Pneumatically Power Assisted Extra-Vehicular Activity Glove

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The effectiveness of Extra-Vehicular Activity (EVA) systems is paramount for enabling humans to perform successful missions. This is particularly true for space suit pressure garment systems. As the bounds of human space exploration continue to expand, this need will become even more critical as the types of tasks necessary for humans to perform increases, as well. This includes maintenance and repair work on vehicles during long missions to erecting structures and dwellings on extra-terrestrial surfaces. A key to successfully achieving such mission operations is dexterous manipulation, and in terms of the EVA system, this need translates directly to the EVA glove. We are developing an innovative pneumatically powered EVA glove exoskeleton to augment the performance capability of the hand inside the EVA glove. The exoskeleton employs novel, miniature pneumatic artificial muscles to proportionally and controllably augment the finger motion in a natural manner to provide assistance in counteracting the loss of functionality when wearing the EVA glove. The technology exploits the high performance, lightweight, and scalability of Pneumatic Artificial Muscle (PAM) actuators to produce an exoskeleton glove with smaller form factor and higher assistive capability than existing electromechanical concepts. A detailed design study and experimental validation is presented, which evaluates the feasibility of this concept and its operational advantages and challenges.

I. Introduction

THE effectiveness of Extra-Vehicular Activity (EVA) systems is paramount for enabling humans to perform successful missions. This is particularly true for space suit pressure garment systems. As the bounds of human space exploration continue to expand, this need will become even more critical as the types of tasks necessary for humans increases, as well. This includes everything from maintenance and repair work on vehicles during long missions, to erecting structures and dwellings on extraterrestrial surfaces. A key to successfully achieving such mission operations is dexterous manipulation, and in terms of the EVA system, this need translates directly to the EVA glove.

Wearing EVA gloves causes substantial performance degradation when compared to a bare hand. Donning the EVA glove has been shown to negatively affect hand strength, task dexterity, time to complete a task, and number of task errors.[1] Endurance is also decreased due to the additional human effort necessary to complete tasks.[2] One study found that the pressurized glove with the Thermal Micrometeoroid Garment (TMG) reduced grip strength by over 50% from baseline values.[3] This study only considered the forces exerted by the glove, whereas unmeasured user exertion is likely more substantially influenced. In another study it was found that donning and pressurizing the glove greatly increased the force applied to identify an object due to decreased tactility.[4] Glove fit has been improved in Phase VI gloves through the use of CAD, CNC machining, and laser scanning,[5] though performance limitations still remain.

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On the Phase VII glove currently being designed, to achieve metacarpophalangeal (MCP) joint mobility, a link-net restraint and a hard exoskeleton were decided upon as a lightweight, effective solution with extra palm protection. With these improvements, MCP joint mobility achieved at least 94% of barehanded mobility in the right hand of four test subjects, but there was still a reduction in grip strength of approximately 40%.[6]

This loss in dexterous capability by donning an EVA glove has motivated research into assistive technologies to counter the multitude of negative effects, namely, powered hand exoskeletons. A variety of devices have been considered, as glove exoskeletons can increase grip strength and range of motion with decreased human work, or rather, restore barehanded capability to a hand in an EVA glove. Primary considerations for each include actuator and mechanism type. Linear pneumatic actuators,[7] pneumatic artificial muscles (PAMs),[8] ultrasonic motors,[9] and piezo-motors[10] have been leading candidates for actuator technology, whereas cable or tendon systems,[11] four-bar linkages,[12] and sliding circular arc links[9] have led the way for mechanisms. However, each concept to date has also met challenges that limit its practical utility, such as speed of response, discomfort, excessive bulk, weight, materials, and safety. An opportunity for innovation has therefore been created.

The proposed technology will exploit the high performance, lightweight, and scalability of PAM actuators to produce an exoskeleton glove with smaller form factor and higher assistive capability than existing concepts. Specifically relevant benefits of PAM actuators in this application include minimal mass, compliant, scalable, reliable, and robust design.[13] Central to the proposed exoskeleton device is the ability to provide practically useful assistive forces in a lightweight and low form factor system. PAMs with tailored braid angles facilitate the ability to successfully carry out this effort and achieve higher performance than past PAM-driven exoskeleton concepts.

II. Mechanical Requirements and Design

The performance requirements of an existing exoskeleton glove actuation system, pictured in Figure 1, were published by Sorenson et al. (1997).[11] This EVA glove has been selected as the test-bed for the PAM-driven exoskeleton actuation of the present work and was available from the prior work. It should be noted that this is a 4000 Series glove that has been modified such that neutral position, when pressurized, has the collective MCP joint in a flexed position. Hence, the actuation system assists joint extension. A sample set of force-stroke points was picked from the published data and they are plotted in Figure 2 as discrete circles. Note that there is significant hysteresis in the glove, so the forces vary for a given stroke value depending on whether the glove is opening or closing. Polynomial curve fits were applied to yield force as a function of stroke for both stages of finger motion. These are represented in the figure by solid lines.

Figure 1. Existing exoskeleton EVA glove with electromechanical actuation.

Mitchell (2011) has performed related endurance testing of EVA gloves and has published useful information for determining this requirement for the PAM system.[14] This data was used to determine the number of cycles per day with an added safety factor, see Table 1. Using these actuation system design requirements, the PAM system design could begin. The properties of the representative PAM actuator are given in Table 2. These properties are used to determine the length of the PAM actuators for the exoskeleton system.

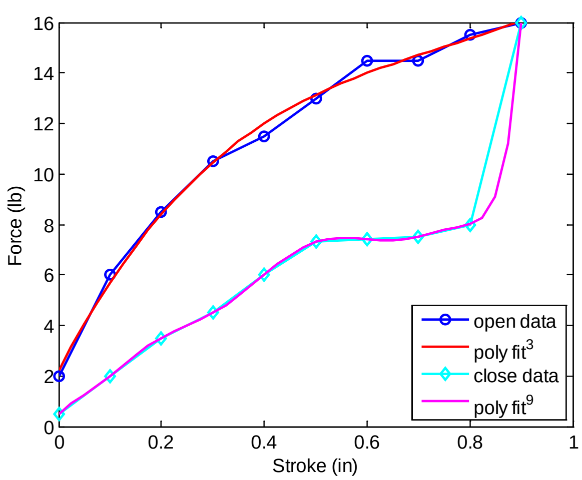
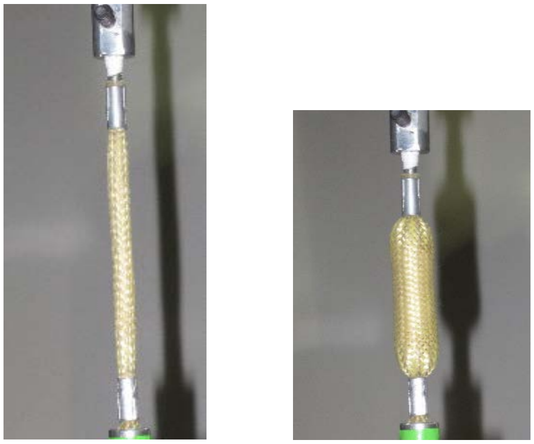


Figure 2. Stiffness requirement for EVA exoskeleton glove.



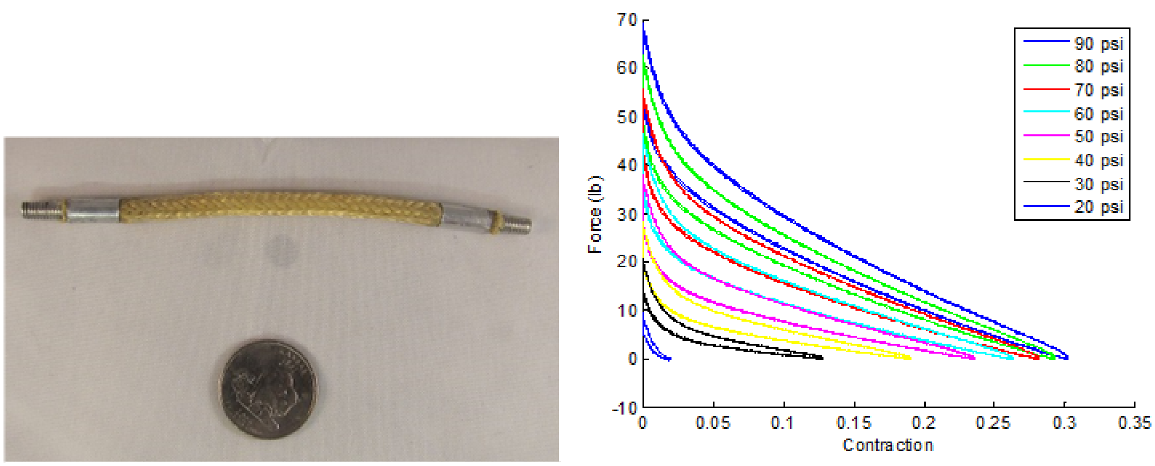
a) b)
**Figure 3. a) PAM in blocked force condition.
b) PAM at free contraction**

Table 1. Estimation of required number of finger cycles.

Estimation	Per Day
Minimum per Glove	92
With Factor of Safety of 2	184
For Two Gloves	368

Table 2. Design parameters for candidate PAM actuators.

Parameter		Parameter	
PAM Length, in	2.98	Bladder Material	Latex
PAM Outer Diameter, in	0.256	Braid Material	Kevlar
Bladder Outer Diameter, in	0.1875	Braid Angle, deg	70
Bladder Inner Diameter, in	0.125		



a) b)
Figure 4. a) PAM actuator. b) PAM Force contraction data.

Since the intended operating frequency of the exoskeleton glove is less than 1 Hz, quasi-static characterization was considered to be sufficient for the design. When pressure is applied to a PAM the bladder radially expands, but is constrained by the stiff braid. This constraint produces axial contraction and an axial force. A PAM in the blocked force and free contraction conditions is shown in Figure 3. At each test pressure, the PAM was pressurized while its length was held constant at the resting length, which gives a measure of blocked force. Next, the PAM was allowed to slowly contract until it reached its natural limit where it no longer produces any force, the free contraction. Then the PAM was stretched back to its resting length to complete a full actuation cycle. Figure 4a shows a representative PAM actuator characterized for design purposes and Figure 4b displays the measured data, where it can be seen that the PAM response contains hysteresis. The PAM hysteresis is far less pronounced than that in the EVA glove though. While experimentally characterizing the PAMs, operating diameter was also measured for different conditions to give a better understanding of how the muscle expands radially as it contracts. This is useful for determining appropriate spacing between the muscles, as well as the overall required volume of the PAM actuation system. Figure 5 shows the diameter data collected from the PAM, with the different curves representing different levels of contraction. This figure shows that diameter is mostly independent of pressure, and depends predominantly on the contraction state of the PAM. This being the case, a third-order polynomial curve fit, solid line, was applied to the measured diameter data (0 to 90 psi).

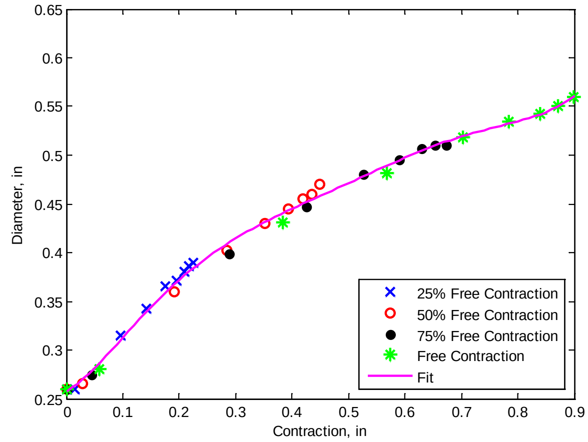


Figure 5. Actuator diameter versus contraction at each test pressures.

Figure 6 shows a concept of the PAM actuator bundle with 4 PAMs of length *L* and the multi-radius pulley that introduces mechanical advantage. Other key system components are also labeled. PAM actuator performance capabilities were next compared to the existing exoskeleton glove stiffness characteristic to determine the best path forward for design. Figure 7 examines the effects of mechanical advantage and varied number of PAMs on the force and stroke requirements. PAMs that meet the length requirement do not produce the required stroke, so mechanical advantage, *MA*, is therefore needed in the design to trade off force and stroke of the PAM actuators such that they can satisfy the stiffness requirements of the exoskeleton glove. This will act essentially as a force multiplier

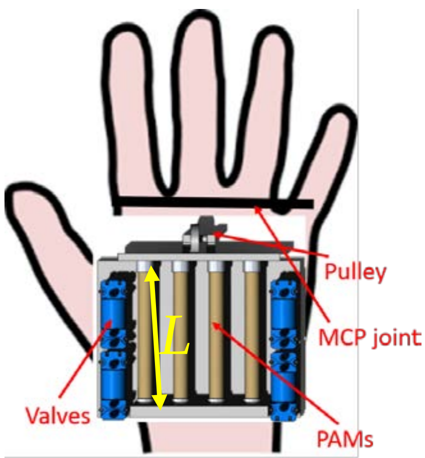


Figure 6. Conceptual Exoskeleton Design. Study to determine PAM Length, *L*, and number of PAMs

$$F_{glove} = Fn_{PAM}(MA) \tag{1}$$

where F is the force of the PAM and F_{glove} is the required force. It should be noted that $MA = 1$ for the direct pull scenario. When multiple PAM actuators are considered for the actuation system, the number of PAMs, n_{PAM}, simply multiplies the input force. It should also be noted that amplifications in force ($MA > 1$) come at the cost of usable stroke, whereas amplifications in stroke ($MA < 1$) come at the cost of output force to the fingers of the glove (MCP joint). Mechanical advantage will be physically realized through a stepped diameter rod, essentially mimicking the effect of different radii gears.

The mechanical advantage can be tailored by manipulating the ratio of the two radii, r_1 and r_2, to affect the force, F, and stroke, s, as necessary to satisfy the requirements (F_2, s_2) for a given PAM system input of (F_1, s_1)

$$F_1\left(\frac{r_1}{r_2}\right) = F_1(MA) = F_2 \tag{2}$$

$$s_1\left(\frac{r_2}{r_1}\right) = s_1\left(\frac{1}{MA}\right) = s_2 \tag{3}$$

where the PAM system input from a parallel arrangement of muscles also multiplies the force output from a single PAM, though the collective stroke remains the same.

Under this framework, the design space was explored for a range of potential PAM actuator lengths, given the force and stroke requirements of the exoskeleton glove, to find regions of acceptable solutions. Mechanical advantage and the number of PAMs employed were varied for each case. Constraints were then applied when considering physical integration with the backhand plate of the existing glove, providing realistic limits on PAM length and inflated diameter. A rotational limit on the mechanism was also applied to prevent any potential issues from arising in relation to spooling. Table 3 summarizes the constraints used in the design analysis.

A simulation model was then run to evaluate the various design conditions in comparison to the actuation requirements. Figure 8 displays sample results for two different numbers of PAMs, where mechanical advantage is plotted against PAM length. In each result, the green shaded region indicates acceptable designs, the red shaded region indicates designs that cannot satisfy the force requirement, and the blue shaded region indicates designs that cannot satisfy the stroke or force requirements. A solid black line was added to show

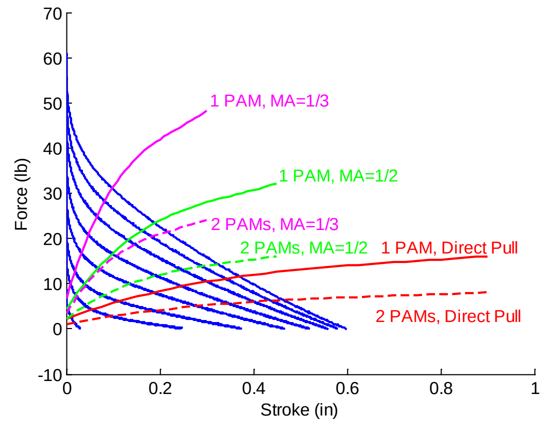
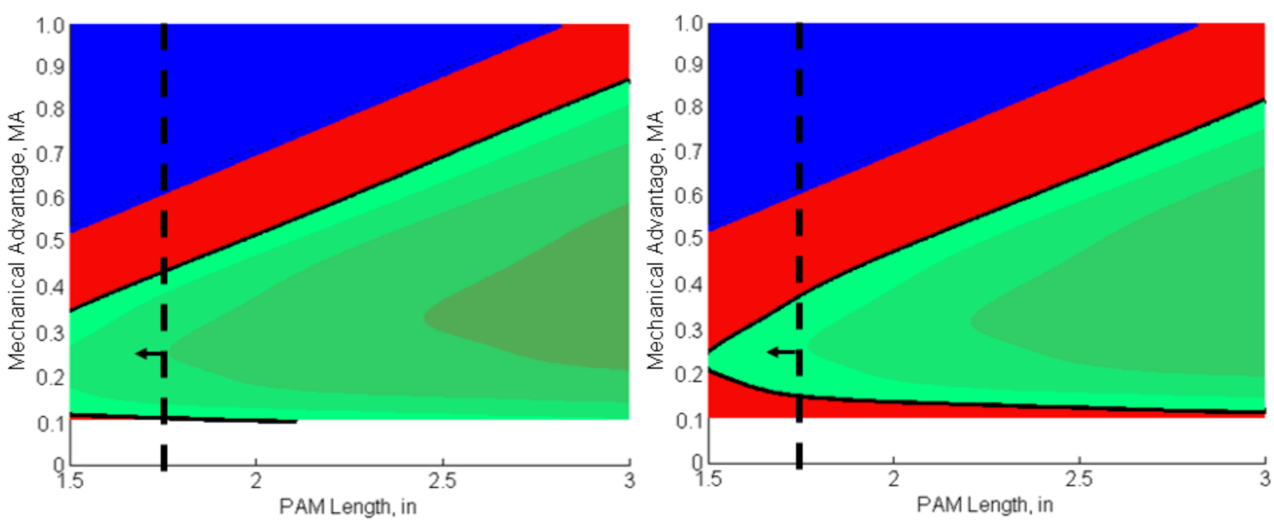


Figure 7. Actuator requirements mechanical advantage and number of PAMs.

Table 3. Physical constraints for exoskeleton glove actuation system.

Constraint Quantity	Value
PAM resting length, in	1.75
PAM inflated diameter, in	0.5
Mechanism rotation angle, deg	270
Pressure, psi	90



a) **b)**
Figure 8. Actuation design space analysis. a) 5 PAMs. b) 4 PAMs.

additional contrast to the border between the region of acceptable and unacceptable designs. Note that within the green area, max actuation pressure increases closer to the dark border line, as the shade of green becomes lighter. For a given acceptable design then, the horizontal axis will determine the PAM length, the vertical axis the mechanical advantage needed, and the shade of green the pressure needed, such that the contracted force meets the requirement. Note also the black vertical dashed line, which represents the upper bound on acceptable PAM lengths based on the glove geometry. Overall, the range of PAM lengths shown here are beyond the noted constraint value for the sake of better visualizing the design space for different numbers of PAMs.

In narrowing down the options, the first consideration made was in terms of required air volume to complete an actuation cycle. Under this notion, the PAM systems that use the least amount of air will be preferred because they will also need smaller pneumatic reservoirs to be carried by the astronaut, or they will achieve a greater number of potential cycles within a fixed reservoir size. Adding this to the analysis, a cylindrical volume approximation of inflated PAM shape was made

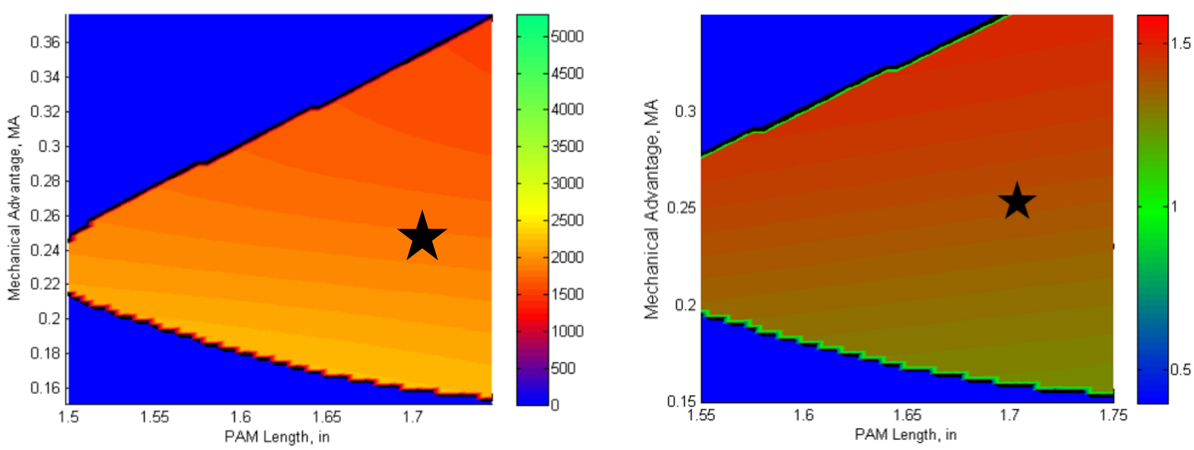
$$V_{PAM} = \frac{\pi}{4} D^2 \left(L_0 - x_{req} \right) \tag{4}$$

where V_{PAM} is the PAM volume D is the inflated diameter, L_0 is the initial length, and x_{req} is the required PAM contraction. Note that this provides a conservative estimate because the true PAM shape is rounded down at both ends. An existing portable tank size was assumed as the pneumatic supply (68 in^3 at 4500 psi fully charged) for the selected PAM system design. With this tank, the number of available cycles could be calculated and compared to the required value in Table 1 to ensure that the design is valid. The stored pneumatic input energy was assumed to be transferred to the PAM actuators through a polytropic expansion process

$$P_T V_T^k = P_A \left(N n V_{PAM} \right)^k \tag{5}$$

where P is pressure, V is volume, subscript T denotes the supply tank, subscript A denotes the actuation system, PAM denotes a single PAM in the system, k is the polytropic index, N is the number of finger extension/flexion cycles, and n is the number of PAMs. In this expression, the exponent k can be bounded by $k = 1$ for an isothermal process and $k = \gamma$ for an isentropic process. For these calculations it was assumed that the gas used would be CO_2, $\gamma = 1.28$.

The actual expansion process will fall somewhere between these two bounds, so calculations were made at each limit to explore the range of potentially achievable cycles and also to verify that the minimum number of cycles exceeds the requirement. Figure 9a displays these results for the preferred 4-PAM configurations with the existing 68



a) **b)**

Figure 9. Additional design considerations with the star representing the chosen design point. a) Number of actuation cycles possible with 4 PAMs and 68 in^3 supply isentropic process. b) Minimum actuator width for 4 PAM system (inches).

in^3 tank, where the blue regions again denote unacceptable designs and the orange and red shaded regions denote acceptable designs. Here, orange represents larger numbers of cycles than red, as noted in the color bar, and is hence preferred. Comparing the minimum values here to the 368 cycle requirement, it can be seen that all designs in the identified region of acceptable solutions satisfy this value with large margins, ranging from a factor of 5 to 12. This means that the existing pneumatic tank is far over-sized for a single EVA, or the same tank could be used for multiple EVAs without needing to be recharged.

Having identified the 4-PAM arrangement as the preferred design choice, a final decision was still needed for a number of other design parameters. Design margins were preferred for PAM length, mechanical advantage, and pressure. Thus, a value of mechanical advantage nearly in the middle of the acceptable range was chosen ($MA = 0.25$).

Resting PAM length and operating pressure are somewhat competing parameters, so the decision was made to keep the pressure as low as possible without being right on the length constraint. Hence, a pressure of 82 psi and length of 1.7 in were chosen. The resulting width of the 4-PAM system is shown in Figure 9b, excluding braid thickness, where a star has been placed at the selected design condition. This, and other parameters of the design that fall out of the above analyses given the noted selections are summarized in Table 4. For the chosen 4-PAM design with *MA* = 0.25, this means that excess force is being traded for stroke by a factor of 4. A value of 0.191 in was selected for the larger radius (output) and 0.04775 in for the smaller radius (input), ensuring that the 270 deg rotation constraint is satisfied.

Table 4. Summary of Phase I design parameters.

Design Parameter	Value
Number of PAMs	4
PAM resting length	1.7 in
PAM resting diameter	0.1875 in
PAM contracted diameter	0.431 in
Mechanical advantage	0.25
Mechanism input radius	0.04775 in
Mechanism output radius	0.191 in
Max width of PAMs	1.65 in
Max volume of PAMs	0.7904 in^3
Max operating pressure	82 psi

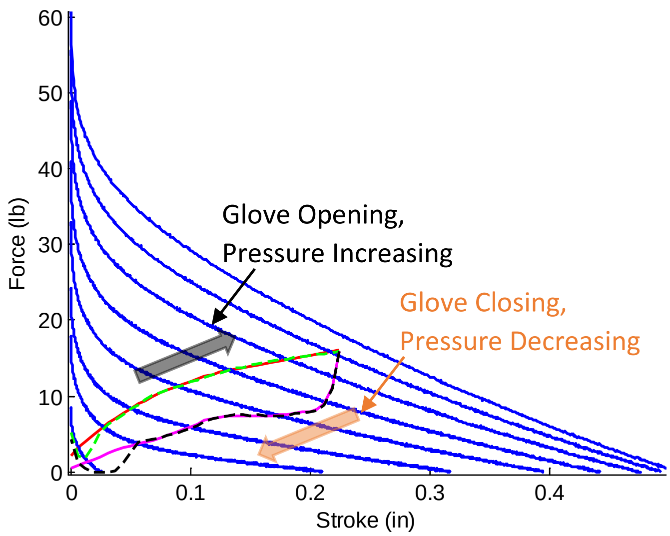


Figure 10. Predicted response of actuation system on EVA glove force-contraction profile against glove stiffness

Now that the design parameters for the exoskeleton EVA glove actuator were specified, the analysis was used to predict the quasi-static response in relation to the glove stiffness, and the required operating pressure at each step of the extension/flexion cycle. Figure 10 shows these results for the force-contraction profile of the chosen 4-PAM actuation system, where it can be seen that the force and stroke can match the requirement during both stages of the cycle. Here the solid blue lines represent the actuation system force-stroke profiles, the solid red and pink lines represent the extension and flexion glove stiffness curves, respectively, and the dashed green and black lines represent the corresponding actuation system response. Note that the discrepancies between the predicted and required response at low stroke are merely due to interpolation error resulting from not having recorded data measurements with fine enough resolution at low pressures.

It should be noted that the use of multiple PAMs also provides a key operational benefit: redundancy. If, for example, one PAM is lost, such as a ruptured bladder, the actuation system can still operate and provide MCP joint assistance, albeit at a reduced level. With one PAM failed, the system would not be able to provide the final 11% of the opening (MCP extension) motion without additional input (effort) from the user or the possible provision of increased actuation pressure (> 82 psi). The loss of half the actuators would reduce the assisted range of motion by 43%, and complete failure of the actuation system would simply take away the assistance capability of the glove. Full range of motion of the glove would remain possible with failed PAMs, which may not be the case for other actuation technologies. Additionally, if desired, future iterations could also include a locking mechanism that would allow the user to lock the glove into a desired (e.g., fully open) position after the loss of one or more actuators.

III. Prototype Fabrication and Laboratory Testing

A test of the parallel PAM actuators alone was conducted on a Material Testing Systems (MTS) machine. The pressure in the PAMs was incrementally increased and then decreased, and force-contraction data points were recorded along the way. This experimental data is presented in Figure 11, where it can be seen that the green x-lines are able to closely follow the model curves that represent the pressurized EVA glove stiffness. The conclusion that the PAM technology did perform as expected and could satisfy the performance requirements of the exoskeleton system is therefore justified.

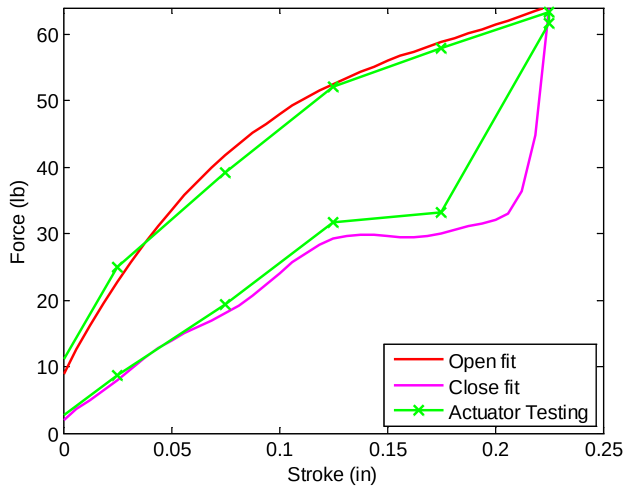
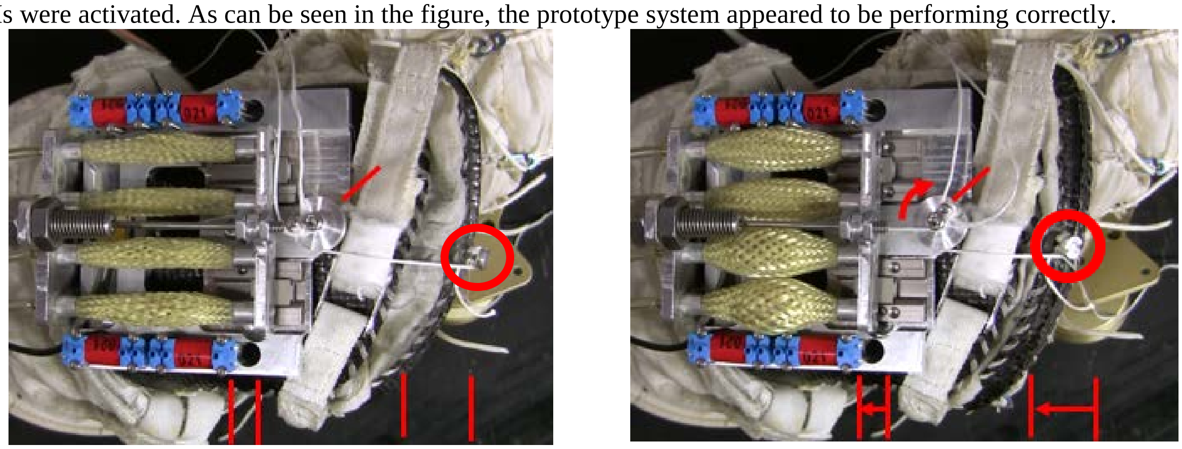


Figure 11. Actuator characterization.

Testing of the exoskeleton actuator could now begin. This began initially on the bench-top in an unpressurized environment. The purpose of the bench-top testing was to ensure proper functioning of the actuation system components, as well as the sensors, prior to entering the glove box. Figure 12 shows a before (a) and after (b) photograph taken from the top of the exoskeleton system, where red lines have been added to highlight the motion that occurred while activating the PAMs. The diagonal red line shows the pulley rotation angle that resulted from the PAM contraction and led to the MCP joint extension. Arrows were also added to show the direction of motion that took place while the PAMs were activated. As can be seen in the figure, the prototype system appeared to be performing correctly.



a) **b)**

Figure 12. Bench-top validation testing, with circle highlighting the center of the MCP joint. a) Actuator off. b) Actuator on.

I. Conclusions

Fabrication and testing of a representative PAM was conducted to produce a mathematical model that captured the force-stroke-pressure behavior of the chosen PAM size. This model was then applied to an optimization study of the design parameters, subject to physical constraints of the glove and related components. A parallel arrangement of PAMs was employed with a pulley mechanism to trade the high force, low stroke output of the PAMs for the desired low force, high stroke output to extend the MCP joint. The design analysis varied the mechanical advantage ratio of the two-diameter pulley and the number of PAMs to arrive at an optimal configuration for the prototype, wherein force, stroke, occupied volume, and number of achievable actuation cycles were all considered. Physically designing the device followed, such that it could be integrated with the existing modified EVA glove for testing. This actuator grouping was then tested to confirm that it operated as designed. Once the exoskeleton system was installed on the EVA glove, basic functionality experiments were conducted on the bench-top in the absence of pressure to ensure that all components were performing as expected. The next stage of testing will involve inserting the prototype into a glove box and operating it in a pressurized environment.

Future development of a feedback control system for the exoskeleton actuator is also critical in proving that the technology can sufficiently off-load the stiffness of the pressurized EVA glove and restore barehanded capability to the user. Various feedback control algorithms will be considered, though it is expected that nulling the EVA glove stiffness experienced by the user will best be accomplished by implementing force feedback. Secondary feedback variables will also be considered, such as position, velocity, and direction of motion. Control algorithms developed previously for a related electromechanical assist glove will be the starting point for control design here, where augmentation of the controller output will be required to drive the pneumatic solenoid valves of the present system.

Acknowledgments

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