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NASA RESEARCH ANNOUNCEMENT PHASE II FINAL REPORT FOR THE DEVELOPMENT OF A POWER ASSISTED SPACE SUIT GLOVE

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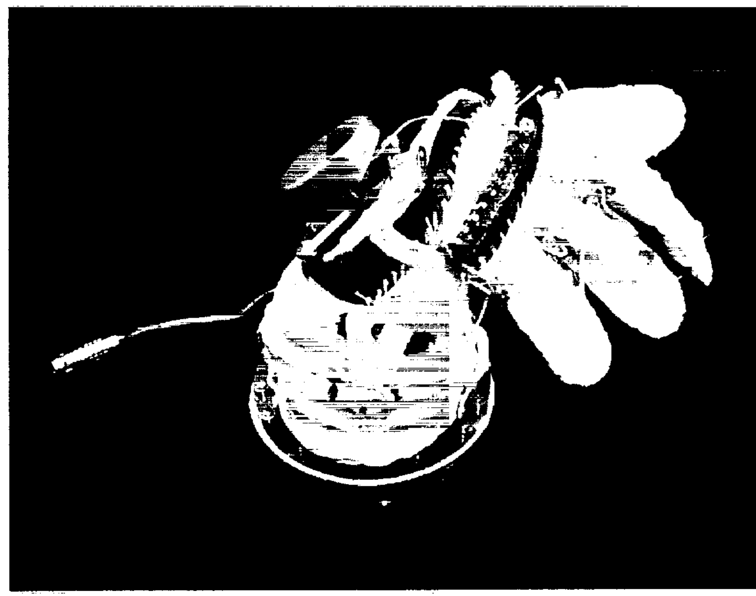

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As part of the delivery goals of Phase I and II of the program, the following activities were completed:

- System modeling - a complete system modeling effort was completed to characterize and predict the performance of the MCP joint. This information was then used to design the control algorithms that analyze and control the actuation system.

- Functional prototype - a functional prototype was built and tested to validate the feasibility and effectiveness of the power assist technology. The data obtained from this working prototype was extensive in nature, and is addressed in detail in section 5.4 of this report. As part of Phase II deliverables, this working prototype was demonstrated and delivered to NASA JSC personnel.

- Development of a cognizant development team - a highly skilled development team was created with both ILC and University of Maryland personnel. This team, due in part to activities performed on this effort, is poised to provide continuous improvement to the EVA space suit in the future. Linking industry with academia has been proven to be a viable design approach.

3.0 PHASE I SUMMARY OF RESULTS

During Phase I of the program, the following activities were completed. Specific details of these activities can be found in the Phase I report submitted to NASA by ILC - dated 10/30/96.

- An initial one degree of freedom system modeling effort was developed to predict MCP joint actuation performance.

- A human factors analysis was completed in order to make the power-assist system tailorable for the entire user population.

- Design trade-offs were completed, including the following:

    1. Sensing systems - feedback sensors to measure MCP joint rotation were traded off. An external to the suit optical encoder was deemed to be the best suited technology.
    2. Control systems - a feedback system based on joint position and velocity was selected, with the control algorithm written based on the system modeling effort completed.
    3. Actuator - DC motors were selected to provide the pressure counteracting torques to the MCP joint.
    4. MCP soft goods design - a half rolling convolute MCP joint design was selected for low torque and simplicity of design.

- Test protocols - test protocols capable of quantifying the performance advantages of the power-assist technology were investigated.

- Materials issues - space qualified materials were investigated for use. Section 5.1.3 contains additional materials information.

- Prototype fabrication - several restraint MCP joint prototypes were fabricated to quantify MCP joint torque, range of motion, and hysteresis effects. As mentioned, the half rolling convolute was down selected.

- Report - A Phase I report was written and delivered to NASA.

4.0 PHASE II INTRODUCTION

Phase II of the NRA Power-Assist program commenced on 10/1/96 and continued through the end of 1997. Phase II activities focused on the down selection of the candidate technologies identified in Phase I. Once selected, each candidate technology was mocked up and tested, and represented the bulk of the activity performed in Phase II.

Ultimately one design was selected which was believed to present the best power-assist MCP joint possible with the technology available at the time. This design concept was prototyped and tested, with an additional iteration and refinement performed during the conclusion of Phase II. The results obtained were very promising, and are detailed in the paragraphs to follow.

5.0 PHASE II SUMMARY OF RESULTS

The following paragraphs detail the accomplishments that were achieved on Phase II of the NRA Glove Power-assist program. The effort is divided into four main sections to aid in understanding of the program activities. The first section, 5.1, discusses the softgoods aspects of the design process. Sections 5.2 through 5.4 describe activities performed on the robotics aspects of the design, and the manned performance testing that was accomplished.

5.1 Glove Metacarpalphalangeal Joint Design & Manufacture

The following sections describe the design activities that were performed by ILC Dover on the softgoods (i.e. glove restraint) portion of the power assist glove.

5.1.1 Restraint

A restraint based on the current state-of-the art Phase VI Space Suit Assembly (SSA) glove assembly was selected as a starting point for the NRA Glove restraint design. The Phase VI restraint offers the best performance relative to tactility, range of motion, and torque that is currently available. This MCP joint design is a purely softgoods design that does not provide nude hand performance, however.

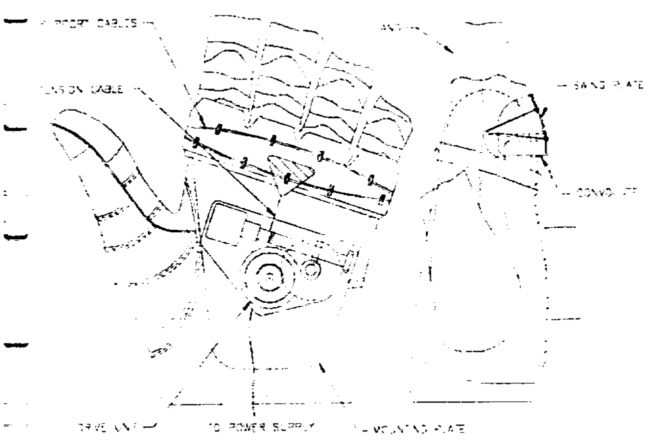


Figure 1 – Half Rolling Convolute

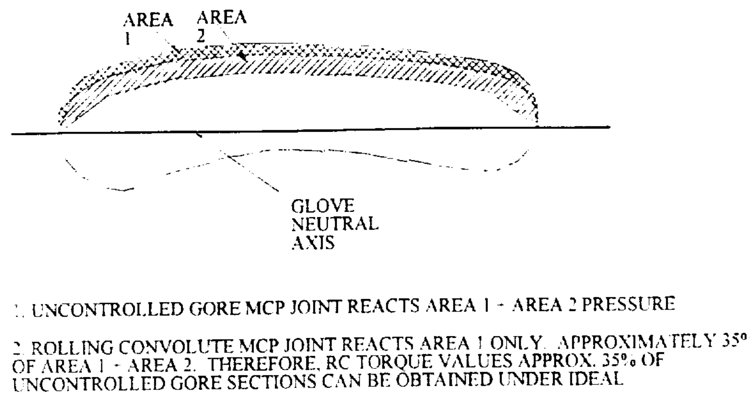


Figure 2 – RC torque

As part of the NRA Glove, a half rolling convolute (RC) as shown in Figure 1 was selected for this application. The reason for this is that the half rolling convolute potentially offers the lowest possible joint torque in a softgoods joint while meeting the other constraints on the glove such as palm tactility and low profile hardware in the thumb crotch area. The reason for the potential low torque in an RC joint is described in Figure 2.

As can be seen from Figures 1 and 2, the RC MCP joint design has a very small volume change (seen as the shaded area marked "Area 1" in Figure 2) during MCP rotation. Understanding that the amount of energy required to actuate a joint is directly proportional to the product of glove internal pressure and volume change of the joint during actuation, it become obvious why the RC MCP offers potentially very low torque to actuate the joint. Other MCP joint concepts such as patterned gore MCP joints have much larger volume changes during actuation and have, therefore, higher actuation torque values.

The performance benefits of the half RC joint acquired from low joint actuation torque include:

- decreased actuation motor size
- decreased power consumption of the system
- increased response time
- improved, **non**-powered actuation system performance (i.e. during actuation system failure)

ILC's goal during Phase II of the program was to obtain a maximum actuation load below 10 pounds at full MCP opening. This goal was derived from actuator capability and power requirements as well as on theoretical, best case performance capabilities of a rolling convolute joint. This requirement was met as discussed in paragraph 5.1.4 below.

The flat pattern used to fabricate the half rolling convolute is shown in Figure 3. The patterning is such that the neutral position of the pressurized glove is in a hand closed configuration. This type of neutral position is required so that the actuation system may be placed on the back of the hand. Another option is to place the actuation system in the palm of the hand, and pattern the glove to have a hand open neutral position. This option provides a more fail safe design. However, this approach places unnecessary encumbrance (increased bulk and reduced palm tactility) upon the hand during grasping activities, and is not an acceptable option given current actuator technologies.

The selected pattern shown in Figure 3 is the result of four iterations to minimize MCP joint torque while providing the required amount of RC travel. The pattern replaces the knuckle back gore panel in the current Phase VI glove restraint assembly, with slight alterations at the base of the finger stalls required. The shape of the pattern is such that full MCP joint rotation is possible, with minimal MCP joint torque.

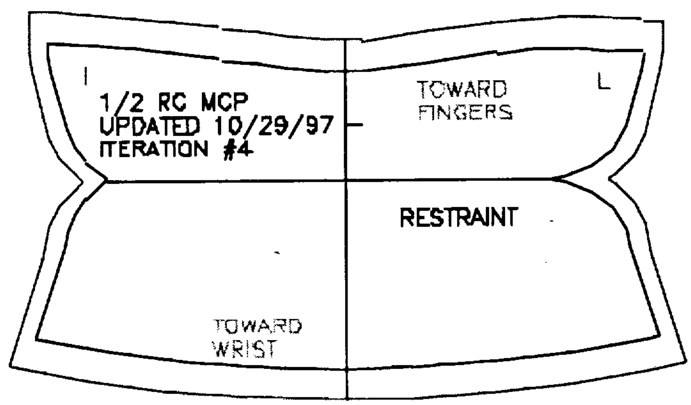


Figure 3

The hardware used to form and control the rolling convolute was laid up and vacuum bagged on a mandrel from a graphite/epoxy prepeg. The 3-D shape of the composite plate mandrels was derived from Phase VI dip mold SLA data, which was initially derived from laser scan data for crewmember Musgrave. This method of part fabrication allows complex, 3-D parts to be accurately fabricated and interfaced with other 3-D parts. In this case, the composite plates were modeled to fit the outer profile of the pressurized restraint. This method allows the NRA power-assist hardware to be tailored to any size glove.

5.1.2 Bladder

The baseline Phase VI Musgrave dip form was altered to include the rolling convolute design. When completed, this dip mold was used to dip a latex bladder which was integrated in the prototype glove. This method of integrally dipping the rolling convolute eliminated any seams or wrinkles in the rolling convolute area, and their potential increase in MCP torques. The remaining portions of the dip form (i.e. fingers, convolutes, wrist section, etc.) were not altered for this activity.

5.1.3 Materials

All materials selected for the Phase II deliverable prototype were chosen based on safe manned usage, no off-gassing characteristics, and compatibility with Neutral Buoyancy Lab (NBL) requirements. Additionally, low mass/low profile components were a design driver, and thus, affected the materials chosen for this application.

The following paragraphs describe the materials used in each component of the power-assist system, with rationale for each:

- Mounting hardware and plates - High stiffness to weight ratio composite materials were investigated for use in the mounting hardware and plates used to transfer loads across the MCP joint. Composite materials offer very low weight and low profile as a result. A graphite epoxy of suitable strength and stiffness was the material ultimately selected for this application. The attachment bosses for both the hand back plate and knuckle panels were machined from aluminum. The use of lighter weight composite materials in these areas will be explored in future efforts.

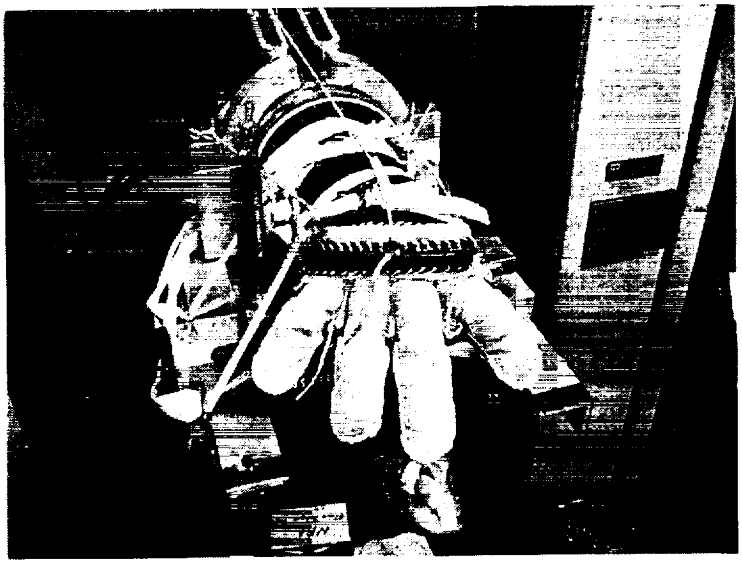
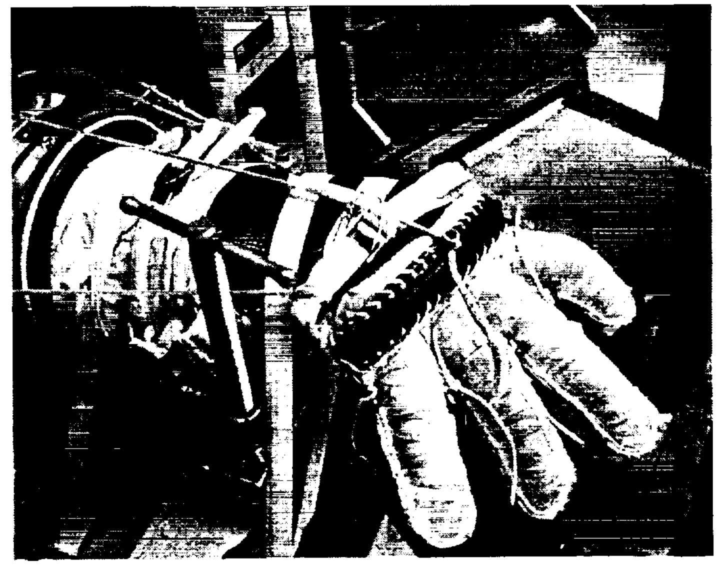
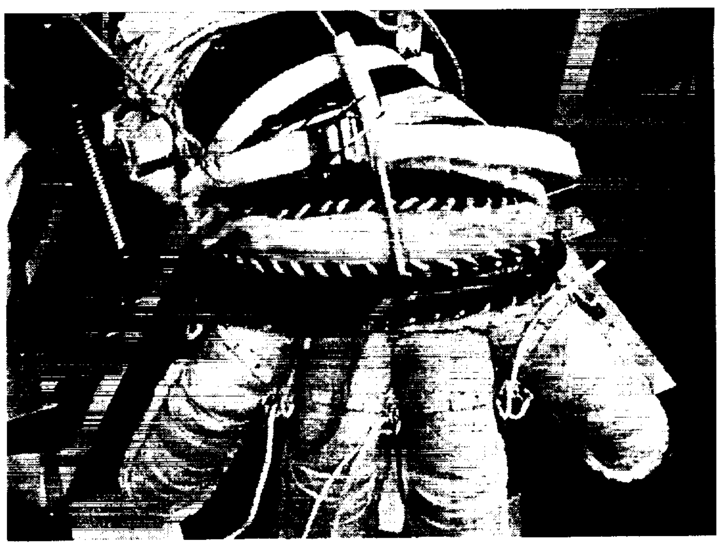
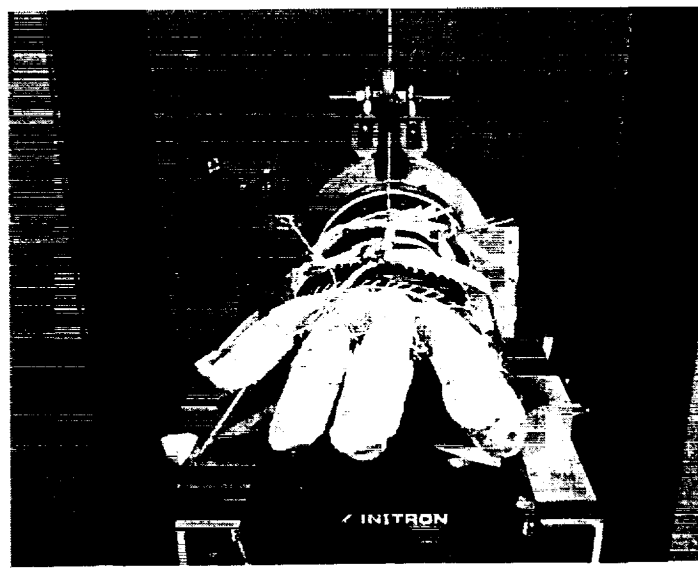
- Actuation cord - A high modulus, low elongation Spectra 1000 cord material was selected for use in the tension cord which connects the actuation system to the glove. Spectra cord stores very little strain energy and, as a result, will not create oscillations or instability in the control system.

- Rolling convolute gore - the rolling convolute gore was fabricated from the baseline nylon ripstop material currently used in the Phase VI glove restraint. The material was chosen due to its demonstrated toughness and excellent performance in the current Phase VI and 4000 Series glove assemblies.

- Bladder assembly - The bladder assembly was dipped from a natural rubber latex material. Latex was chosen for this effort due to its ease of manufacture, which allowed multiple, low cost design iterations to be performed. Future NBL and/or flight bladders will be fabricated from the Ruccothane material used on the current Shuttle SSA Glove assemblies. This material offers higher tensile and tear strength properties required for NBL and flight, but is much more difficult to dip.

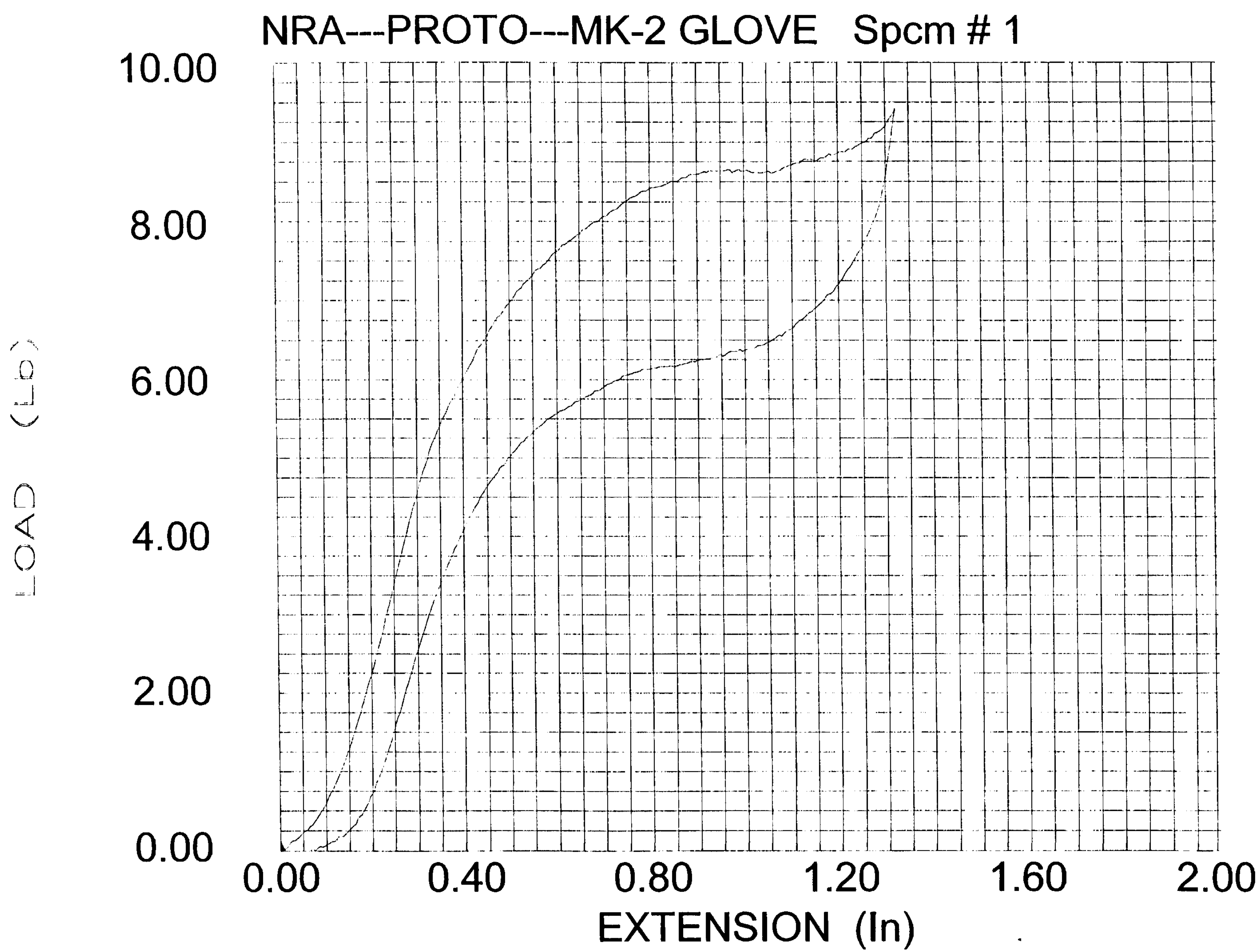
5.1.4 MCP Joint Testing, Actuation System Non-Operational

A special test fixture was used to test MCP joint load vs. deflection. See the photos on the following page which show the test setup.

This test was used to determine the effectiveness of the softgoods design for the MCP joint. Minimal MCP joint loads and hysteresis were the design goals.

Figure 4 on the following page shows the data generated for the latest generation MCP joint design. These results show significant reductions in both joint hysteresis and loads. As can be seen from the chart, the maximum MCP joint load occurs at full extension of the MCP joint, and has a magnitude of 9.5 pounds. This represents a 37% decrease in MCP joint torque as compared to the first generation MCP joint design, which had a maximum MCP joint load of 15.0 pounds. The higher torque in the first RC MCP is attributed to an unoptimized design in terms of the MCP joint pattern shape and integration of the air retaining bladder into the RC. These results are well within the capabilities of the actuation system. Reduced MCP joint load decreases power consumption through the actuation system, increases system response, and presents a better "fail-safe" condition for the glove wearer. It is predicted that future R&D efforts could reduce this torque even further by further refining the RC MCP joint design.



NRA---PROTO---MK-2 GLOVE Spcm # 1
10.00
8.00
6.00
4.00
2.00
0.00
LOAD (Lb)
0.00
0.40
0.80
1.20
1.60
2.00
EXTENSION (In)

Figure 4

Finally, manned subjective glove box testing of the second generation MCP joint revealed improved performance as compared to the first generation prototype. In both cases, the level of fatigue associated with MCP joint actuation was dramatically reduced with the actuation system active, as discussed in paragraph 5.4.2 below.

5.2 System Modeling

The design of the feedback compensation strategy for the power assist system assumes a single degree of freedom model, corresponding to ideal, rigid rotations of the MCP joint:

$$I_h\, q''(t) + f_h(q(t),q'(t)) = t_h(t) \qquad (1)$$

where q, q', and q'' are the MCP joint angle, velocity, and acceleration respectively, I_h is the rotational inertia of the joint, t_h are torques applied by the muscles, and f_h represents the angle and velocity dependent torques inherent in MCP joint motions. Equation (1) is a model of the barehanded dynamics of the MCP joint; when the hand is instead snugly enclosed in the actuated glove, the dynamics can be modeled as

$$(I_h + I_g)\, q''(t) + f_h(q(t),q'(t)) + f_g(q(t),q'(t)) = t_h(t) + t_a(t) \qquad (2)$$

where now $f_g(q(t),q'(t))$ are torques imposed on MCP joint motions by the pressurized glove, I_g is rotational inertia added by the glove, and $t_a(t)$ are the compensating torques which may be applied by the external actuator.

The causes of fatigue during repeated manual operations are now clear by comparing equations (1) and (2): without external actuation ($t_a = 0$) an astronaut's muscles must supply the additional energy needed to overcome the (substantial) additional torques f_g imposed by the pressurized glove. On the other hand, by using a feedback control strategy for the assist torques,

$$t_a(t) = f_g(q(t),q'(t)), \qquad (3)$$

the gloved MCP joint dynamics become

$$(I_h + I_g)\, q''(t) + f_h(q(t),q'(t)) = t_h(t) \qquad (4)$$

so that the barehanded dynamics (1) are almost completely recovered. . With this control law, the actuator acts as an "active spring", whose force-displacement characteristic is chosen to exactly counterbalance the torques applied by the glove. As a result, it attempts to keep the glove "neutrally stable" at all MCP angles, so that the slightest additional force in either direction will cause a commensurate rotation.

Implementation of the control strategy (3) requires an accurate estimate of the torques f_g applied by the glove. These torques are dominated by a spring-like "stiffness" term, reflecting the glove's tendency increasingly to oppose opening motions as the MCP joint angle is deflected from the neutral ($q = 0$) position. Figure 5 shows a graph of the stiffness characteristic of the latest generation power assist MCP joint design design. These curves were generated by applying progressively greater tension to the cable and recording the resulting steady-state MCP joint orientations (or, equivalently, the length of cable taken into the actuator); this process was then repeated, progressively reducing tension from its maximum.

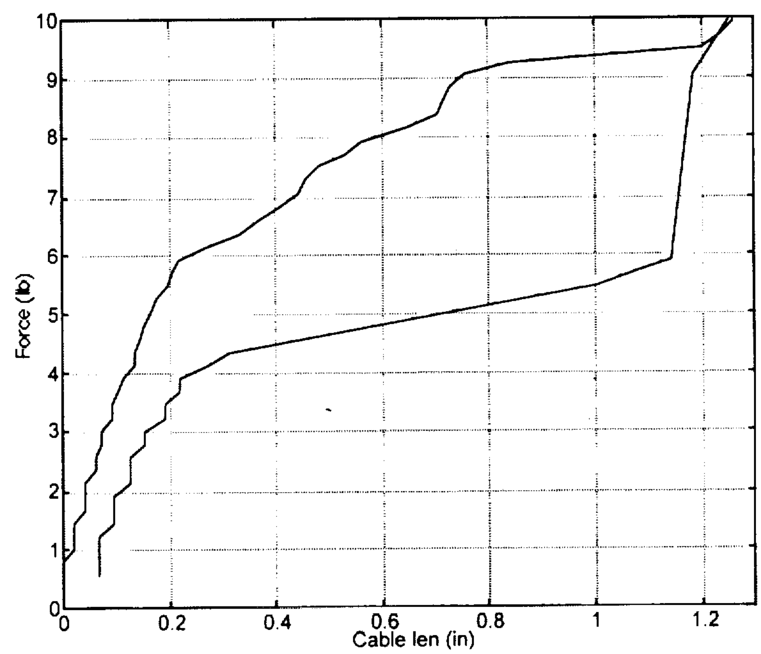


Figure 5: Stiffness characteristics of the latest power assist MCP joint design. The top curve is the glove stiffness measured when the glove is opening, the bottom curve was measured when the glove is closing.

A significant feature of the glove stiffness characteristic in Figure 5 is its hysteresis; that is, the tension required to maintain a particular MCP deflection depends upon the prior direction of joint motion. If only the top curve is used to represent the glove stiffness, the actuator would provide too much cable tension when the glove is closing, and the hand would have to provide torques equivalent to the difference between the top and bottom curves to force the joint to close. The software compensation strategy thus includes this hysteresis, so that the cable tension commanded at a particular joint angle is chosen from the top curve of

Figure 5 if the instantaneous direction of MCP motion is positive (opening), and from the bottom curve if the direction is negative (closing).

The actuation system itself also introduces undesirable torques influencing the motion of the MCP joint, due mostly to friction in the motor and gearing. To counteract these effects, the controller uses a small *dither* torque to break the static friction. Dither is a high frequency ripple on the commanded motor torques, causing small amplitude, high frequency vibrations of the motor shaft which help to reduce the effect of static friction. Experiments have shown the level of static friction in the motor to be about 0.15 oz-in, and this parameter is used as the amplitude of the dither -- the dither frequency is 180 Hz. Note that this level of static friction is approximately a factor of four less than that observed in the Mark I design.

The control law is implemented in the prototype system using a dedicated microprocessor (66 Mhz Intel 80486), and software written in C. The computer also interfaces with the Hall effect encoder circuit, calculating the amount of cable spooled and estimating the spool velocity, as well as with the DDC module which controls the current through the motor, and hence the tension in the cable.

A block diagram of the complete power assist strategy is presented in Figure 6, showing schematically the interconnection of the different components and the flow of information throughout the system. Glove angle, measured via cable displacement is sensed with the Hall effect sensors in the brushless motor. Velocity is estimated in software and the state measurements are used in the glove stiffness model. The resulting torque command is converted to an analog signal for the DDC motor driver, controlling the current to the motor, which places tension on the cable.

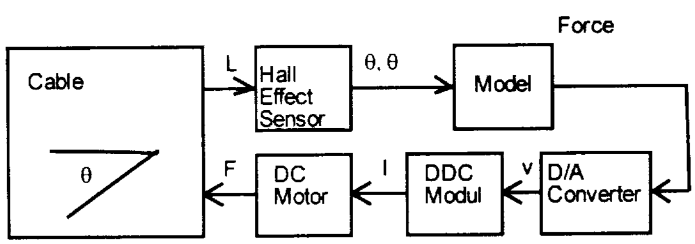


FIGURE 6: Block diagram of the prototype power assist system.

Figure 7 shows the load-displacement curve which results when this control strategy is employed: the force required to open the glove to a particular MCP angle with the power-assist turned on is shown by the lower curve in Figure 7, while the top curve shows the corresponding curve obtained when the actuator is off, repeated from Figure 5. As shown, the force needed to open the glove is reduced from 9.5 lbf to approximately 0.75 lb, a reduction of over 90%.

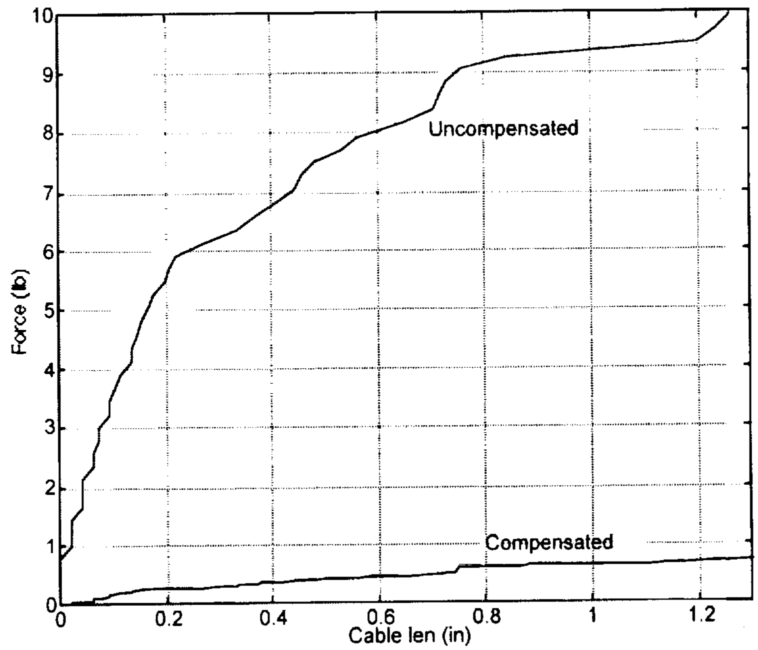


FIGURE 7: Comparison of force required to open the glove with the power assist active (solid line) and inactive (dashed line).

5.3 Actuator System

The following paragraphs describe the effort completed relative to actuation system design and the improvements that were realized between Phase I and the end of Phase II of the power assist program.

5.3.1 Actuation System Overview

The pressurized glove may be viewed as a system which places additional torque loads on the rotation of the MCP joint. The task of the active control system then, is to nullify the effects of these torques, relieving the astronaut's muscles from the burden of continually displacing the joint, and thereby reducing fatigue. The power assist mechanism thus attempts to act as a kind of "active spring," counterbalancing torque loads due to the glove. To be useful for space operations, this mechanism must constitute a self-contained package which can be unobtrusively integrated with a space suit glove. In particular, the palm and fingertips of the glove should be free of external hardware to avoid impeding dexterity and tactility, and safety considerations dictate that all hardware and electronics be mounted external to the glove pressure bladder.

Figure 8 shows an illustration of the power assist design concept. The actuation system is mounted externally on the dorsal side of the hand, and creates torques about the MCP joint by applying tension to a cable attached to a composite plate mounted just past the knuckles. The glove has been specially tailored to create a flexed (closed) neutral position of the MCP joint when pressurized; required compensating torques are thus always in the opening (extension) direction. Sufficient closing torque is inherent in the glove's tendency to return to the neutral position when pressurized. Compensating torques about the MCP joint are exerted by means of a Spectra cable attached to a composite plate mounted on the exterior of the glove just above the joint. The cable runs to the dorsal side of the glove, and connects to the power assist actuator, as shown in Figure 8.

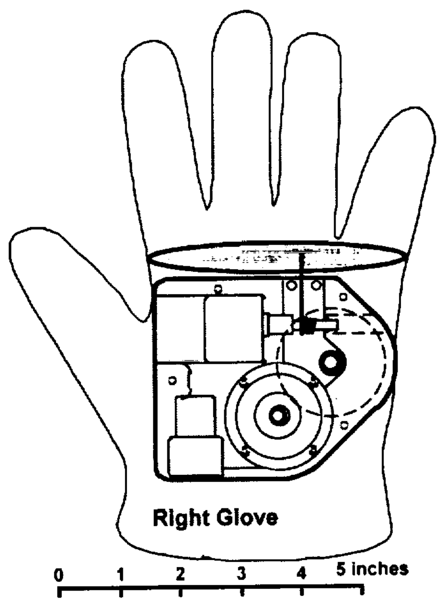


Figure 8: Power-assisted glove design concept (view from dorsal side)

5.3.2 Actuation System

The Mark II actuator applies tension by winding the end of the cable about a geared shaft driven by a brushless DC servomotor. Rotation of the motor winds cable onto the shaft, applying torque about the glove MCP joint. The cable path is designed to ensure that cable spools onto the shaft without overlap, ensuring a consistent relation between commanded motor torque and resultant output tension. To meet the force requirements, the motor selected requires a gear ratio of 3.05:1 and draws a maximum of 3 amps at 12V. Power to the motor is regulated by a DDC module in response to commands from the computer control system, as described below. The motor assembly is relatively low-friction and back-driveable, so that cable taken up by the motor in response to glove motion can be spooled out again with no perceptible additional effort by the astronaut.

To maintain tension as the MCP joint rotates, the actuator needs to take up the slack in the cable, resulting in a shortening of the length of cable external to the actuator. As long as the cable is in tension, there is a one-to-one relation between the glove MCP angle and the amount of cable which has been spooled onto the shaft, and hence to the angle through which the DC motor has rotated. This latter quantity can be sensed using the Hall effect sensors internal to the brushless motor together with a special purpose digital circuit. This system can resolve motor rotation in increments of 20 degrees, corresponding to approximately .007 inches of cable travel, which is sufficient resolution to implement the feedback control strategy described below. With the cable length measurements calibrated so that 0 in. corresponds to the glove's neutral position, a length of approximately -0.1 in. corresponds to the maximum flexion possible in the glove, while 1.2 in. corresponds to the maximum possible extension. The rate of change of cable length, and hence an estimate of the MCP joint rotational velocity, can be obtained in software by low-pass filtering successive differences in cable length measurements.

Figure 9 shows the complete Mark II sensor/actuator system and its packaging. All of the major components of the system are shown including a motor, two gears, and an electrical connector. When closed, the entire package measures approximately 1.0 x 2.0 x 1.0 inches (excluding the mounting supports, which were designed to be common with the Mark I form factor).

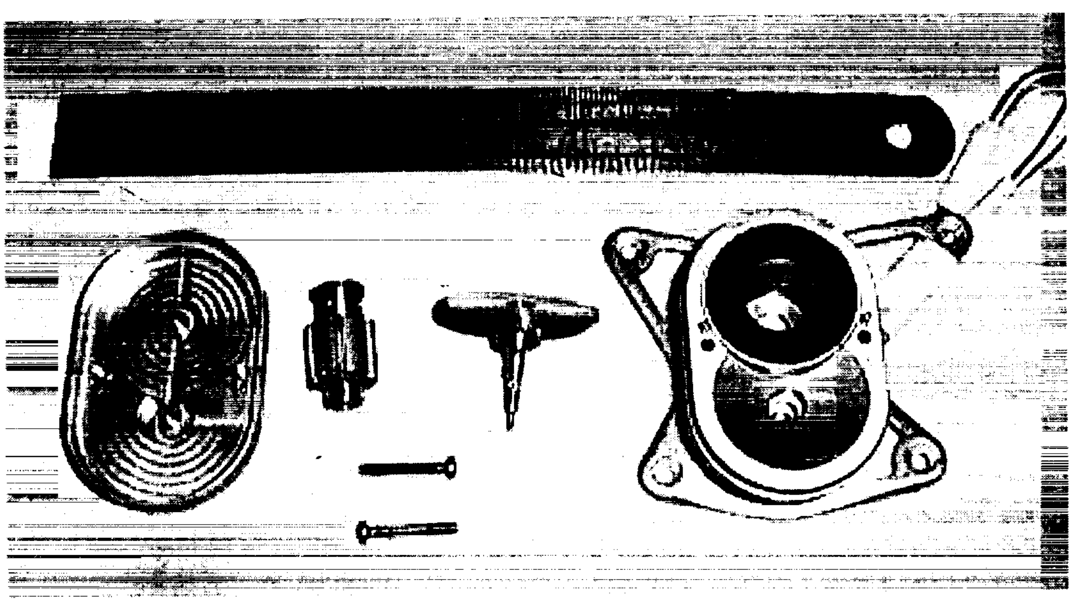


FIGURE 9: Sensor and actuator system package.

The actuator is controlled by a Gateway 2000 80486-based computer system equipped with a National Instruments NIDAQ board which performs digital I/O with the sensor circuit as well as D/A conversion to drive the DDC module. An Astec switching DC power supply provides up to 12 amps at 24V to run the motor, and a Sola linear power supply provides +/- 15V and +5V for the sensor circuit and DDC module respectively. These components of the power assist system are currently external to the actuator housing, although it is expected that these can also be miniaturized, similar to the SSL's JAMS bio-instrumentation system [20].

5.3.3 Comments on Mark II improvements

The switch to a brushless DC motor has provided a factor of four reduction in static friction levels, allowing for much smoother motion and less tendency for the system to exhibit unwanted "twitches" caused by limit cycling. The new motor and the reduction of stiffness in the Mark II softgoods has resulted in a factor of 2 decrease in required power: maximum power consumption is now approximately 35W, and average power consumption during typical glove usage is closer to 12W. A custom, optimized motor design combined with further refinements to the softgoods should enable a further factor of 2 reduction in power requirements in future iterations.

Use of the brushless motor also enables a significant reduction in the size of the actuator -- the Mark II actuator is 1.6 in thinner and 1 in shorter than the Mark I actuator. This reduction is achieved by using sensors already embedded in a brushless motor to quantify the extent of motor rotation, and hence the amount of MCP rotation, and thus the Mark II design can dispense with the optical encoder used in Mark I resulting in a more compact system. The reduced form factor and smaller power requirements also results in a design which runs significantly cooler than Mark I -- while the Mark I actuator would reach almost 200 deg F after 15 minutes of continuous use, the Mark II actuator has never been observed to run hotter than 140 deg F regardless of its usage.

5.4 Glove Testing

The following paragraphs describe the manned testing that was performed to quantify performance of the power assist glove system. As with any man operated system, full proof of concept cannot be realized until manned evaluations are performed. With space suit glove design, this is especially true.

5.4.1 Manned Testing

Manned glove box demonstrations were performed both at ILC Dover, NASA JSC, and NASA Headquarters. Subjective feedback from those evaluations revealed that the power assist system provided dramatic improvements in MCP joint range of motion and torque over current space suit gloves.

Additionally, at the NASA Headquarters demonstration a 4000 series flight restraint was donned, pressurized, and evaluated to define the current baseline MCP joint performance. In all cases, subjective feedback indicated that the 4000 series glove MCP joint torque was very high, and that full range of motion of the MCP joint was not possible. This conclusion is consistent with the fact that the 4000 series glove doesn't have a MCP joint. Visual examination of the palm side of this glove during attempts to rotate the MCP joint revealed that MCP joint movement occurs by forming a bubble on the palm side of the glove, with the majority of apparent MCP joint rotation occurring at the base of the fingers. This is not a natural method by which the hand is opened and closed.

The power assist glove was then donned, pressurized, and evaluated. In all cases, increased range of motion and lower torque in the MCP joint were realized. Both of these improvements allowed more natural MCP joint rotation, which is consistent with the program goal to obtain nude hand performance in the MCP joint.

5.4.2 Performance Data - Quantitative Fatigue Evaluation Protocol

Raw reduction of torque requirements is not necessarily a good metric of system performance; it is more important to determine if the design enhances gloved hand performance during common manual tasks. Even with a "perfect" power assist, unnatural joint orientation or controller chatter may make use of the power-assisted system awkward and may thus actually increase required effort. It is necessary, therefore, to more precisely quantify the glove-hand interaction as manual tasks are performed.

Physiological metrics which can be used to this end include range of motion and some measure of relevant muscle activity. Movement of the metacarpalphalangeal joint is produced primarily by contraction of the large flexor and extensor muscles in the forearm; the activity of these muscles during joint actuation may be quantified via electromyographic (EMG) techniques. Typical EMG metrics are based on signal amplitude, which scales primarily with muscle tension, and signal frequency content, which declines with muscle fatigue. In the results described below, range of motion studies and EMG spectral analysis are used to quantify the improvement in glove performance during MCP flexion and extension when the power assist system is active.

5.4.2.1 Experimental Protocol

Testing of the Mark I design (described in the previous progress report) was performed at ILC Dover Inc. in Frederica Delaware; testing of the Mark II design is currently in progress. The tests were performed in a small glove box, evacuated to a pressure differential of 4.3 psi, which contained the experimental glove and actuator system. The subject pool consisted of eight test subjects, five male and three female, ranging in age from 29 to 44 years. Subjects were selected on a volunteer basis from employees of the Space Systems Laboratory and ILC Dover, Inc.

Bipolar surface electrodes (Delsys DE-02, Wellesley, MA) were applied to abraded, cleaned skin over flexor and extensor musculature in the forearm in the locations described by Zipp, and a reference electrode was affixed to the skin over the medial epicondyle of the humerus. Electrodes were secured with adhesive tape, and subsequently the subject's forearm wrapped in self-adhesive covering (Vetrap) to cushion the electrodes and reduce inadvertent jarring from contact with the glove's wrist ring and glove box fitting. EMG signals were amplified and bandpass filtered to 20-500 Hz, and were collected at a rate of 1 kHz/channel throughout each 1-minute test session using Labview software on a Macintosh IIci platform. Good electrode contact was ascertained by visually examining EMG data from test contractions, and electrodes were repositioned as necessary. EMG gain settings were adjusted for each test subject to match the ±10V data acquisition apparatus range.

Prior to data acquisition, the test protocol was explained to the subject, and the glove actuator system calibrated with the subject's hand in place. Actuator calibration involved incrementally increasing cable tension until the initial cable slack was eliminated; the resulting cable length was then used as the zero reference for the duration of the trial. During unassisted trials, sufficient tension was maintained on the cable to continue to eliminate slack without augmenting force. This enabled collection of cable length data, representing MCP joint motion, during these trials.

Subjects were asked to actuate the glove MCP joint through its full range of motion in time with a metronome at a rate of 30 flexion-extension cycles per minute. Each test subject performed this task both with and without powered assistance, with a five minute rest between the sets. Subjects alternated set sequence to eliminate order effects.

5.4.2.2 Range of Motion Results

Examples of raw range-of-motion data from assisted and unassisted trials of a representative subject are shown in Figure 10. Note the large improvement in overall range of motion with power assist, and the time-dependent reduction in range during the unassisted trials.

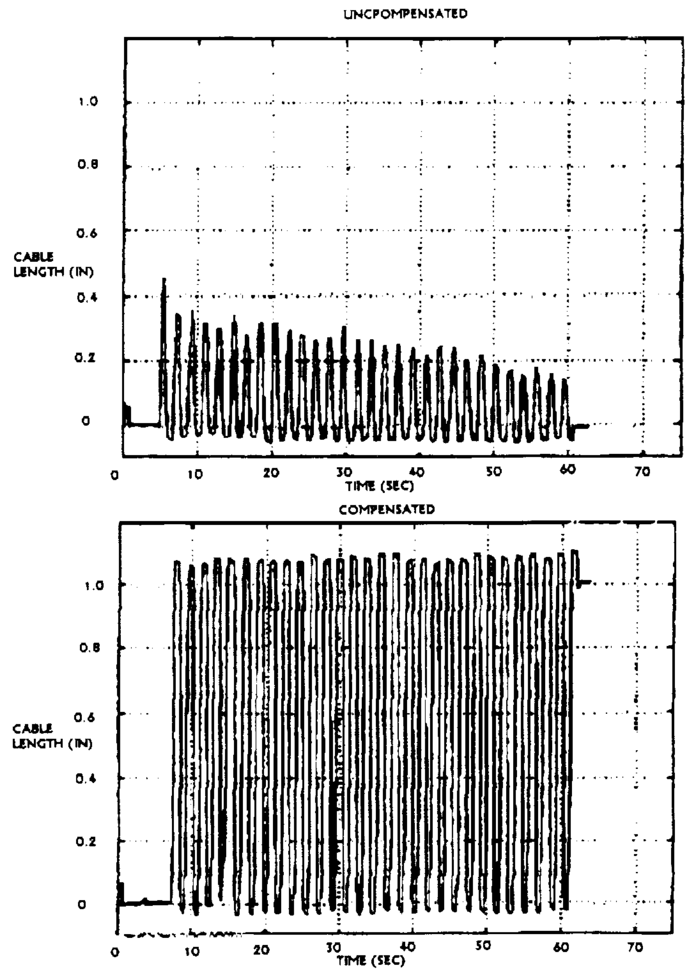


Figure 10: MCP joint range of motion in assisted and unassisted glove configurations.

One measure of system success is the dramatic increase in MCP joint range of motion (the difference between maximum and minimum cable travel) when power assist is enabled. Average range of motion for each flexion-extension cycle across all eight test subjects in both the power-assisted and unassisted cases is presented in Figure 10. Note that the maximum joint deflection in the assisted trials is initially more than four times that seen without power assist. Furthermore, joint deflection decreases with cycle number in the unassisted case, indicating that the muscle force required to open the joint cannot be sustained at the same levels throughout the trial.

In order to more clearly illustrate the differences in the power-assisted and unassisted ranges of motion, linear curves were fit to the data as shown in Figure 11. Average assisted range of motion of all subjects across all cycles can be represented as a constant with a slope of zero; thus, regardless of individual strength, all subjects performed equally throughout the 30 cycles. In contrast, range of motion in the unassisted case is noticeably reduced as the trials progress.

Additionally, the variation between subjects (as manifested by the standard deviation) is greater in the unassisted trials; this reflects the variability in unassisted subject strength. Thus, the unassisted range of motion is strength dependent while the full power-assisted range is achievable by all of the test subjects throughout the duration of the trial.

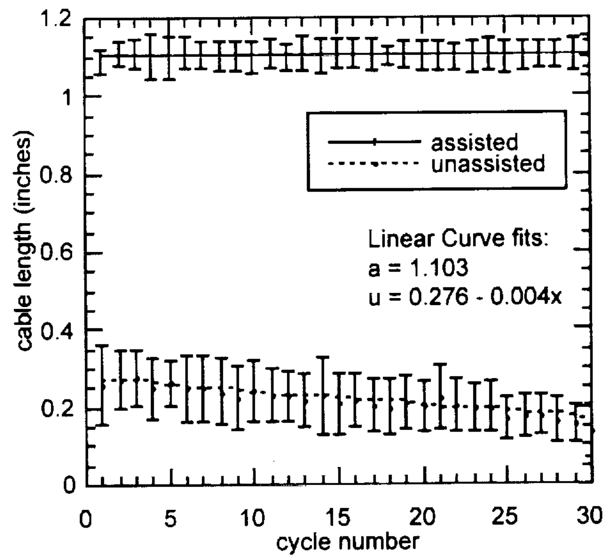


Figure 11. Mean and standard deviation of cable travel for each cycle across all eight test subjects

Further quantification of range of motion differences is shown in Table 1, which provides the average range of motion across the first 10 flexion-extension cycles of each trial. The 10-cycle averaged power-assisted range of motion is greater than the unassisted range of motion by a factor of 4.4. A two-sample t-test indicates that the averages are significantly different with $a<0.0005$.

Test subject	Unassisted	Power-Assisted
1	.253	1.082
2	.162	1.100
3	.316	1.120
4	.294	1.169
5	.368	1.105
6	.230	1.030
7	.268	1.097
8	.135	1.116
Average	.253	1.102
Std. Deviation	.072	0.036

Table 1: Average range of motion for the first ten trials for each test subject.

Note that the variance in the global average of the unassisted cases is twice that seen with power assist. This is due both to subject strength variation, and to time-dependent reductions in joint deflection within the ten cycles averaged here.

Since motions of the unassisted MCP joint may be modeled as subject to spring-like opposing torques, the cycle-dependent reduction in overall joint extension reflects a decline in the muscle force which is produced by the subjects. Thus, one metric of fatigue is a comparison of the joint range of motion during the first and last ten cycles of each trial. The ratio of these values is shown in Table 2.

Test subject	Unassisted	Power-Assisted
1	.613	1.025
2	.778	0.981
3	.851	1.029
4	.833	0.981
5	.666	1.014
6	.830	1.008
7	.672	0.983
8	.704	0.977
Average	.743	1.000
Std. Deviation	.085	0.020

Table 2: Ratio of the average of the first ten trials to the average of the last ten trials for each test subject.

A ratio of 1.0 in the power-assisted case, again indicating that range of motion is constant throughout trials, argues that muscle fatigue does not impede performance under these loads. However, in the unassisted case, the range of motion decreases to an average of 74% of the initial range, with a minimum decrease of 85% for every subject. Thus, muscle fatigue has grown to such an extent that task performance is significantly impeded. These results are significant for a two sample t-test with a<0.0005.

Since a reduction in range of motion is seen throughout the entire set of thirty trials in the unassisted case, the ratio of first ten trials to last ten trials is a conservative measure of apparent fatigue. A more accurate assessment of range of motion reduction is derived from the linear curve fit equation shown in Figure 10; comparison of first to last cycle values results in a reduction ratio of 57%.

5.4.2.3 Task Intensity Results

Task Intensity (I_{task}), an EMG-based subject-independent metric of task effort, was selected to compare muscle workload during power-assisted and unassisted trials. A complete description of the derivation and calculation of this metric may be found in the literature. Briefly, cumulative amplitude distributions of rectified EMG signals are calculated for all tasks performed by an individual subject, and then normalized by task length and maximum EMG amplitude. The area above each distribution curve is a measure of the muscle activity required to perform a task; this task intensity is expressed in percent and (provided that the tasks require equivalent relative effort from all subjects) can be compared across all subjects performing the same tasks.

Three groups of 10 flexion-extension cycles were extracted from flexor and extensor EMG data. Cumulative distribution functions and I_{task} values were calculated for each group of ten cycles, and the average group I_{task} determined for both assisted and unassisted tasks. Sample distribution functions from the extensor musculature of a representative subject are shown in Figure 12, and the I_{task} averages for all subjects are presented in Table 3.

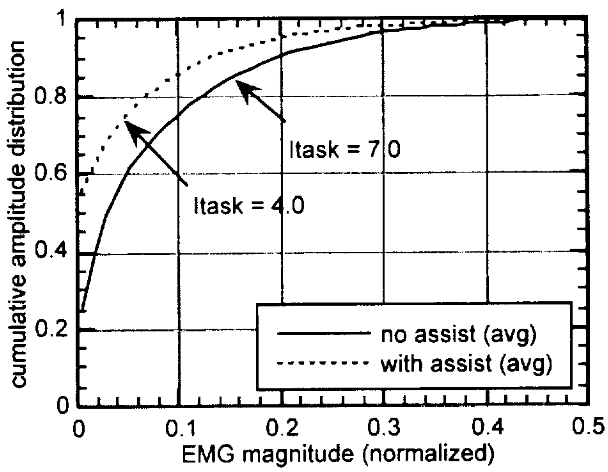


Figure 12: Average cumulative amplitude distribution curves for 10 flexion-extension cycles from extensor musculature. Note that the activity without power assist incorporates a greater proportion of higher-amplitude EMG values.

Subject	Extensor I_{task}(%)		Flexor I_{task} (%)	
	no assist	power assist	no assist	power assist
1	7.0	4.7	5.9	4.8
2	7.4	4.5	3.2	1.6
3	4.3	2.8	3.8	2.5
4	7.9	6.7	7.5	3.8
5	6.0	4.6	3.6	2.6
6	7.0	4.0	4.1	2.0
7	5.4	4.8	3.1	2.9
8	5.0	3.9	5.6	4.6
mean (stdev)	6.2 (1.3)	4.5 (1.1)	4.6 (1.6)	3.1 (1.2)
ratio (stdev)	0.73 (0.11)		0.68 (0.17)	

Table 3: Average Task Intensity values of 3 groups of 10 MCP flexion-extension cycles with and without power assist. Means are statistically significantly different at the a< 0.001 (extensor) and a<0.005 (flexor) levels.

Average difference in mean I_{task} values is 1.7 units in extensor musculature, and 1.5 units in flexor musculature. Statistical significance of these differences was determined to the a<0.001 (extensors) and a<0.005 (flexors) via paired t-test. The ratio of task intensities with and without power assist indicates that the powered system reduces task effort by 27% in extensor musculature, and 31% in flexor musculature over the unpowered system.

Informal EMG analysis of barehanded performance during similar activities reveals average I_{task} values of approximately 0 for flexor and 2 for extensor musculature. Negligible I_{task} values for barehanded MCP flexion are not unexpected, as the relaxed joint naturally assumes a closed position. The extensor I_{task} value suggests that assisted glove extension requires roughly twice the effort of barehanded motion; this quantity was verbally confirmed by some test subjects. Similarly, unassisted gloved extension appear to require approximately three times the effort of barehanded activity; this ratio may be misleading, however, as full extension was never attained during unassisted efforts. Use of 2 as a baseline extensor effort level indicates that power assist reduces extension effort by 40% rather than the 27% indicated above. Further testing is required to more precisely quantify barehanded I_{task} values and to further describe these ratios.

5.4.2.4 Discussion

Power assist significantly decreases the physiological effort required to extend and flex the metacarpalphalangeal joint, while at the same time greatly increasing the achievable range of motion. Power assist enables a 440% increase in average range of motion while simultaneously decreasing by 30-40% the effort (as measured by the I_{task} parameter) required to accomplish these motions. Moreover the effects of fatigue, as quantified by diminution in range of motion during repetitive MCP joint rotations, are not apparent when the assist mechanism is active, in contrast to the unassisted case where fatigue decreases range of motion by an average of over 40% during the thirty flexion-extension cycles studied.

The compensation from the assist also serves to greatly reduce the effects of physiological differences between subjects: while subjects varied by almost a factor of 3 in their ability to actuate the MCP joint when the assist was inactive, this difference was reduced to less than 10% when assisted. Indeed, the assist mechanism allowed all subjects to obtain nearly the full range of motion permitted by the glove design for each of the thirty cycles examined. Comparisons with "nude body" performance are also favorable: assisted extension I_{task} values are approximately twice as large as those seen in barehanded motions, with a full range of motion; without assist this ratio exceeds three, while achieving only 25% of the full range of motion.

It is interesting to note that decreases in flexor I_{task} values with power assist occur even though the assist mechanism does not directly aid MCP flexion. Indeed, the passive tension on the actuating cable during flexion makes glove deflection marginally more difficult than in the unassisted case; reduction of flexor effort must therefore be due to other factors. One possible explanation notes that high-force muscle activity typically requires cocontraction of antagonist muscles to provide adequate stability of the involved joints; thus large flexor activity may be required to maintain appropriate posture of the carpal and metacarpal joints during the maximal extensor activity seen while unassisted. This unexpected result illustrates the need for physiological analysis as a component of glove testing.

While the results presented are encouraging, they should be considered only an initial assessment of the true effectiveness of the proposed power assist strategy. Indeed, the test protocol adopted may actually have made the intensity of assisted motions appear excessively large: during the experiment, maximum MCP extension was not externally defined, so that subjects may have strained to open the glove further than its mechanical design permitted, resulting in unnecessarily large extensor I_{task} values. A revised test protocol should employ precisely defined external targets for maximum MCP flexion and extension to eliminate this potential variable. Efforts were made to utilize existing glove test protocols to evaluate the utility of the power assist, however subjects were observed to perform these tasks with roughly constant MCP orientation, regardless of the state of the assist mechanism, frustrating efforts to evaluate changes in MCP mobility. This observation suggests that the true extent of MCP joint involvement in manual tasks common to space operations should be more carefully investigated, and the results used to develop a more complete picture of the utility of the proposed power assist design.

6.0 SPIN-OFF TECHNOLOGIES

The NRA Power Assist Technology has potential application in the following areas:

- Prosthetic devices - the power assist technology, integrated with state-of-the-art EMG sensors, could facilitate movement of prosthetic devices or appendages of persons with loss of mobility.

- Virtual reality - this technology could benefit by using force feedback suits to enhance sensory feedback in the virtual reality environment.

- Ergonomics and rehabilitation - these fields could use the power assist technology to perform ergonomic evaluations of persons suffering from compromised mobility and reduced strength in their hands or limbs. In addition, the power assist glove technology could be modified to provide force feedback, thereby acting as a rehabilitation device.

7.0 IMPLEMENTATION CONSIDERATIONS & PROPOSED FOLLOW-ON

The current power assist technology is functional in a ground based, dry environment. However, the technology will require the work described below to make it NBL and flight ready. These modifications are considered to be refinements and minor changes that can be easily accomplished in Phase III of the program.

- Miniaturize control system support hardware - currently, the control system support hardware is housed in a desk top PC, with additional support hardware, including a power supply, also required. Current state-of-the art surface mount and microprocessor technology will allow all of this hardware to be mounted onto one electrical board approximately 6" x 6" x 1".

- Minimize power consumption and power via batteries - the estimated power for two gloves for an 8 hour EVA is 96 watt-hours. This power requirement is similar to that of the visor illumination system, and could be accommodated by batteries of approximately 6" x 6" x 6" in size. Minimization of the batteries required is an on-going program objective.

- Location of control and power systems remote to the glove - it is proposed that the power supplies be either located on the PLSS, or use current PLSS batteries. The power assist technology will use cable design and routing schemes much like the current Phase VI heated gloves do. Additionally, the control board will be located in an area remote to the gloves, probably on the PLSS as well.

- Water-proofing and vacuum compatibility of the system - the entire system will be hermetically sealed so as to be NBL compatible. Additionally, the system is already designed to operate in a vacuum in support of a flight evaluation.

It is recommended that Phase III of this NRA be awarded. The following activities would be proposed for a Phase III program effort:

- Demonstrate the power assist technology on orbit - the technology has demonstrated performance improvements of substantial enough magnitude that ILC believes this technology should be NBL tested and ultimately flown on a Detailed Test Objective (DTO) flight.

- Investigate the feasibility of using the power assist technology in the SSA shoulder joint - ILC believes that the power assist technology is at a mature enough state to be implemented in a higher torque, more complex SSA joint such as the shoulder joint. Implementation of this technology will benefit both zero g missions such as Space Station, as well as partial g missions such as a Martian mission.

1.0 ABSTRACT

In July of 1996, ILC Dover was awarded Phase I of a contract for NASA to develop a prototype Power Assisted Space Suit glove to enhance the performance of astronauts during Extra-Vehicular Activity (EVA). The need for such EVA improvements has been identified by many studies, including the Advanced EVA Systems Project Plan (Callaway, 1994 and Eppler, 194). Based on that need, a NASA Research Announcement (NRA) development contract was awarded to ILC in response to a proposal submitted by ILC Dover in April of 1995 for NASA Research Announcement 95-OLMSA-01. Following completion of Phase I efforts, Phase II activities were kicked off at ILC on 10/1/96, and continued through the end of 1997. This report summarizes the work that was completed in both Phase I and Phase II of the program, with an emphasis placed on Phase II activities. The reader is encouraged to refer to the Phase I final report, dated October 30,1997, if more specific details of Phase I are required.

Phase I of the program consisted of research and review of related technical sources, concept brainstorming, baseline design development, modeling and analysis, component mock-up testing, and test data analysis. ILC worked in conjunction with the University of Maryland's Space Systems Laboratory (SSL) to develop the power assisted glove.

Phase II activities focused on design maturation and manufacture of a working prototype system. The prototype was tested and evaluated relative to comfort, range of motion, and fatigue in conjunction with existing space suit glove technology to quantify the performance enhancement obtained with the implementation of the power assisted joint technology in space suit gloves.

2.0 PROGRAM OBJECTIVES, GOALS, AND ACCOMPLISHMENTS

The main goal of this program was to develop an unobtrusive power-assisted EVA glove metacarpalphalangeal (MCP) joint that could provide the crew member with as close to nude body performance as possible, and to demonstrate the technology feasibility of power assisted space suit components in general. The MCP joint was selected due to its being representative of other space suit joints, such as the shoulder, hip, and carpometacarpal joints, that would also greatly benefit from this technology.

In order to meet this objective, a development team of highly skilled and experienced personnel was assembled. The team consisted of two main entities. The first was comprised of ILC's experienced EVA space suit glove designers, who had the responsibility of designing and fabricating a low torque MCP joint which would be compatible with power assist technology. The second part of the team consisted of space robotics experts from the University of Maryland's Space Systems Laboratory. This team took on the responsibility of designing and building the robotics aspects of the power-assist system. Both parties addressed final system integration responsibilities.