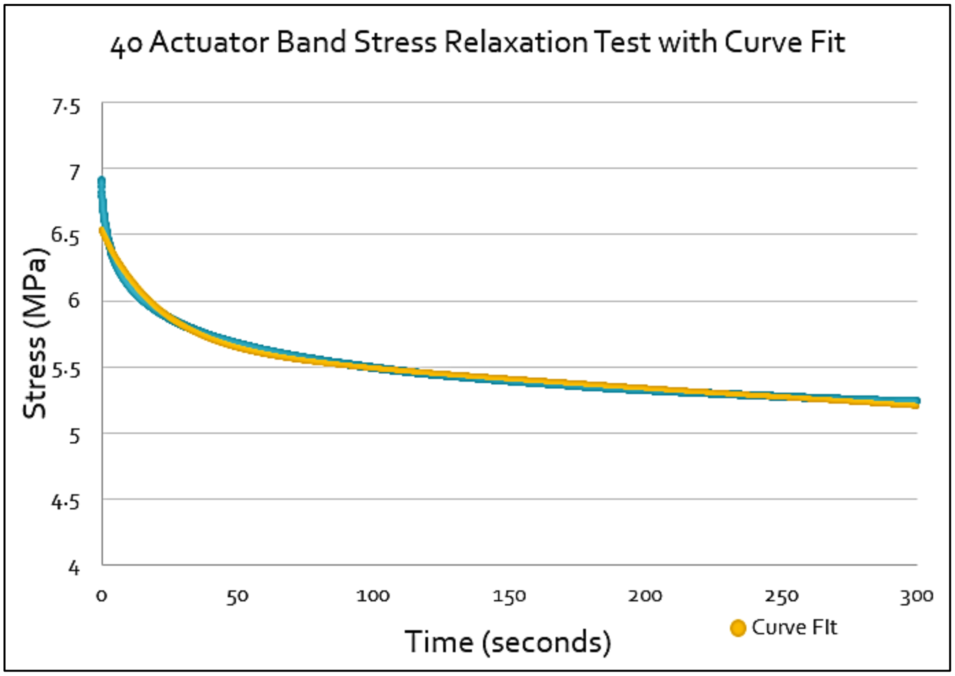

Figure 13 *depicts the stress-relaxation test of the 40 actuator band with the generalized Maxwell model fit (orange line).*

Creep Testing of 40 Actuator Band

Finally, creep testing of the 40 actuator band showed similar concerns as the results for the single actuator tests. Both stress and strain oscillate over time, but using only the last 250 seconds, a regression equation with two terms (like results mentioned) above was calculated:

$$\varepsilon(t) = 23.06e^{t/6.6050\times10^3} - 0.6944e^{-t/38.8802}$$

The R^2 value is 0.9928, so this relationship is fairly strong, though of course this only applies to the last couple hundred seconds. ***Figure 14*** clearly shows the exponential characteristic overlaying oscillations in the data. This specific experiment needs to be repeated with a different testing set-up to obtain high resolution data that encompasses all 500 seconds of data.

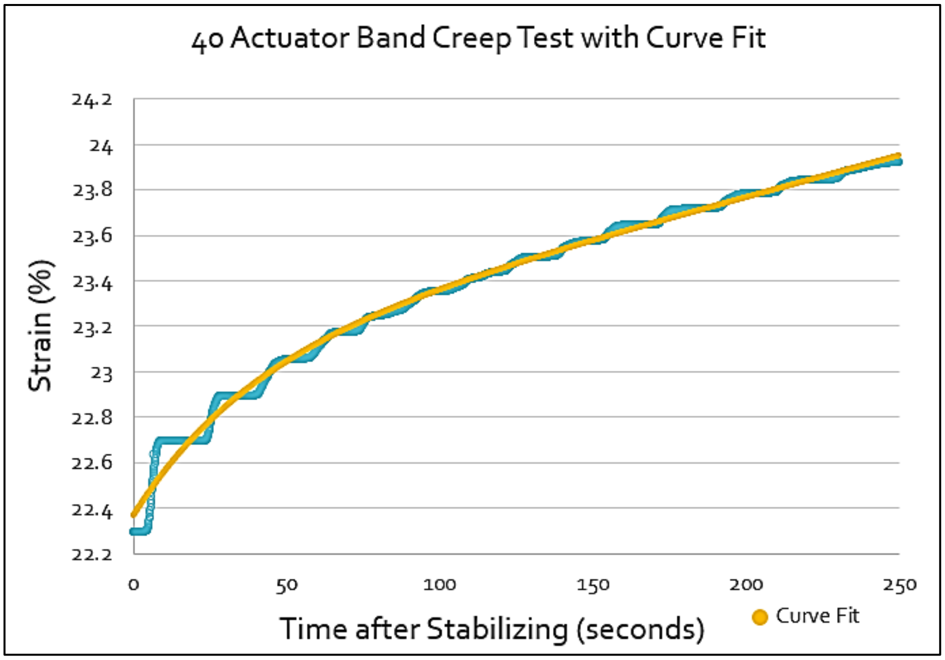

Figure 14 *depicts the creep behavior of the 40 actuator band, specifically the last 250 seconds of data. The oscillations in strain can be seen clearly, but the generalized Maxwell model fit is fairly strong.*

DISCUSSION

Summary and Meaning of Results

Based on the high-resolution stress-relaxation data, nylon-6,6 actuators are robust enough for the intended application. Stress values remained well above the one Newton that each actuator has to apply to generate at least 20mmHg of abdominal compression. In fact, it would take more than 90 minutes of continuous compression for an actuator to relax to below 1N, which should not ever occur. The 40 actuator band also stayed above the minimum threshold of 38N for compression. Given that nylon-6,6 withstands high levels of tension, this data are consistent with what I expected and what has been shown so far by the UT Dallas research team. Nylon-6,6 actuators are strong and robust, and seem to retain these properties for long periods of time while stretched. I hesitate to draw similar conclusions from the creep data and models – the oscillations seen in stress and strain present a significant obstacle to obtaining an accurate and useful analysis. After initial data points are removed to fit data to the generalized Maxwell model, over half of the data could not be used, decreasing the accuracy of the findings, especially since only 10 samples were taken.

Limitations and Sources of Error

Despite the promising results, this study is severely limited. The small sample sizes are a large source of error, especially for the 40 actuator band tests, for which only one sample was used for each test. This was because despite the improvements in the speed of actuator production with the automated actuator twisting device, it still took a considerable amount of time to make them. Sample sizes of ten for the 40 actuator band tests would have taken 5.55 days of work, or 133.33 hours. Samples cannot be reused for multiple tests to prevent confounding factors due to samples relaxing a little during their first tests. The 40 actuator band tests were also limited by the shape of the band. When embedded in the abdominal band, actuators should be lined in a flat band, but because the Instron clamps are too small, the actuators had to be bound together in a band with a circular cross-sectional area. Fortunately, however, this means that these tests actually underestimate the band's strength and elasticity, because lower loads would have been applied on actuators in the center of the band.

Another significant constraint of the study was the low resolution of creep testing. This was an inherent limitation of the Instron machine used. It did not have the processing power or speed to hold load perfectly constant. This is because holding load constant is much more difficult than maintaining extension. The Instron can easily pull to a certain extension and lock the clamps in place, whereas for load, the clamps must be moved slightly as the coil stretches and load decreases. Thus, the limitations in the Instron PID controller resulted in overcompensations that caused oscillations. To ensure that the creep behavior determined by data obtained in this experiment is accurate, further tests needed to be conducted on a more powerful measurement device or on a measurement system made from scratch with necessary sensors, actuators, and/or motors.

One final concern is that no tests were conducted on actuators with conductive thread running through them or with applied voltage, although conductive thread and applied voltage are both important considerations for the final product and probably influence viscoelastic behavior of nylon-6,6 coils. Conductive thread was not threaded through the actuators because it was difficult to provide enough slack in the thread so that the actuators can still compress and extend fully while also ensuring proper and even distribution of current and voltage throughout the actuator. Despite low levels of voltage needed for these actuators to contract, tests were conducted without applied voltage to protect the $40,000 Instron machine. A new testing setup and effective integration of conductive thread into actuators are definitely needed in the future.

Future Work

Apart from conducting further tests, using a different testing setup, integrating conductive thread, and applying voltage, I plan on working on a prototype of the active abdominal band. The first step toward this goal is embedding nylon-6,6 actuators in a textile that will insulate the user from current running through them and from heat generated from the applied voltage. I will incorporate a very elastic textile that allows the actuators to contract and expand fully. The active abdominal band must also consist of a blood pressure sensor and a microcontroller to modulate current and voltage effectively. The sensor and the band connected to a phone application via Bluetooth would provide the user with significant functionality, improving their quality of life by effectively mitigating orthostatic hypotension. The preliminary results of this study along with research conducted by the UT Dallas team indicate that nylon-6,6 actuators are promising artificial muscles that have many possible applications, including “smart” fabrics (like the abdominal band), exoskeletons, and robotics. I look forward to working on them and the active abdominal band in the future.

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