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The Effects of Extravehicular Activity Gloves on Human Hand Performance

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ABSTRACT

Past approaches to space suit glove evaluation have primarily been subjective. This report details efforts at the University of Maryland Space Systems Laboratory to use standardized dexterity tests and advanced biomechanics instrumentation to provide objective measures of glove performance. Ten subjects participated in the study. Tests were conducted barehanded, and wearing pressurized and unpressurized space suit gloves. Data on performance time, range of motion, dexterity, strength, fatigue, and comfort were collected. Range of motion data was measured using an experimental data glove that instrumented the movement of the joints of the right hand. The results indicated that performance time wearing pressurized gloves is not adequately estimated by performance wearing unpressurized gloves. Also, joint angle results indicated a decrease in the range of motion from the barehanded condition, but no significant difference between the gloved-hand conditions. Thus, range of motion is adequately estimated for the pressurized condition by examining range of motion wearing unpressurized gloves. Results of this research indicate that the use of standardized dexterity tests, with appropriate modifications to accommodate the restricted dexterity, provides a useful basis for evaluating space suit glove performance.

INTRODUCTION

Human hand capabilities such as dexterity, object manipulation, and tactile perception are unique factors that make the hand a versatile and effective tool during extravehicular activity (EVA). In the EVA environment the hand is not only a multipurpose tool but also the primary means of locomotion, restraint, and object handling. However, existing EVA gloves significantly reduce hand dexterity, range of motion, tactility, strength, and endurance. In addition, they are often uncomfortable to the point of pain and/or minor physical injury to the hands. The development of comfortable gloves, with improved dexterity and tactility, is considered essential to maximize the productivity of EVA (Shepherd and Lednicky, 1990). By researching improvements to gloves commonly used in a microgravity environment, it is hoped to limit astronaut fatigue and improve overall EVA efficiency.

BACKGROUND – Glove evaluation in the past has been highly subjective. In general, astronauts with extensive experience using EVA gloves provided their opinion on the designs of new gloves, but no quantitative analysis was performed. In recent years, there has been a movement toward less subjective and more quantitative glove evaluation. The glove evaluation variables that have been quantitatively studied in recent years include range of motion, tactility, strength, dexterity, fatigue, and comfort.

Previous Work – Range of motion has traditionally been measured using video tracking of joint angles. However, this technique has been highly unreliable due to the requirement that the joint angles of interest be directly perpendicular to the plane of the camera. Ranniger (1993) examined joint angles by using fiberoptic bend sensing technology. However, the results obtained examined joint motion for the thumb and index fingers of only two test subjects. In general, a reliable quantitative means for measuring range of motion has been absent from previous glove evaluation studies.

Previous studies have found range of motion of the thumb and fingers to be substantially affected by EVA gloves. In studies conducted by Durgin et. al. (1985) and Garret (1968, 1976) pressure was found to have a large effect on range of motion; in fact, more of a contribution than the gloves themselves. Range of motion results obtained by O'Hara et al. (1998) reported no effect due to the gloves or pressure differential on thumb MCP flexion and extension, wrist flexion, and wrist adduction. The gloves affected PIP flexion and extension of the index finger, and both gloves and pressure affected MCP joint motion of the index finger. Decreased MCP use for all glove conditions was reported in the EVA Glove Test Protocol report (Hinman-Sweeney, 1994). The Extravehicular Activity Limitations Study performed by O'Hara et. al. (1998) indicates that the results should be taken as general trends due to problems associated with accurately videotaping the bending of the joints.

Dexterity is reduced when wearing unpressurized gloves, and the introduction of a pressure differential reduces it further. O'Hara et al. (1998) showed that unpressurized gloves reduce dexterity by 50%, and that wearing pressurized gloves decreases dexterity by an additional 30%. Bishu and Klute (1993) found that gloves increase performance time for a given task, and the addition of a pressure differential further increases performance time. They indicated that this decrease in dexterity is likely due to a reduction in range of motion and tactile sensitivity. Bishu et al. (1993) found that performance while wearing gloves is nearly five to six times slower than barehanded performance. The Human Role in Space (McDonnell Douglas Corporation, 1984) study estimated that it took 50% longer to do fine motor tasks while wearing pressurized EVA gloves than while barehanded; however, coarse hand and arm movements took approximately the same length of time. Studies suggest that the time difference in performing fine hand motions is due to sensitivity and dexterity differences between the gloved and ungloved hand (McDonnell Douglas Corporation, 1984; Shepherd and Lednicky, 1990).

<u>Anatomy of the Hand</u> – There are 27 bones in the hand and wrist and over 25 degrees of freedom, many of which are coupled. There are five metacarpal bones that form the skeleton of the major part of the hand. The skeleton of the fingers is formed by phalanges. The three phalanges of each finger are called proximal, intermediate or middle, and distal phalanges, respectively. The thumb has only two phalanges, referred to as proximal and distal. The digits are commonly referred to as the thumb, index, middle, ring, and little/fifth digits, or fingers.

The joints of the hand are named for the bones they connect. The interphalangeal joints are the joints between the phalanges in the fingers. Each finger has two interphalangeal joints (IP's); the distal interphalangeal joint (DIP) and the proximal interphalangeal joint (PIP). The thumb has only one IP joint, connecting the proximal and distal phalanges. The metacarpophalangeal (MCP) joints are the joints between the metacarpal bones and the proximal phalanges of the fingers. The IP and MCP joints are capable of flexion (bending) and extension (straightening). In addition, the MCP joints are capable of abduction (spreading of the fingers) and adduction (bringing the fingers together).

Because range of motion may be a critical component of dexterity, examination of joint motions during simple as well as complete, realistic activities can provide useful information about hand performance. However, measuring all degrees of freedom of the hand while performing a particular task would be extremely difficult. Additionally, for assessing range of motion of the hand while wearing EVA gloves, this level of instrumentation would be unnecessary. Therefore, the flexion and extension of the PIP and MCP joints of the five digits was examined in this study, since these joints have simple motions that may be easily measured, and are of prime importance in typical EVA manual tasks.

OBJECTIVE – The objectives of this research were:

- to determine the effects of gloves on hand performance, for a variety of conditions, using standardized dexterity tests;
- to collect and examine range of motion data using an experimental data glove; and
- to establish baseline data that will be used in future research.

Two approaches were taken in order to fulfill the objectives. The first was to collect and examine hand performance data for barehanded, unpressurized, and pressurized glove conditions for each standardized dexterity test. The performance data was used to determine the differences between the dexterity tests and their application to glove testing. The second approach was to collect joint angle data for the test conditions while performing each dexterity test. The data for range of motion was examined to quantitatively identify the limitations that EVA gloves impose on hand function.

METHOD

PROCEDURE – The effects of several independent variables on hand performance capabilities were investigated. The first independent variable was the test condition - barehanded versus unpressurized and pressurized gloves. The second independent variable was the type of dexterity task performed. Grip strength and hand size were also examined.

Four test conditions were investigated, and each subject participated in all four conditions for each test in the test battery. The four conditions were: barehanded outside the glove box (B); wearing unpressurized gloves outside the glove box (WGO); wearing unpressurized gloves and arm segments inside the glove box (WG&AI); and wearing pressurized (4.3 psid, 30 kPa differential) gloves and arm segments (P). While the barehanded and pressurized cases are of most direct relevance to EVA studies, it was felt that examining the two intermediate unpressurized cases might provide useful information on the relative importance of hand and arm mobility, and on whether pressure forces or glove bulk plays a larger role in limiting EVA manual performance.

Range of motion, dexterity, strength, fatigue, and comfort were measured in this study. Range of motion data was collected using the joint angle sensors located within the data glove and measured in terms of percentage of maximum bend. Strength was determined using a hand dynamometer and was indicated in pounds of force. Standardized tests of dexterity were used. For each test the performance measurement was the amount of time (in seconds) for task completion, and the number of test pieces dropped. A subjective fatigue scale, modified from the Borg 10-grade Perceived Exertion Scale, was given to the test subjects upon completion of each test and condition. The scale ranged from 0 (No exertion - at rest) to 10 (Extreme exertion - can not continue). The test subjects indicated comfort in the form of a post-test questionnaire.

TEST SUBJECTS – For this study, a total of ten test subjects participated. Test subjects were chosen following an initial pre-selection based on hand size. The two requirements imposed on the test subjects were: (1) that their left and right hands fit into the left-handed Skylab A7L-B suit glove and right-handed 4000 series Shuttle suit glove currently possessed by the SSL, and (2) that subjects be right-handed. The test subject pool included four females and six males, ranging in age from to 22-34 years. Participants were not experts, but some had limited experience using EVA gloves. All test subjects were volunteers and consisted of SSL employees and students. Each subject completed an informed consent form prior to participation in the study.

It was determined that the most likely differences in performance when using the gloves would be the subject's hand strength and size. These parameters influence range of motion and dexterity between subjects. Because of this, test subjects were not only classified by hand size, but also by hand strength, measured by cylindrical grip strength. Hand size was expressed as a volumetric parameter that was determined by multiplying the length of the hand, width of the hand, and width of the middle finger. By examining a volumetric measure, hand size differences become apparent, and can be associated with glove fit and performance.

DEXTERITY TESTS – Quantification of hand performance during EVA can be performed in many different ways. Testing of different glove designs must be objective, accurate, and reliable. Standardized testing allows us to address all of these desirable objectives. Standardized testing involves establishing a set of procedures to be followed using a determined set of equipment. It allows the same results to be obtained for tests performed in different locations, and/or by different test conductors. There were numerous standardized dexterity tests reviewed for use in this study. The Hand Tool Dexterity Test, the complete Minnesota Dexterity Test, and Purdue Pegboard were selected from among the tests as having the greatest applicability for EVA operations.

The Hand Tool Test consists of two wooden uprights with three sets of holes on each side that hold nut-and-bolt assemblies of three varying sizes. The test requires subjects to use common hand tools, such as wrenches and screwdrivers, to loosen, transfer to the opposite upright, and tighten the nut-and-bolt assembly. The use of common tools and the range of movement of the Hand Tool Test made it a desirable test for this application.

The Minnesota Dexterity Test consists of a rectangular tray that holds cylindrical disks. The disks are approximately one inch (2.5 cm) in diameter, and are colored red on one side, black on the other. Two tests were chosen for this research. The Minnesota Displacing test requires subjects to transfer the disks from one hole in the tray to another. The Minnesota Turning Test requires subjects to pick up a disk, transfer it to the other hand while turning it over, and replace it with the opposite side facing up.

The Purdue Pegboard has been used extensively for various applications. It has two types of activity: one measures gross movements of the hands, fingers, and arms, and the other measures assembly or fingertip dexterity.

A pilot study was conducted to determine the feasibility of using the three chosen standardized manual dexterity tests for this glove research project. The study indicated several changes to be made to the test equipment and procedures to improve the overall test protocol for a subsequent study. The procedure for the Hand Tool Test (HTT) was changed to include using only the top row of nuts and bolts, as manipulating the smaller nuts and bolts proved to be extremely difficult with gloves on. Also, the amount of time required to remove and replace each nut-and-bolt assembly was recorded. To accommodate a limited reach envelope inside the glove box, the Minnesota Displacing Test (MDT) and Minnesota Turning Test (MTT) procedures were changed from using an array of 60 disks, to using a smaller array of 9 disks. Finally, a Modified Purdue Pegboard (MPP) test was created, resized to scale, using cylindrical pins four inches (10 cm) in length and 3/8 inches (0.95 cm) in diameter. This pin size was selected to correspond to the average pip pin size used during EVA. The original pins of the Purdue Pegboard test were one inch (2.5 cm) in length and approximately 0. 125 inches (0.318 cm) in diameter. These pins were nearly impossible to pick up while wearing space suit gloves. The dexterity tests, with the equipment changes made as a result of the pilot study, are shown in Figure 1.

The test matrix incorporated four one-hour test sessions, and was designed to optimize the lengths of the session and reduce subject fatigue. The first test session included a description of the testing methods for the subjects, and measurements of hand size and grip strength. Performance for the barehanded and unpressurized conditions of the MPP was measured. The second test session measured performance for the barehanded and unpressurized conditions of the HTT, and the pressurized condition of the MPP. The third session measured the performance for the barehanded and unpressurized conditions of the MTT, and the pressurized condition of the HTT. The final test session included measuring performance of all four conditions for the MDT, and the pressurized condition for the MTT.

TEST ENVIRONMENT AND GLOVES – Glove testing was conducted at the Space Systems Laboratory (SSL) at the University of Maryland, College Park. The glove box used in this study was on long-term loan to the University of Maryland by NASA Goddard Space Flight Center. The box is cylindrical in shape and is approximately 0.6 m in diameter and 1.2 m in length, giving an internal volume of approximately 0.37 cubic meters. There are two 15 cm circular openings in the cylinder, placed shoulder width apart, which provide access for the EVA arm segments and attached gloves.

For this study, the glove used on the right hand was a donation from ILC-Dover that was made of surplus glove components, including a full thermal/ micrometeoroid garment (TMG). While it closely resembles a series 4000 EMU glove in configuration and performance, it should be emphasized that data obtained from this glove is not necessarily representative of the performance of the current Phase 6 EMU gloves. A Skylab A7L-B glove, also including the TMG, was used on the left hand. Each glove mates with shuttle series arm segments, also loaned to the University of Maryland by NASA Goddard Space Flight Center.

EXPERIMENTAL DATA GLOVE – The data glove is a lightweight silk glove liner with flexible sensors attached that accurately and repeatably measures the position and movement of the fingers and wrist. The 14 sensor glove features two bend sensors per finger; one sensor over the PIP joint and the other on the MCP joint of each digit. The remaining sensors measure thumb abduction/ adduction, palm arch, wrist flexion/extension and wrist abduction/adduction. The sensors are attached to an inner silk glove liner, as shown in Figure 2. Another glove liner is placed over the inner liner to offer protection for the sensors, and also to aid in conforming the sensors to the joint when the hand is flexed.

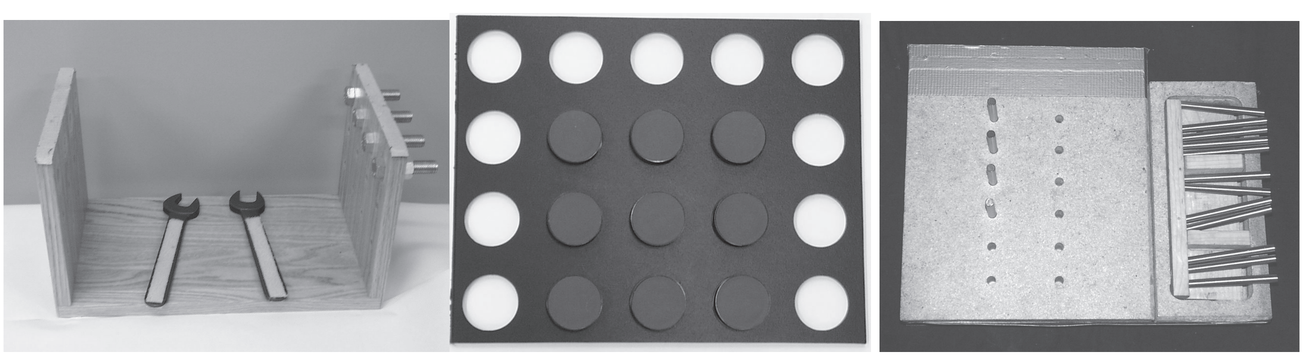

Figure 1
Standardized Dexterity Tests
(l. to r. – Hand Tool Test, Minnesota Dexterity Test, Modified Purdue Pegboard)

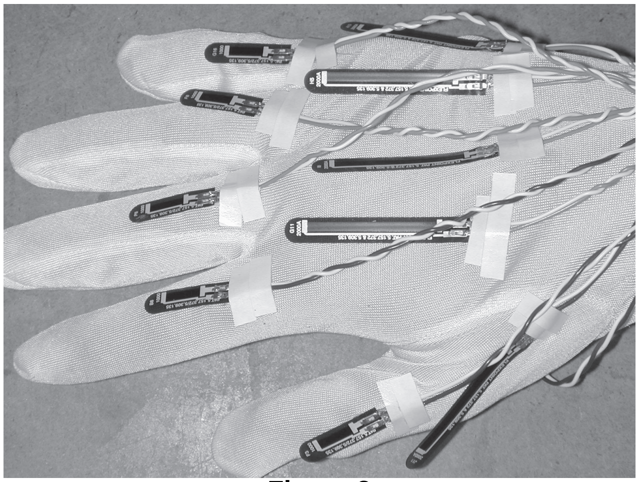

Figure 2
Biomechanics Sensor Glove
showing placement of bend sensors

The primary requirements imposed on the data glove system design were to be safe, to be economical, and to not interfere with normal hand activity. The data glove was developed to meet these requirements. The system noninvasively monitors joint motion of the right hand. The constraints of the EVA glove result in significant reductions in the hand's range of motion and finger dexterity. Thus, using a subset of the barehanded degrees of freedom to quantify the limited gloved hand motion can be justified. Examination of hand motions during typical EVA tasks indicates that finger flexion/extension cycles are significantly more prevalent than wrist flexion/extension, abduction/adduction, or rotation during all phases of EVA. For example, during airlock operations, Cleland and Windield (1985) estimated 2287 finger flexion extension cycles per hour, with only 11, 29, and 39 wrist flexion/extension, abduction/adduction, and roll cycles per hour, respectively. Therefore, a system primarily focused on providing information about position and motion of the fingers was selected for this application, with a secondary focus on wrist movement, palm arch, thumb abduction/adduction.

Several different mechanisms by which to track joint angles of the hand were considered in the course of this research. Candidate joint angle tracking systems included flexible film resistors and fiberoptic systems. The Flexpoint Bend Sensor potentiometer was selected due to its lightweight, robust, and cost effective characteristics. Initial testing with the sensors proved them to be a simple and reliable indicator of bend for this application. Because both two-inch (5 cm) and one-inch (2.5 cm) long Bend Sensors were to be used with the data glove, rate of change profiles were completed for three of each sensor length.

Each sensor was inserted into a voltage-divider circuit with a +5 V excitation voltage and 30 kOhm. resistor. The sensors were bent around a diameter of 0.95 cm. Measurements were taken in increments of ten degrees. A linear regression was performed for each curve and the results indicated a strong linear correlation for each sensor's rate of change profile. In this case, the r-value (Pearson product-moment correlation coefficient) for each sensor was greater than 0.976 and the significance value, p, for each of the six sensor profiles was 0.0001. This is much less than the significance level of 0.05, and therefore, a linear approximation is a reasonable assumption. Thus, for simplicity, all sensors were assumed to have linear bend profiles in this research.

When integrated into a voltage divider circuit, the voltage changes as the sensor is bent. The voltage ranges from the minimum resting voltage acquired from the sensor to +5 VDC when the sensor is bent to saturation. The one-inch sensors were placed over the PIP joints, and the two-inch sensors were placed over the MCP joints. Joint angle data was taken at a sampling rate of 10 Hz.

Range of Bend and Range of Motion – Range of bend and range of motion (ROM) data were collected by the data glove, which examined the joint angles of the right hand during each task. All joint angles were transformed into a percentage of maximum bend. Range of bend focuses on the minimum and maximum values of a joint during a task. For example, suppose a test subject is able to bend a particular joint between 0 and 100 degrees. During a given task and condition, this same test subject bends the joint between 10 and 50 degrees. Therefore, the range of bend is between 10% and 50% of the maximum bend. Range of motion focuses on the range of movement of a joint during a task. Using the same example, the test subject uses a range of motion of 40% during the task. While performing the same task in a different test condition, the subject has a range of bend between 30 and 70 degrees, or 30% and 70% of the maximum bend. However, the test subject is still using a range of motion of 40%.

The sensors were assumed to have a linear relationship between voltage and degree of bend. Each test subject completed a calibration program prior to testing which indicated the minimum and maximum voltages for each test subject, and thus the minimum and maximum bending of each joint. Because hand size varied between test subjects, and the data glove sensors varied in profile, a calibration of the data glove to the hand of each test subject was necessary.

During calibration, the test subject was instructed to hold his/her hand in a variety of positions that were designed to yield the minimum and maximum joint angles of the hand. For example, holding the hand in a fist allowed the maximum values, V_{MAX}, of the PIP and MCP joints to be found, while holding the hand in the full open position allowed the minimum PIP and MCP values, V_{MIN}, to be found. The calibration joint angle data was transformed into a percentage of maximum bend by linear interpolation.

RESULTS

APPROACH TO DATA ANALYSIS – Upon completion of data collection the following results had been obtained:

- Performance time for each condition (barehanded, pressurized, etc.), task (Pegboard, Hand Tool Test, etc.), and trial.
- Joint angle data for each condition, task, and trial.
- Grip strength for each subject taken barehanded, while wearing unpressurized gloves, and pressurized.
- Subjective perceived exertion scale values
- Subjective comfort comments from questionnaire

By using the calibration results, the joint angle data was transformed into percentages of maximum bend. The last two trials for each test subject, condition and task were examined and used in the range of motion averages, in order to minimize learning effects. Learning effects create noise in the data and make the determination of performance effects more difficult to determine. Data from the tests were statistically analyzed using analysis of variance (ANOVA). Analysis of variance was chosen as it allows evaluation of both the main effects due to pressure glove use, and interaction effects among the independent variables. The significance level (alpha) was set at 0.05. Effects with a p-value < alpha are referred to as statistically significant. The Statistical Analysis Software (SAS) package was used for the analysis.

TIME DATA RESULTS – An ANOVA test was performed to examine performance time differences for each of the four conditions over all tasks. The Duncan groupings given by the ANOVA test indicated that there is a significant difference between pressurized performance and all other test conditions. It is also interesting to note that there was no statistical significance between the barehanded and unpressurized glove conditions for three of the four tasks (Hand Tool Test, Minnesota Displacing Test, Modified Purdue Pegboard). Thus, the results indicated that the best way to determine human hand performance for a task while wearing pressurized gloves is to perform the task pressurized. Wearing unpressurized gloves does not appear to be a reliable estimate of performance for the pressurized case.

Performance degradation, from the barehanded to pressurized condition, was evident in the average test times of each subject. Pressurized performance decreases from the barehanded condition by a factor of twelve for the HTT; nearly double the amount seen for the Minnesota Turning Test, and triple the amount seen for the Minnesota Displacing Test. However, performance for barehanded and unpressurized glove conditions demonstrates a comparable decrease for all four tests. Thus, the difference between the tests is seen clearly for the pressurized condition. The Hand Tool Test sees the greatest increase in pressurized performance time from the barehanded baseline, while the Minnesota Displacing Test sees the least. These values give insight into the degree of difficulty of the different dexterity tests.

In an attempt to explain performance differences seen in the pressurized case, grip strength and hand size were examined. A linear regression was performed comparing grip strength and hand size to performance time. While a linear relationship was statistically significant for some of the pressurized cases of the dexterity tests, the r-values were low. A statistically significant correlation with a low r-value could mean that the relationship between the variables is not actually linear, but rather a nonlinear relationship (i.e. quadratic, exponential, etc.). Or, a low r-value may indicate that there are additional factors affecting the variables that are not taken into account by the linear correlation.

Because a linear correlation does not indicate which variables significantly affect hand performance when compared with all other hand variables, an ANOVA was performed. The ANOVA was used to determine the degree to which hand strength and hand size variables influence performance time. The variables compared were grip strength, hand length, hand width, hand size metric, and the combination of grip strength with the three hand size parameters. The results indicated that, for all four dexterity tests, there is no pattern that identifies a single hand variable, or combination of variables, affecting performance time. None of the hand variables affected pressurized performance time. Thus, the results suggest that there are other variables affecting performance than hand size variables and grip strength.

Other factors that may have influenced performance time in this study were factors associated with the glove box and the arm segments. The glove box itself and the fit of the arm segments forced some subjects to work in a manner that they felt was uncomfortable and unnatural, and may have affected performance times.

Factors affecting hand performance were identified and examined to determine their relevance to predicting performance time. Ultimately, the conclusion remains that the best predictor of performance time for a task done while wearing pressurized gloves is actual performance of the task in the pressurized condition. Unpressurized gloves, and/or hand strength and size are not adequate for predicting pressurized performance time.

JOINT ANGLE DATA RESULTS – Joint angle data was examined to identify restrictions in range of motion for each of the four conditions and tasks. An ANOVA was performed to determine the change in range of motion for each joint across the four conditions. Figure 3 shows the average range of bend during the Hand Tool Test for the two measured joints of each finger, for all four conditions. The results indicate that proximal interphalangeal (PIP) use significantly decreases once gloves are donned. The metacarpophalangeal (MCP) joints show a similar decrease in motion, but on a smaller scale. This is surprising due to the fact that the glove is not designed to allow for MCP joint movement, but rather provides articulation at each PIP joint.

Based on the ANOVA analysis, there is a significant difference between the minimum and maximum barehanded values and the minimum and maximum values for the other three conditions. However, this data only describes the changes in the minimum and maximum bend. It does not describe how the actual range of motion changes. Figure 4 shows the changes in the actual range of motion for each joint and for each condition.

The ANOVA groupings indicate that there is a significant change in range of motion as soon as the gloves are donned for most of the joints. However, the thumb and index finger MCP joints have no decrease in the range of motion, even though the minimum and maximum percent of bend significantly decreases. These groupings also support the findings that PIP range of motion significantly decreases, even though PIP motion is incorporated into the design of the gloves. Additionally, MCP usage does not decrease as much as PIP usage, as indicated in Figure 4. The greater decrease in PIP range of motion may also be due to the fact that flexion of the PIP joints is weaker than flexion of the MCP joints. This difference in strength, corresponding to a difference in range of motion, should be investigated further.

This same analysis was performed for the other three dexterity tests. The groupings for the MPP provide additional support of the findings that PIP range of motion significantly decreases from the barehanded condition as soon as gloves are donned. However, there are differences in joint range of motion when comparing the four dexterity tests. Therefore, the total

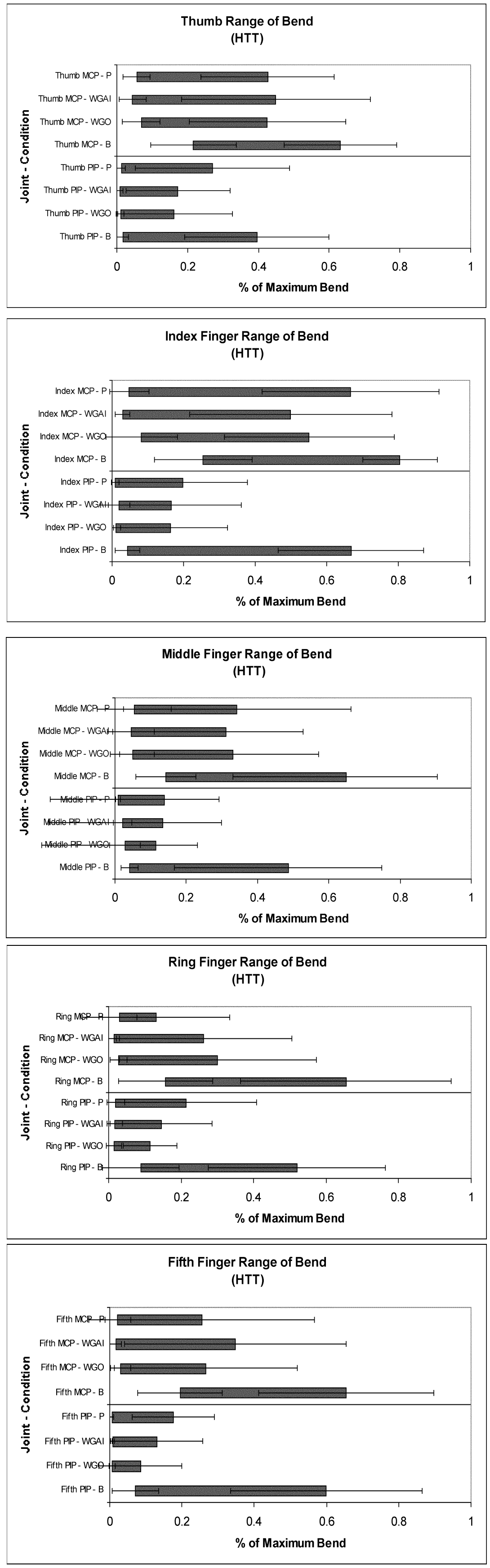

Figure 3
Range of Bend for Fingers During Hand Tool Test

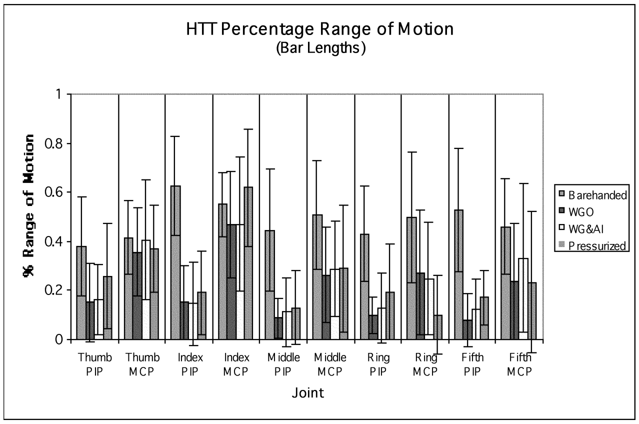

Figure 4
Range of Motion for Hand Tool Tests

range of motion used during the four tasks was assessed. Figure 5 shows the average PIP and MCP joint range of motion used during the four tasks and the four conditions.

From the graphs, it is evident that the Hand Tool Test requires subjects to use an average of 50% of their total PIP joint range of motion when barehanded. In contrast, the Minnesota Displacing and Turning tests only require subjects to use an average of 15-20% of their total PIP joint range of motion. Therefore, when testing during the glove conditions, the decrease in PIP range of motion for the Minnesota tests is less than the decrease seen during the HTT. The Modified Purdue Pegboard requires subjects to use approximately 40% of their total PIP range of motion during the barehanded condition, and again there is a similar decrease in joint movement during the glove conditions, as is seen in the HTT.

For MCP joint range of motion, similar results are seen. The HTT and MPP tasks require subjects to use a greater degree of range of motion during barehanded testing than both Minnesota tasks. HTT and MPP range of motion for the MCP joint is approximately 35-48% during the barehanded condition. For all of the tests however, there is a smaller decrease in MCP joint range of motion than PIP joint range of motion. When testing for range of motion during gloved-hand operations, it is preferable to select tasks that require subjects to use a large range of motion when barehanded. Thus, the effects of the gloves on range of motion are more clearly seen. Therefore, when comparing the four standardized dexterity tests, the HTT and MPP emerge as being able to provide more applicable and valuable data.

In general, range of bend and range of motion for tasks performed in a pressurized glove condition can be adequately estimated by wearing unpressurized gloves. However, for the ring and fifth fingers it is uncertain whether or not the decrease in range of motion for the gloved conditions is presumably a factor of test subjects

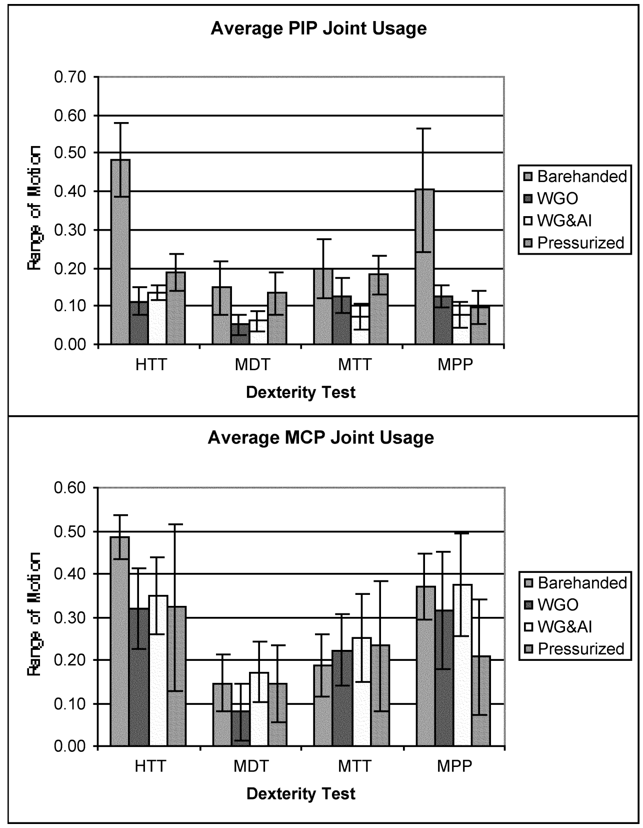

Figure 5
Average PIP and MCP Joint Usage

not using the two fingers, rather than an actual decrease in range of motion. Therefore, while performance time is not accurately estimated by wearing unpressurized gloves, as stated in the previous section, range of motion for the thumb, index, and middle fingers is. Also, because the Hand Tool Test and Modified Purdue Pegboard require subjects to use a greater barehanded range of motion, they are more applicable tests to assess the effects of gloves on range of motion. These conclusions support a means for quantitative assessment of the effects of EVA gloves on range of motion and hand performance, and provide valuable information on predicting hand performance.

SUBJECTIVE FATIGUE AND COMFORT RESULTS – Perceived exertion for each condition significantly increases for each of the four tasks despite no significant differences in performance time between barehanded and unpressurized glove conditions. Thus, although test subjects perceive that they are working harder for each successive condition, they are able to compensate and achieve an adequate performance time. Additionally, it was apparent from the results that the HTT and MPP tasks were perceived to be more difficult than the Minnesota Dexterity tasks for all gloved conditions. This is likely because the HTT and MPP require the fullest range of motion and hand dexterity, while the Minnesota tests require the least range of motion and are limited to gross hand movements.

PHASE RESULTS – During testing, the test conductor noticed many test subjects positioning their fifth finger in such a way that it would not interfere with testing. Many test subjects did not use their fifth finger during gloved tasks, as it seemed to interfere with grasping and moving objects. Many test subjects commented that they did not have sufficient strength to bend the fifth finger during the pressurized condition. This led to a phase analysis for the joint angle data of the fifth and ring fingers. It was hypothesized that test subjects moved their ring and fifth fingers together when grasping objects. Phase data was examined to determine whether or not the ring and fifth finger PIP joints and MCP joints bent together during grasping tasks. Because the HTT included more grasping motions, the results from this test were examined for joint phasing. Examples of the results are shown in Figures 6 and 7 for test subject eight (TS8) for the HTT.

The graphs for test subject eight show the barehanded and pressurized set of conditions for the Hand Tool Test. For all of the dexterity tests, it becomes increasingly difficult to analyze the phase results for the pressurized condition due to the small amount of joint movement for that condition. As shown in the graphs for the HTT, the PIP joints and MCP joints of the ring and fifth fingers have a similar profile during the tasks. They show a corresponding bend in the fifth finger joints when bending the ring finger joints.

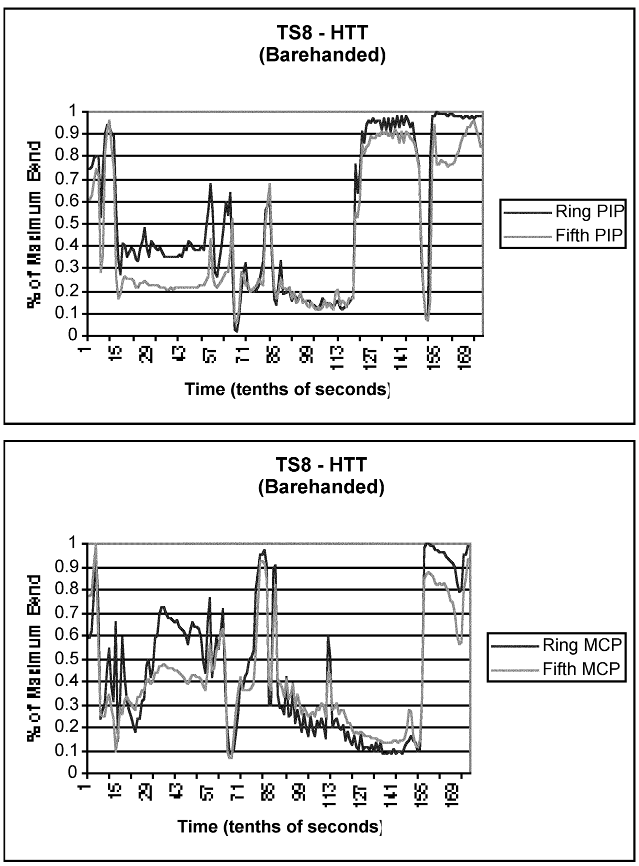

Figure 6
PIP and MCP Joint Phasing of Test Subject 8 for Barehanded Case of the Hand Tool Test

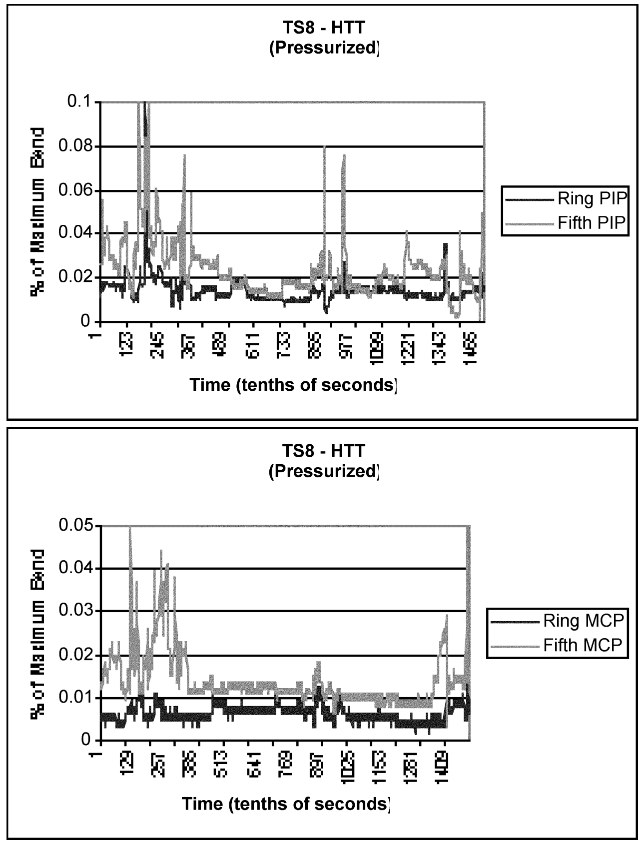

Figure 7
PIP and MCP Joint Phasing of Test Subject 8 for Pressurized Case of the Hand Tool Test

Interestingly, the greatest degree of phasing for the ring and fifth finger PIP and MCP joints is seen during the barehanded condition. This leads to the determination that, for subjects showing a large degree of phasing, it is a natural hand movement to correlate the bending of the two fingers during the tasks. When gloves are donned, this motion persists, but the effect of the gloves makes it difficult to bend the joints of the two fingers together. Synchronized bending becomes even more difficult when a pressure differential is introduced. Therefore, the gloves may be restricting a motion that is inherently natural for the two test subjects.

This corresponding bend for the PIP and MCP joints of the ring and fifth fingers is not seen in all test subjects, for all tasks and conditions. While no definitive conclusions can be made that the ring and fifth fingers always bend together during grasping motions, the results indicate that often times they do, especially during the barehanded condition. One possible future glove design could examine the performance changes associated with combining the ring and fifth fingers into a single fourth glove finger. This "fourth" finger would combine the strength of the two weakest fingers of the hand, and might make using the “fourth” finger during grasping motions less difficult than using the two fingers separately.

Amis (1987) found that the relative amount of force available at each finger for grasping is 30% at the index finger, 30% at the middle finger, 22% at the ring finger, and 18% at the fifth finger. For cylindrical grasping, the ring and fifth fingers are used primarily for stability. After examining over 250 currently used EVA tools, it was determined that only one required the use of five fingers. Tools requiring a cylindrical grasp accounted for approximately 50% of the tools, while another approximately 40% are used by the thumb and index finger, and/or middle finger (NASA Johnson Space Center, 1993; Foster, 2001). By joining the ring and fifth fingers together to form a single fourth finger, the strength of the combined finger would be significantly greater than the individual fingers. Therefore, the fourth finger would likely be used more frequently for grasping during the pressurized condition than is seen currently with the individual fingers. Thus, the idea of a four-fingered glove design should be investigated further. Factors such as range of motion and performance should be examined to determine whether or not the new design offers any significant improvements over current glove designs.

DISCUSSION

The data collected in this research has demonstrated the usefulness of standardized dexterity tests as a measure of gloved-hand performance. The standardized dexterity tests chosen offered a range of hand motions. From the test results presented, it appears that the Hand Tool Test incorporates the greatest range of motion, and is thus perceived to be the most difficult. The Modified Purdue Pegboard is also a useful test because it too uses a sufficiently large range of motion. However, the two Minnesota dexterity tests did not seem to be optimal choices for testing the effects of gloves on range of motion, or new glove designs. Test subjects were not required in these tests to use the joints of their hands in a range of motion that could supply useful data on changes in hand movement due to unpressurized and pressurized gloves. In fact, the hand was kept more or less in the same position throughout the test. The test also was not perceived to be very difficult, another indication that the complete range of motion of the subject’s hand was not being utilized. Because range of motion is a strong indicator of dexterity, choosing tests that will require subjects to use a greater range of motion is a better means of quantitatively measuring the limitations that a pressure suit glove imparts on hand dexterity. Thus, the Hand Tool Test and Modified Purdue Pegboard tests, which require subjects to use 40 - 50% of the barehanded range of motion, emerge as being the most useful of the four tests for assessing dexterity while wearing unpressurized and pressurized suit gloves.

The ANOVA tests indicated that the barehanded and both unpressurized glove conditions did not result in significantly different performance times. Pressurized performance time was significantly greater than all other conditions. Therefore, if one desires to know how gloves will affect performance time for the pressurized condition, they cannot use the unpressurized glove condition to estimate performance. Only tasks performed while wearing pressurized gloves can be used to estimate the actual performance time during the pressurized condition.

On the other hand, there is no significant difference in range of motion between the unpressurized and pressurized glove conditions. Barehanded range of motion, however, is significantly different than all gloved-hand conditions. Therefore, if one desires information about how wearing pressurized gloves affects a subject’s range of motion, they can obtain a reliable estimate by measuring range of motion in the unpressurized glove. In other words, hand range of motion while wearing pressurized gloves is not significantly different than hand range of motion while wearing unpressurized gloves.

Joint angle data obtained during this research provided information about the range of bend and range of motion of the PIP and MCP joints of the right hand. The results indicate that for the hand tool test there is a significant decrease in range of bend for all of the joints when comparing the barehanded condition with all of the gloved hand conditions. In general, there is no significant difference in range of bend between the unpressurized and pressurized glove conditions for both the HTT and MPP. The actual range of motion is not affected for any of the gloved hand conditions for the metacarpophalangeal joints of the thumb and index finger. For the middle, ring, and fifth fingers, there is a significant decrease in range of motion for the MCP joints going from the barehanded to gloved-hand conditions during the HTT. The range of motion for the MCP joints of the outer three fingers is not significantly different for the unpressurized and pressurized glove conditions. The PIP joints of the thumb and four fingers show a significant decrease in actual range of motion from the barehanded case to all three of the gloved-hand conditions. However, once again, there is no significant difference in the PIP range of motion between the unpressurized and pressurized conditions. The results also show that there is a greater decrease in PIP range of motion than MCP range of motion for the hand between the barehanded and gloved-hand conditions. The gloves that were used for this research have no joint incorporated into their designs at the MCP joint of the hand. They do, however, have joints at the PIP joints of the hand. Thus, it is surprising to see a greater decrease in range of motion at the PIP joints than at the MCP joints. This result indicates that test subjects continue to rely on and use the MCP joints of their hands over the PIP joints of their hand while wearing gloves. Thus, glove design should be reexamined to allow for greater MCP movement.

Perceived exertion results from this research indicated which tests the subjects found more difficult. Not surprising, the tests that required the greatest range of motion were perceived to be the most difficult for the pressurized conditions. Additionally, perceived exertion values increased for all four tasks as subjects progressed from the barehanded to the pressurized conditions. However, performance times do not show a significant change as subjects progress from the barehanded to the unpressurized condition. Therefore, the test subjects may perceive that they are working harder, but in fact they are able to compensate and achieve a similar performance time while wearing unpressurized gloves.

Finally, joint angle data for the ring and fifth fingers indicate that they often bend together during hand operations. Phasing of the PIP and MCP joints is seen more often for the test subjects during tasks performed while barehanded. Therefore, the observed "natural" motion of bending the two outer fingers simultaneously could be emphasized by developing a four-finger glove design that would combine the ring and fifth fingers. The effects of this new design on hand performance should be investigated in future research.

FUTURE WORK – Future work should be directed at testing new glove designs using a test protocol that includes range of motion measurements. The results obtained from this research will be used as a baseline for the next phase of testing conducted at the SSL for mechanical counterpressure glove designs. By comparing the results from this research with similar results obtained while wearing a mechanical counterpressure glove, or other experimental glove, one can obtain quantitative data to support the improvements of a new glove design. Because range of motion is an indicator of dexterous hand performance, joint angle data collected from a data glove can be used to quantify the dexterity limitations a glove imposes.

More specifically, range of motion for the PIP and MCP joints should be examined while wearing experimental glove designs to assess their limitations at these joints. Using the Power Glove developed by the SSL, which aids in MCP flexion, would also be a valuable future research project. In particular, a priority should be placed on assessing the range of motion at the MCP joint and corresponding performance times for unpressurized and pressurized glove conditions, with and without power assist to the joint.

Phasing of the PIP and MCP joints is often observed during barehanded tasks. Therefore, the proposed four-finger glove design should be tested in a manner consistent with the procedures used in this research. The new glove design may have a significant beneficial effect on performance, or it may degrade performance. Either way, this unconventional design should be investigated as a possible future glove design that may improve hand effectiveness in a pressurized glove.

Finally, hand performance during standardized tests should be correlated to "real-world" EVA tasks. This should be done in order to verify and extend the usefulness of standardized testing for evaluation of EVA gloves.

CONCLUSIONS – With the expected increase in EVA for the International Space Station, satellite repair missions, and future human planetary exploration, it is essential that EVA glove design be improved to allow better hand performance. The data glove used in this research provides an economical means of accurately measuring joint angles during simulated EVA tasks. The glove offers a more reliable means of range of motion data collection than previously used video tracking procedures.

Using standardized dexterity tests is one way researchers can verify new designs, using nonexpert test subjects. This type of testing allows the researcher to develop nonbiased data regarding the comfort, dexterity, and tactile sensitivity of pressure suit gloves. Further research efforts should be made to improve the range of motion, and associated dexterity, of the human hand while wearing pressurized gloves. By examining the results of this research, and considering corresponding design implications, it is hoped that engineers and scientists may soon improve the design of suit gloves to allow for more productive EVA operations in coming decades

REFERENCES

Amis, A.A. (1987). "Variation of finger force in maximal isometric grasp tests on a range of cylinder diameters". Journal of Orthopedic Research, 3, 202-211.

Bishu, R.R., & Klute, G. (1993) Investigation of the

Effects of Extravehicular Activity (EVA) Gloves on Performance (NASA Technical Paper 3401). National Aeronautics and Space Administration.

Bishu, R.R., Klute, G., & Kim, B. (1993). "The Effects of Extravehicular Activity (EVA) Gloves on Dexterity and Tactility", Proceedings of the Human Factors and Ergonomics Society: 37th Annual Meeting (pp. 826-830).

Cleland, J., & Winfield, D. (1985). NASA Workshop Proceedings: Extravehicular Activity Gloves-Report of a Workshop to Define Design Criteria for Improved EVA Gloves (NASA Contract No. NASW-3841). Research Triangle Institute.

Durgin, W.W., Hoffman, A.H., Ault, H.K., & Lutz, E.G. (1985). "The WPI Space Glove Design Project", Proceedings of the Space Tech Conference and Exposition (pp. 27-41). Dearborn, MI: Society of Manufacturing Engineers.

Garret, J. (1976). "The Adult Human Hand: Some Anthropometric and Biomechanical Considerations". Human Factors, 13 (2), 117-13 1.

Garret, J. (1968). Clearance and Performance Values for the Barehanded and the Pressure Glove Operator (AMRL-TR-68-24). Wright Patterson Air Force Base: Aerospace Medical Research Laboratories.

Foster, A. W. (2001), Development of a Four-Fingered Dexterous Robot End Effector for Space Operations. Master of Science thesis, Department of Aerospace Engineering, University of Maryland, College Park.

Hinman-Sweeney, E.M. (1994). Extra-Vehicular Activity (EVA) Glove Evaluation Test Protocol (NASA TM-108442). National Aeronautics and Space Administration.

McDonnell Douglas Corporation & National Aeronautics and Space Administration. (1984). The Human Role in Space, Volumes I, II, and III. (MDC H 1295, NASA Contract No. NAS8-3561 1).

National Aeronautics and Space Administration. (1993). EVA Tools and Equipment Reference Book (Formerly EVA Catalog Tools and Equipment, JSC 20466, Revision B).

O'Hara, J.M., Briganti, M., Cleland, J., & Winfield, D. (1998). Extravehicular Activities Limitations Study Volume 11: Establishment of Physiological and Performance Criteria for EVA Gloves-Final Report. (NASA Contractor Report AS-EVAL-FR-870 1). National Aeronautics and Space Administration.

Pelton, M. (2000). The Effects of Extravehicular Activity Gloves on Human Hand Performance. Master of Science thesis, Department of Aerospace Engineering, University of Maryland, College Park.

Ranniger, C. (1997). Electromyographic Quantification of Hand Performance During Simulated Extravehicular Activity. Doctor of Philosophy dissertation, Department of Aerospace Engineering, University of Maryland, College Park.

Shepherd, C., & Lednicky, C. (1990). EVA Gloves: History, Status, and Recommendations for Future NASA Research (NASA JSC23733). Lockheed Engineering and Sciences Company.

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