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Evaluation of a Hybrid Elastic EVA Glove

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ABSTRACT

The hybrid elastic design is based upon an American Society for Engineering Education (ASEE) glove designed by at the Space Systems Laboratory (SSL) in 1985. This design uses an elastic restraint layer instead of convolute joints to achieve greater dexterity and mobility during EVA (extravehicular activity).

Two pilot studies and a main study were conducted using the hybrid elastic glove and a 4000-series EMU (extravehicular activity unit) glove. Data on dexterity performance, joint range of motion, grip strength and perceived exertion was assessed for the EMU and hybrid elastic gloves with correlations to a barehanded condition.

During this study, 30 test subjects performed multiple test sessions using a hybrid elastic glove and a 4000-series shuttle glove in a 4.3psid pressure environment. Test results to date indicate that the hybrid elastic glove performance is approximately similar to the performance of the 4000-series glove.

INTRODUCTION

This paper describes the evaluation and comparison of a 4000-series EMU and an experimental hybrid elastic space suit gloves. The increased emphasis on EVA during the construction and maintenance of the International Space Station (ISS) in the next few years will result in a need for an EVA glove that allows the astronaut to make an increased number of fine dexterous and highly mobile movements with minimal fatigue. Glove design is generally accepted as the most complicated and demanding portion of the space suit. The decrease in performance and grip strength associated with wearing pressurized gloves has been well documented. The development of a more dexterous glove requiring a lower metabolic demand is highly sought after.

Two pilot studies and a main study were performed on the 4000-series EMU and hybrid elastic glove. The procedures used in this study were mainly based upon the Pelton 2000 study. These tests included a hand dexterity test, grip strength test and subjective pooling. The results of these studies will lead to the development of a flight certified space suit glove, which allows for increased dexterity and reduced fatigue.

BACKGROUND

One of the first attempts to increase dexterity and to reduce pressure-induced stiffness was developed by Henry in the 1940s. Henry proposed substituting the then extremely cumbersome high altitude pressure suits with a positive pressure-breathing suit. This suit incorporated the use of inflatable bladders, which produced a mechanical counter pressure on the skin instead using a constant pressure gas-tight suit. The resulting suit developed by Henry suggested that the concept was feasible, however the suit only provided a non-uniform counter pressure, which resulted in edema and discomfort throughout the suit. The suit designed by Henry was designed for high altitude aircrafts and was never intended for use in a full vacuum.

The idea of applying a mechanical counter pressure to the skin in place of a gas was revisited in the 1960s by Dr. Webb and associates. Dr. Webb proposed using an elastic material over the entire surface of the body to apply an appropriate counter pressure for use in a pure vacuum. He called the resulting suit a “Space Activity Suit” (SAS). The SAS underwent a number of near vacuum tests, which resulted in increased dexterity at a decreased metabolic cost. One of the biggest problems with SAS was the excessive time required to don the suit. If the suit was not properly donned, severe edema sometime resulted. Unfortunately, even if the SAS was donned correctly, edema and discomfort resulted from non-constant counter pressurization on the skin. Swelling occurred near the zippers of the elastic material and in several joints such as the elbows and knees. The SAS suggested that the mechanical counter pressure concept was an interesting research concept, however not practical.

In the mid 1980s research was conducted at the SSL involving a hybrid inflatable glove concept. That design incorporated the elastic restraint layer, used in previous experimental mechanical counter pressure gloves as the restraint layer, over a gas-tight pressure bladder. The elastic properties of the restraint layer helped reduce the pressure-induced stiffness and increased tactile feedback. Traditional EMU gloves use convolutes, which create friction between each fold of restraint layer fabric. The elastic material used in the hybrid elastic glove minimizes any friction by utilizing the elastic properties of the material itself. This was the first use of a hybrid elastic concept, however the actual hybrid glove had never been fully developed.

The hybrid elastic glove concept focuses on using the elastic properties of suits designed by Henry and Webb, while maintaining a gas-tight pressure envelope around the hand at all times. This concept was incorporated into a series of hybrid elastic gloves during 2001 at the SSL at the University of Maryland. The third generation hybrid elastic glove was used in a series of tests, which are discussed in this paper.

GLOVES TESTED

A 4000-series EMU glove and experimental hybrid elastic glove were used in this study. The Phase VI EMU glove has replaced the 4000-series EMU glove. The performance of the 4000-series glove is not indicative of the Phase VI glove performance.

Figure 1: Hybrid elastic glove

The 4000-series EMU space suit gloves consist of a constant volume gas-tight pressure bladder surrounded by a non-elastic nylon restraint layer. This restraint layer incorporates convolute at each metacarpal phalangeal (mcp), proximal phalangeal (pip) and dorsal phalangeal (dip) finger joint. These convolutes assist in alleviating the pressure-induced stiffness produced by the 4.3psid.

The hybrid elastic glove was developed in 2001 at the SSL and was based upon the 1985 ‘inflatable glove’ designed by Mitchell Clapp. This glove utilizes both a gas-tight elastic bladder and an elastic restraint layer. The hybrid elastic glove used in this study is shown in Figure 1. The elastic restraint layer material is similar to the material used in `lymphedema garments.’ These garments are most commonly used to reduce edema as a result of trauma and have been used in experimental mechanical counter pressure space suit gloves. An additional fiberglass restraint layer is also incorporated into the glove to minimize unwanted ballooning. It is hoped that the elastic properties of the restraint layer will produce greater dexterity and mobility in the pressurized fingers than the current EMU gloves.

HARDWARE AND METHODS

Two pilot studies were conducted in preparation of the main study. The first focused on gaining a set of baseline data for the hybrid elastic glove and determining if the current test protocol was suitable for this test study. The second pilot study focused on gathering data on the learning effect experienced during the first pilot study and refining the test protocol. The main study used the lessons learned from the first two pilot studies to collect over 128 hours of test data.

Figure 2: GSFC glove box

All pressurized testing in this study was conducted at 4.3 psid in a glove box on loan to the SSL from NASA Goddard Space Flight Center (GSFC), shown in Figure 2. The glove box is made up of a 1/2" thick two-foot diameter Plexiglas cylinder, which is approximately 4 feet long. The barehanded test runs were performed at 0psid inside the GSFC glove box.

Figure 3: Modified Purdue pegboard

The modified Purdue pegboard (MPP) test, shown in Figure 3. This test was used in the 2001 Pelton EVA glove study and was the primary dexterity test used in this study. To complete a single MPP test run, a subject must fill in twelve peg-hole using cylindrical pins four inches in length and 3/8 inch in diameter. The pin size corresponds to the average pip pin size used during EVA.

Figure 4: Instrumented comfort glove

The time to complete each test run was recorded using a simple stopwatch. The range of motion of the five mcp and five pip joints were recorded using an instrumented comfort glove. The instrumented comfort glove is shown in Figure 4, is comprised of two silk gloves and ten variable resistance bend angle sensors. These sensors, manufactured by Flexpoint, are made up of thin (< 0.0005 inches) flexible film coated with proprietary carbon/polymer based ink. This ink becomes brittle after being applied to the film and forms micro cracks when the plastic film is bent. These micro cracks create consistent changes in resistance as the film is bent through different bend angles. Each sensor is placed over mcp and pip joints and then connected to a personal computer. The resulting changes in voltage can then be recorded at a frequency of 10hz.

Figure 5: Dynamometer

An attempt to quantify fatigue as a measure of the decrease in grip strength was also examined in this study. Static grip strength was measured using a standard JUMAR hand dynamometer, shown in Figure 5. Grip strength measurements were taken with several glove configurations at various times during each test session. These values were used to compare glove grip strength to one another and to a barehanded condition.

PILOT STUDY I (PSI)

The first pilot study (PSI) involved 10 subjects between the ages of 22 and 35. All test subjects had participated in the 6-hour Pelton study in 2000 at the SSL.

PSI was made up of six one-hour test sessions. In the first two sessions, test subjects worked in a non-pressurized environment (0 psid) and completed tasks using either a barehanded or bare hand covered by only a TMG configuration. The remaining four sessions involved using each glove configuration for one-hour each: a hybrid elastic glove with a 4000-series EMU TMG, a hybrid elastic glove without a TMG, a standard 4000-series EMU glove with and a standard 4000-series EMU glove without a TMG. The standard 4000-series TMG was used for both the EMU and hybrid elastic glove configurations.

The tests performed in this study were based mainly on the testing performed by Melissa Pelton at the SSL in 2000. Each test session consisted of test subjects performing ten runs of a modified Purdue pegboard (MPP) test. Test subjects were then instructed to perform a grip strength test using a hand JUMAR dynamometer. Test subjects were finally asked to comment on perceived exertion using a borg10-grade perceived exertion scale. Additional comments on fatigue, dexterity and degree of difficulty were also gathered at the end of each test session.

The results of PSI showed a significant increase in the time required to complete the task when glove conditions using the TMG were compared to conditions not using a TMG. This supports previous research conducted by Bishu in 1993. PSI also suggested that the dexterity performance times of the hybrid elastic glove were between the pressurized EMU and non-pressurized barehanded conditions. A graph showing these results is shown in Figure 6. The perceived exertion results taken at the end of each test session, shown in Figure 7, show similar results. The hybrid elastic configurations were perceived as being easier to use than the EMU glove configurations.

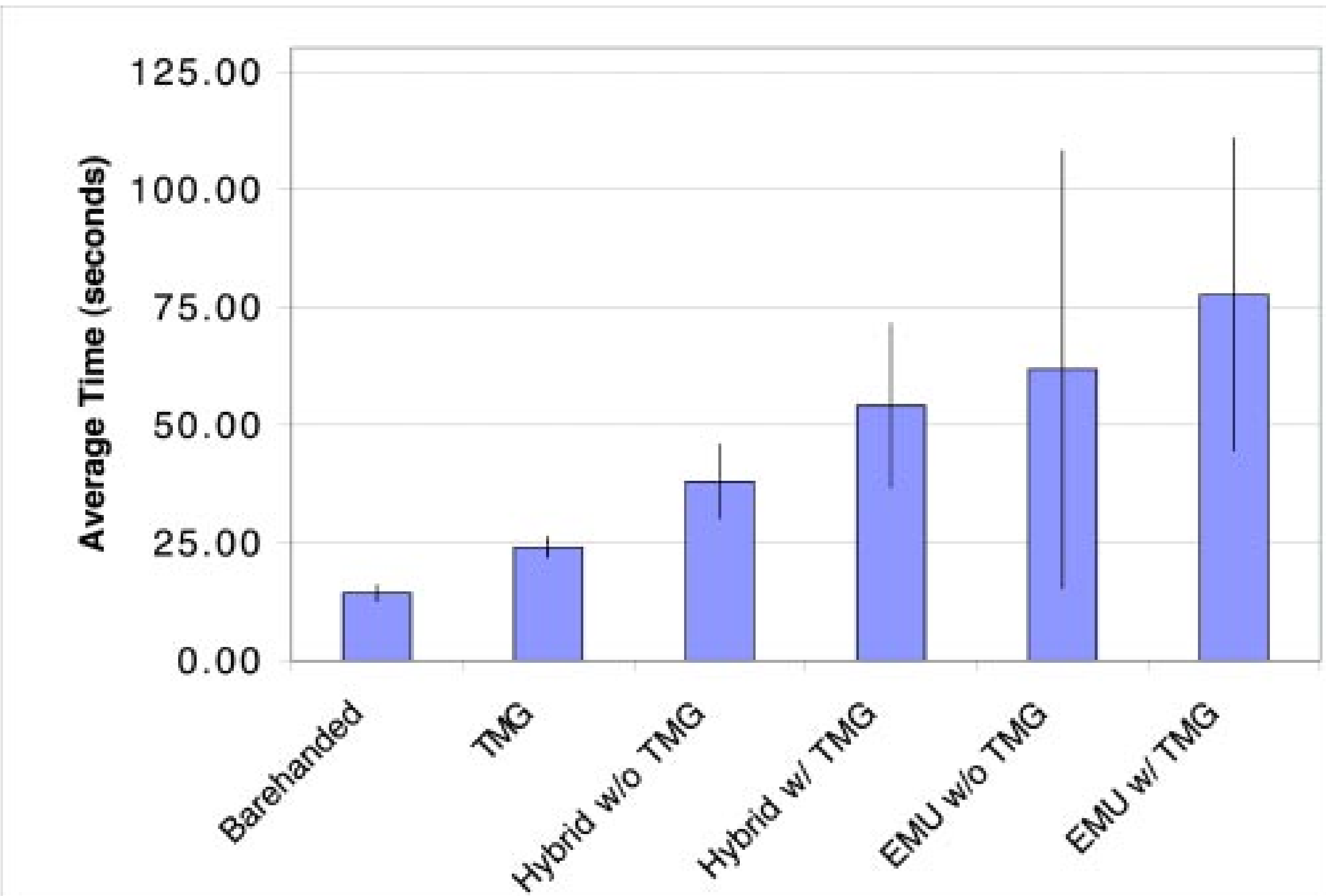

Figure 6: PSI MPP dexterity averages

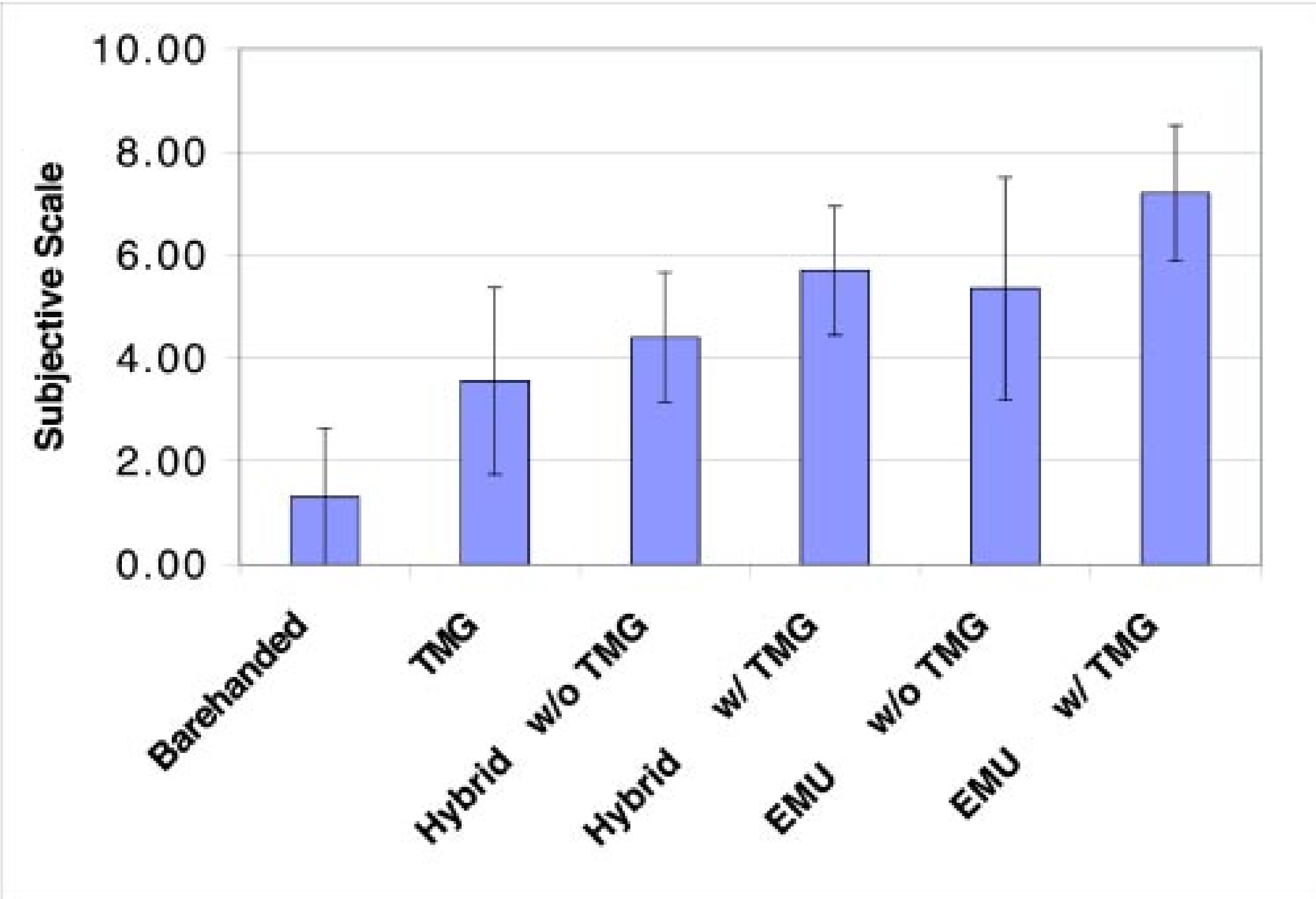

Figure 7: PSI Perceived exertion averages

The number and types of errors performed during each MPP test run were also observed and recorded. These results are shown in Figure 8. The types of errors were categorized as follows:

Type I Error	subject picked up and dropped a peg prior to placing it correctly into a hole
Type II Error	subject unknowingly picked up 2 pegs at once and dropped either one or both pegs
Type III Error	subject tried to pick up a peg and dropped it out of the peg well without ever first having control of the peg\end

The configurations using the TMG have substantially more errors than conditions without TMG. This is mainly a result of more type two errors for glove conditions using the TMG. This was most likely caused by decreased tactile feedback resulting from the TMG.

The grip strength values taken at the end of each session were averaged and are shown in Figure 9. The grip strength data for the EMU and hybrid gloves are similar and indicate a slight decrease for configurations using the TMG.

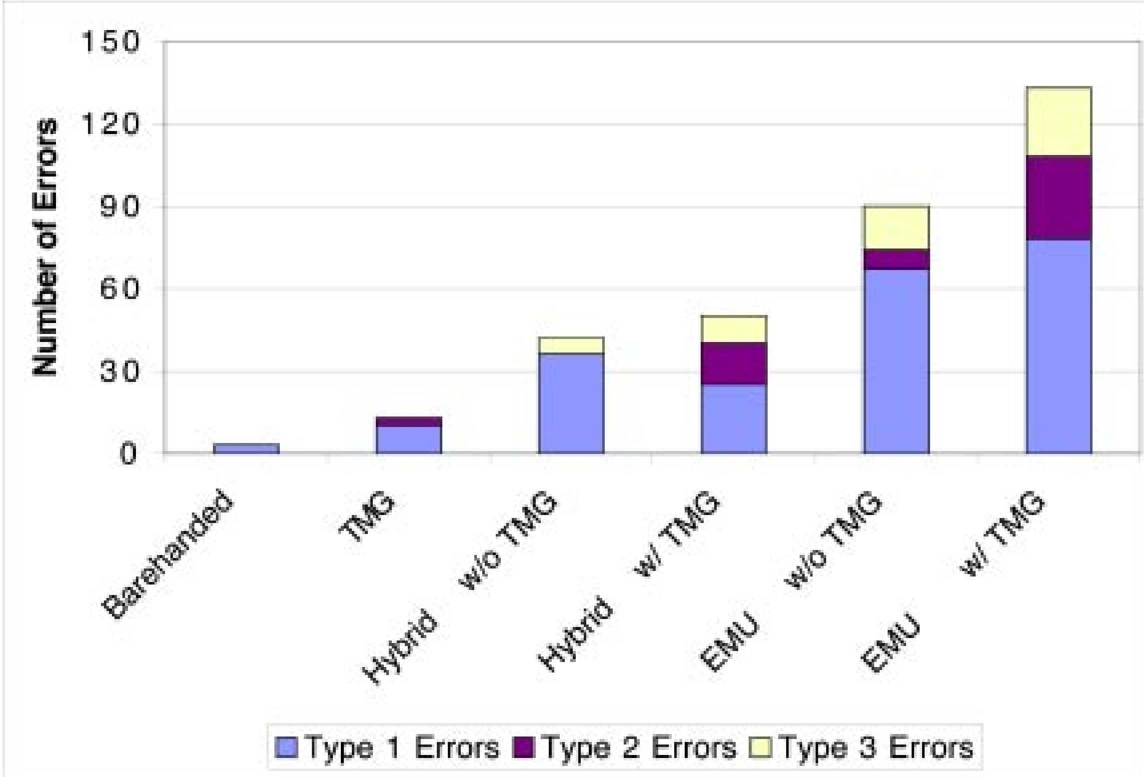

Figure 8: PSI MPP Errors performed

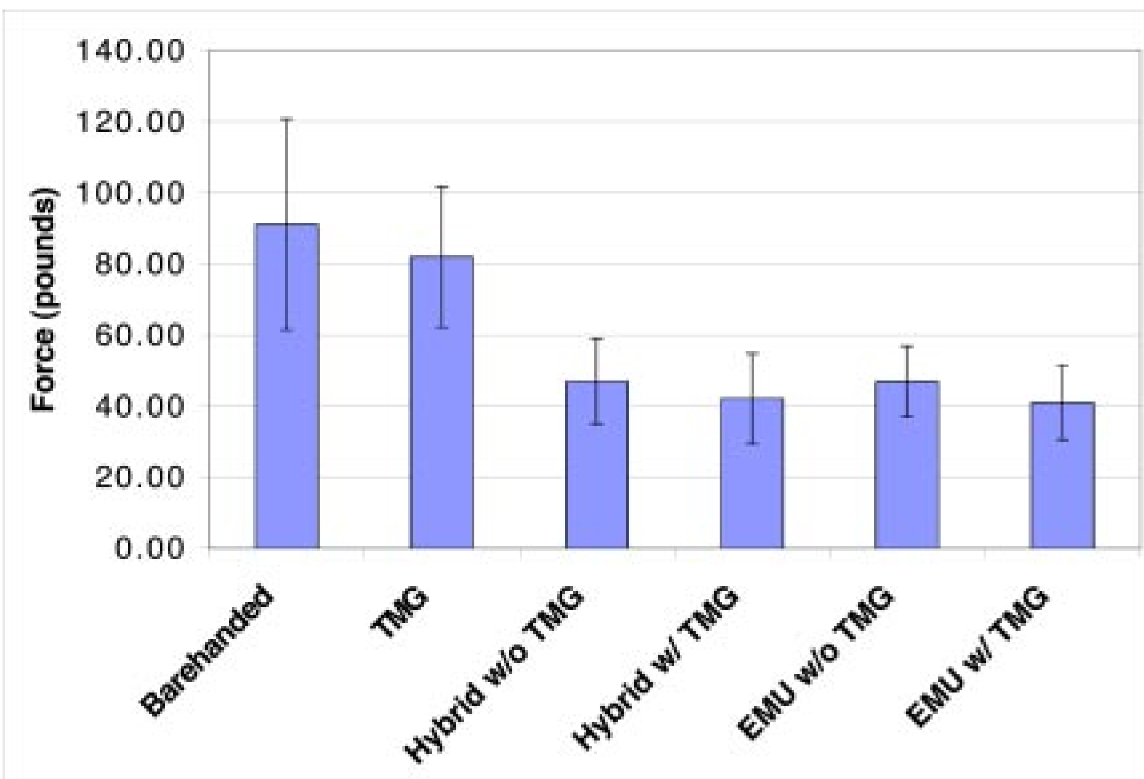

Figure 9: PSI Grip strength averages

The data obtained in PSI verified that quantifiable data could be gathered on the barehanded, EMU and elastic glove conditions using the current protocol. Furthermore, this data could be used to make comparisons between each configuration.

Even with a random order of testing and substantial average differences between glove configurations, it was thought that there was a large degree of learning involved in performing this task. A follow-up study was conducted on two PSI test subjects. This follow-up study, to the first pilot study (PSI) was conducted to identify the presence of any learning effects. These test subjects repeated their first pressurized test session to determine if any overall learning had occurred. The result was a 50% decrease in the time required to complete the task when compared to the first pressurized run using the same glove configuration. This large degree of learning makes direct comparisons of gloves difficult. Because of the large difference in MPP task completion times, a second pilot study was thought to be essential to verify that the modified protocol planned for the main study would produce a more accurate comparison of the two gloves. This would include ensuring that the learning affect did not factor into the final results. The results of the follow-up study were only intended to help design the second pilot study. Any statistically significant conclusions would only be obtained from the main study.

PILOT STUDY II (PSII)

The second pilot study (PSII) involved 4 subjects between the ages of 19 and 25. None of the test subjects had any previous pressurized glove box experience.

PSII was made up of eight one-hour test sessions. The barehanded (B), hybrid using a TMG(H) and EMU using TMG(E) glove configurations were used, but the emphasis was placed on only the E and H configurations.

Test subjects would alternate using the E and H glove for each test session. Half of the test subjects started using H and half started using E. Since a significant level of learning was detected over the four pressurized sessions in PSI, multiple uses of each glove were used to attempt to gather data on the learning effect of each glove. It was hoped that after four or five hours of pressurized glove testing, the majority of the learning effect would have been experienced. This would allow the final two test sessions to be used to compare the two glove configurations.

The test subjects would begin each session by completing a MPP test run wearing only an instrumented comfort glove. This was done to re-familiarize test subjects with the task and to collect range of motion data on a barehanded configuration. The data obtained in the next 10 pressurized MPP pressurized test runs using either the EMU or hybrid elastic glove could then be compared to a barehanded configuration.

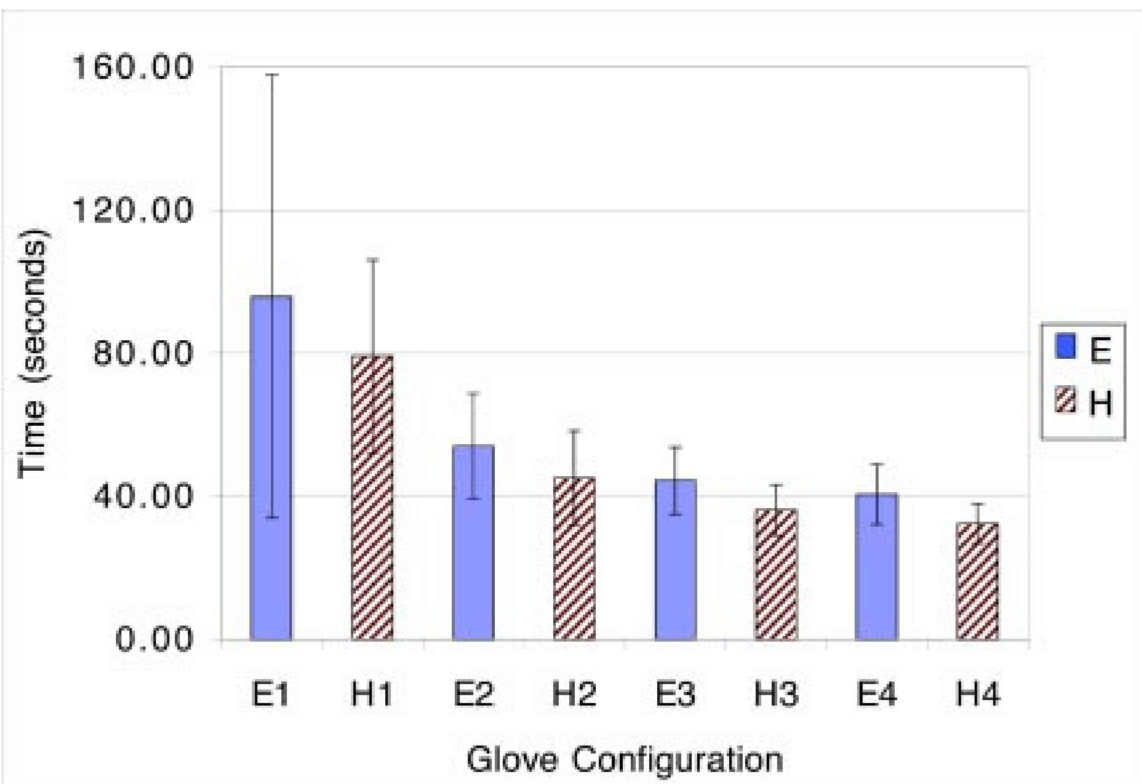

Figure 10: PSII MPP average times

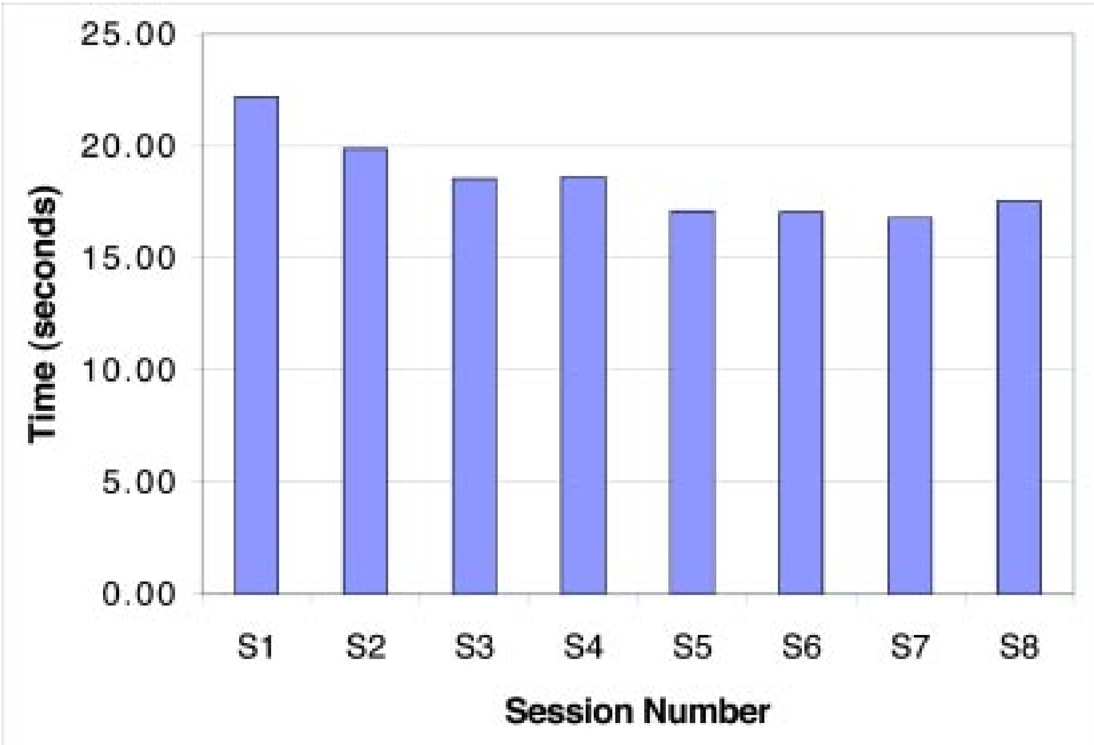

Figure 11: PSII Barehanded MPP average time

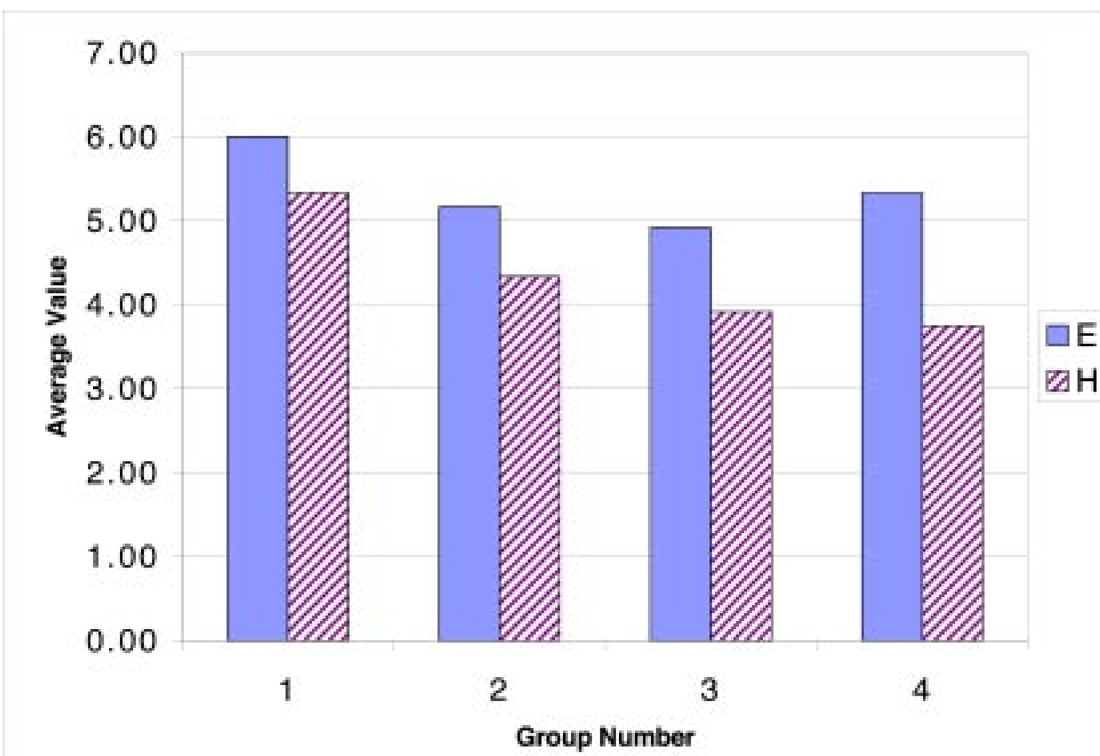

Figure 12: PSII perceived exertion averages

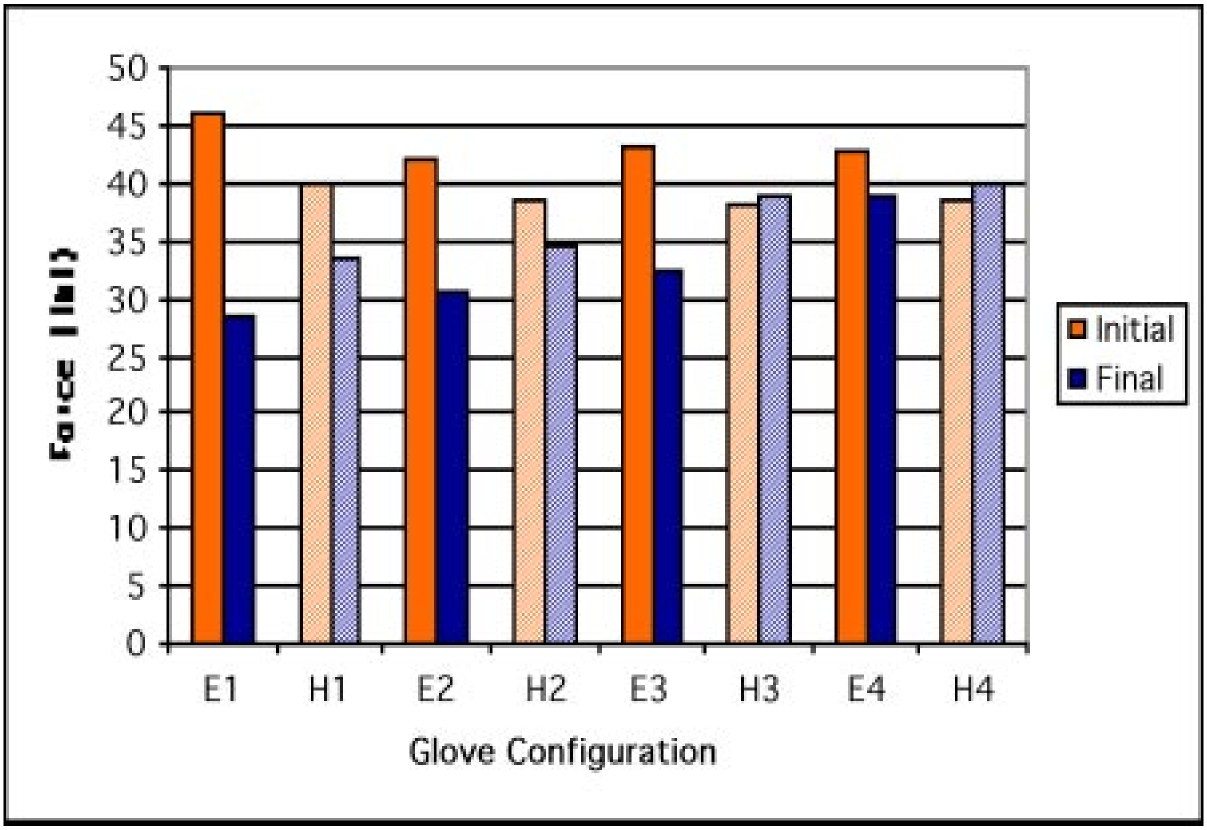

Figure 13: PSII grip strength differences

The results of PSII showed that significant learning occurred throughout the eight test sessions. The average MPP performance times of the final two sessions were approximately 60% (50 seconds) less than the initial two sessions. The majority of the decreases in time required to complete the MPP task occurred in the first 4-5 test sessions. The results of the non-pressurized MPP test runs at the beginning of each session showed that the average decrease in barehanded time required to complete the MPP task was less than 20% (5 seconds). This implies that the majority of the learning was due to working in a pressurized environment and not from the test itself. Average times required to complete the MPP task for the pressurized (EMU and hybrid elastic) and non-pressurized (barehanded) conditions are shown in Figures 10 and 11 respectively.

The perceived exertion scale used in PSI was again used in PSII and produced results similar to PSI, shown in Figure 12. The hybrid elastic glove is perceived to be easier to use than the EMU glove.

The difference between the grip strength values taken at the beginning and end of each session are shown in Figure 13. The data taken for the EMU had slightly higher initial grip strength values, however the EMU glove had lower final grip strength values when compared to the hybrid elastic glove. This may indicate a large degree of fatigue over time when using the EMU glove. The hybrid elastic glove on the other hand, surprisingly had a greater final grip strength average in both the third and fourth groupings when compared to the initial reading. This may indicate some type of learning affect for gripping motions related to the hybrid glove. The 4000-series EMU glove uses palm bar to efficiently minimize palmar ballooning, while the hybrid glove uses a bulkier palm plate. The additional bulk of the hybrid palm plate may be responsible for this learning affect. Another possibility for these grip strength differences is that when using the hybrid elastic glove, the increase in blood flow caused by simple motions, allows the hand to gently stretch and/or warm up, thus improving grip strength. The final hybrid elastic glove grip strength values would eventually be less than the initial values, however more than 10 MPP test runs per session may be needed to test this hypothesis.

PSII demonstrated the ability to collect and analyze data which can be used to show not only the differences between the EMU and hybrid elastic glove, but also the learning effect which is associated with working in a pressurized environment. Range of motion data obtained using the instrumented comfort glove during each MPP test run was analyzed, but is not presented in this paper. The PSII range of motion data was analyzed and was used to verify the test protocol. The overall test protocol used in PSII was verified and ready to be used in a more extensive set of tests.

MAIN STUDY (MS)

The main study (MS) involved 15 test subjects between the ages of 19 and 42. The majority of the test subjects had no previous pressurized glove box experience.

The main study used the same eight one-hour test session protocol used in PSII. Previous testing indicated that the protocols developed in PSII produced a set of quantifiable data that could be used to compare the hybrid and EMU gloves. The only difference was that an additional grip strength test was performed before the initial pressurization in the final two test sessions. This additional grip strength test was performed to gather data on the decrease of grip strength caused solely by the pressurized glove.

RESULTS

The results of the main study indicated that the hybrid elastic glove was comparable to the 4000-series EMU glove in the MPP dexterity test. The average MPP performance times for the non-pressurized (barehanded) and pressurized (hybrid elastic and EMU) configurations are shown in Figures 14 and 15 respectively.

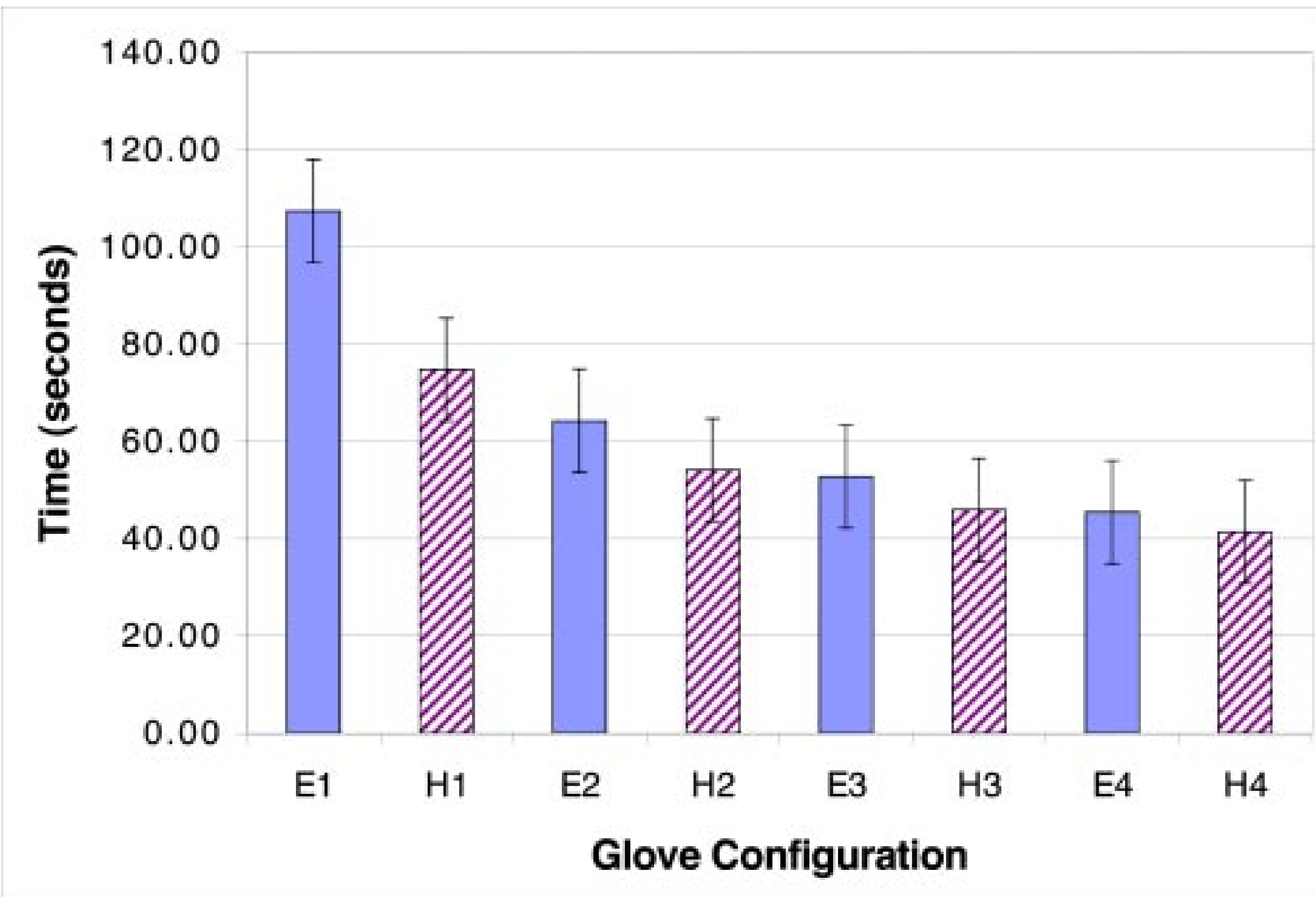

Figure 14: MS average MPP Times

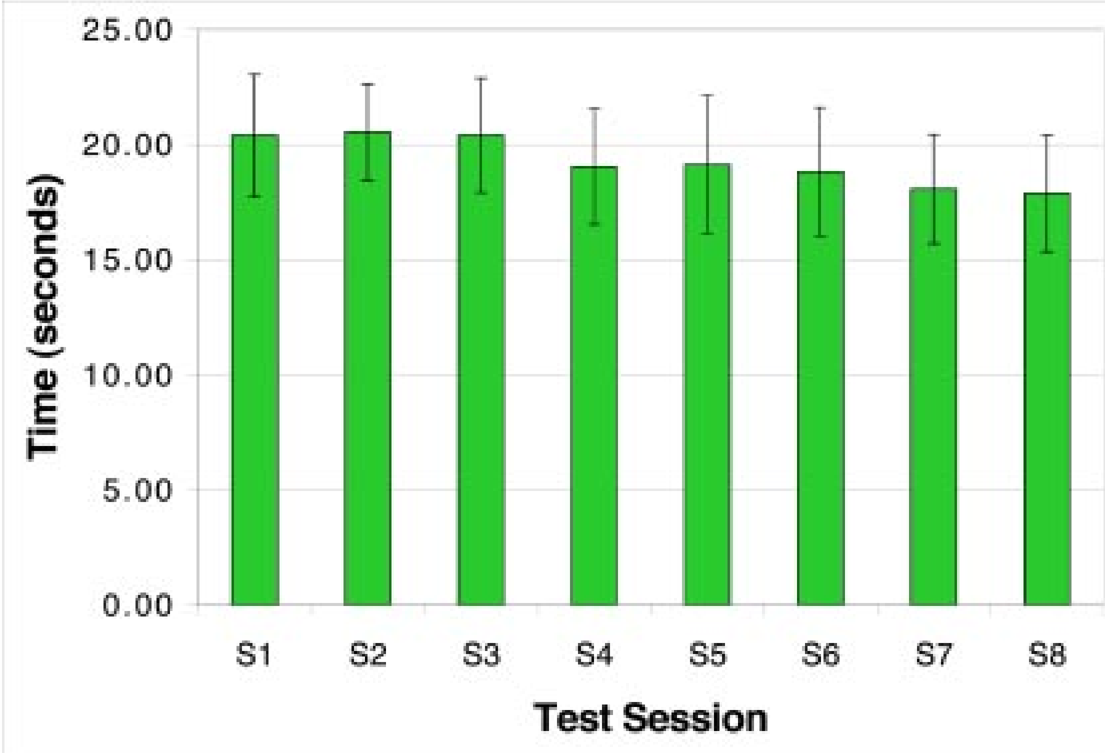

Figure 15: MS barehanded MPP times

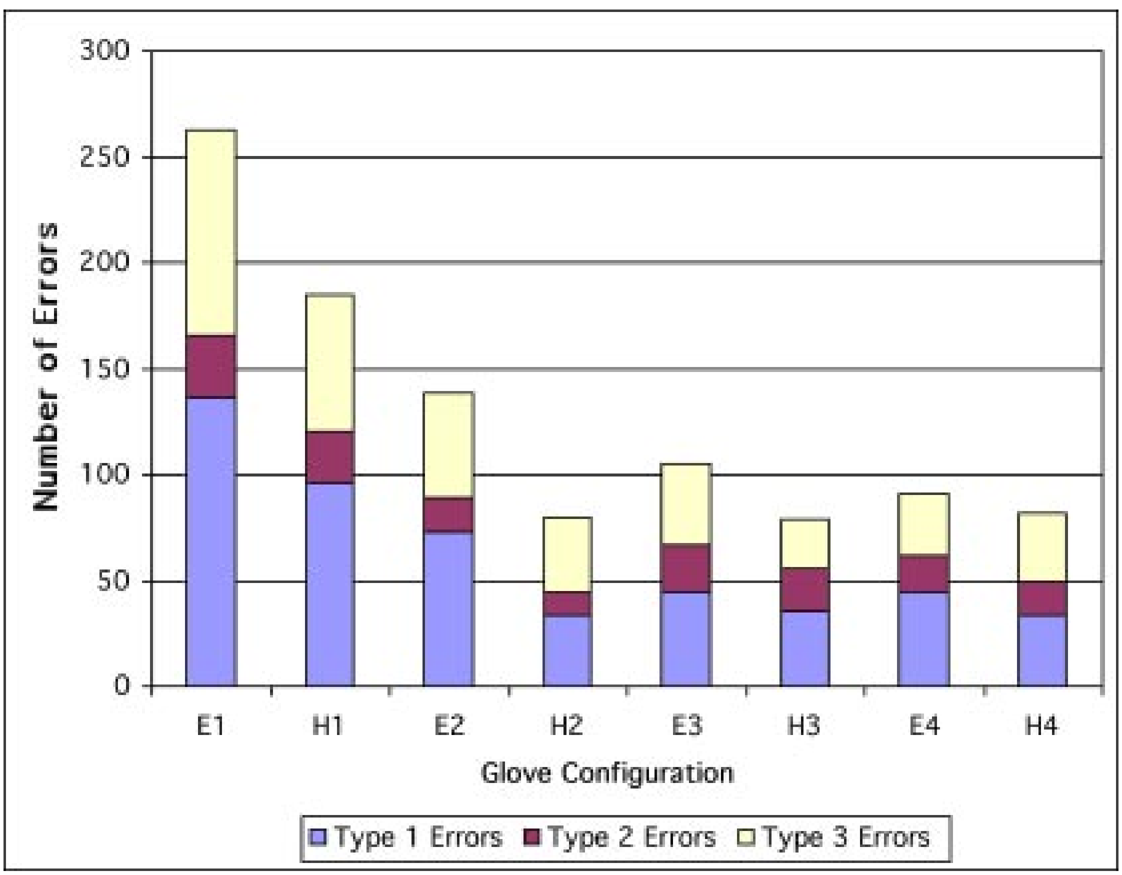

Figure 16: MS MPP Errors per test run

The hybrid elastic glove scored slightly faster average MPP performance times than the EMU glove in each grouping in MS, which accurately reflects trends for individuals. The decrease in MPP performance times from the first two to the last two test sessions was between 50-60% for pressurized conditions and approximately 12% for the non-pressurized barehanded condition. This tends to indicate that there is substantial learning between the first and last pressurized test sessions. The small differences between the initial and final barehanded averages indicates that the majority of the decrease in performance time was not related to the MPP test itself and suggests that the majority of the learning was a result of working in a pressurized environment. The average hybrid elastic glove performance times were faster than the average EMU times for each grouping.

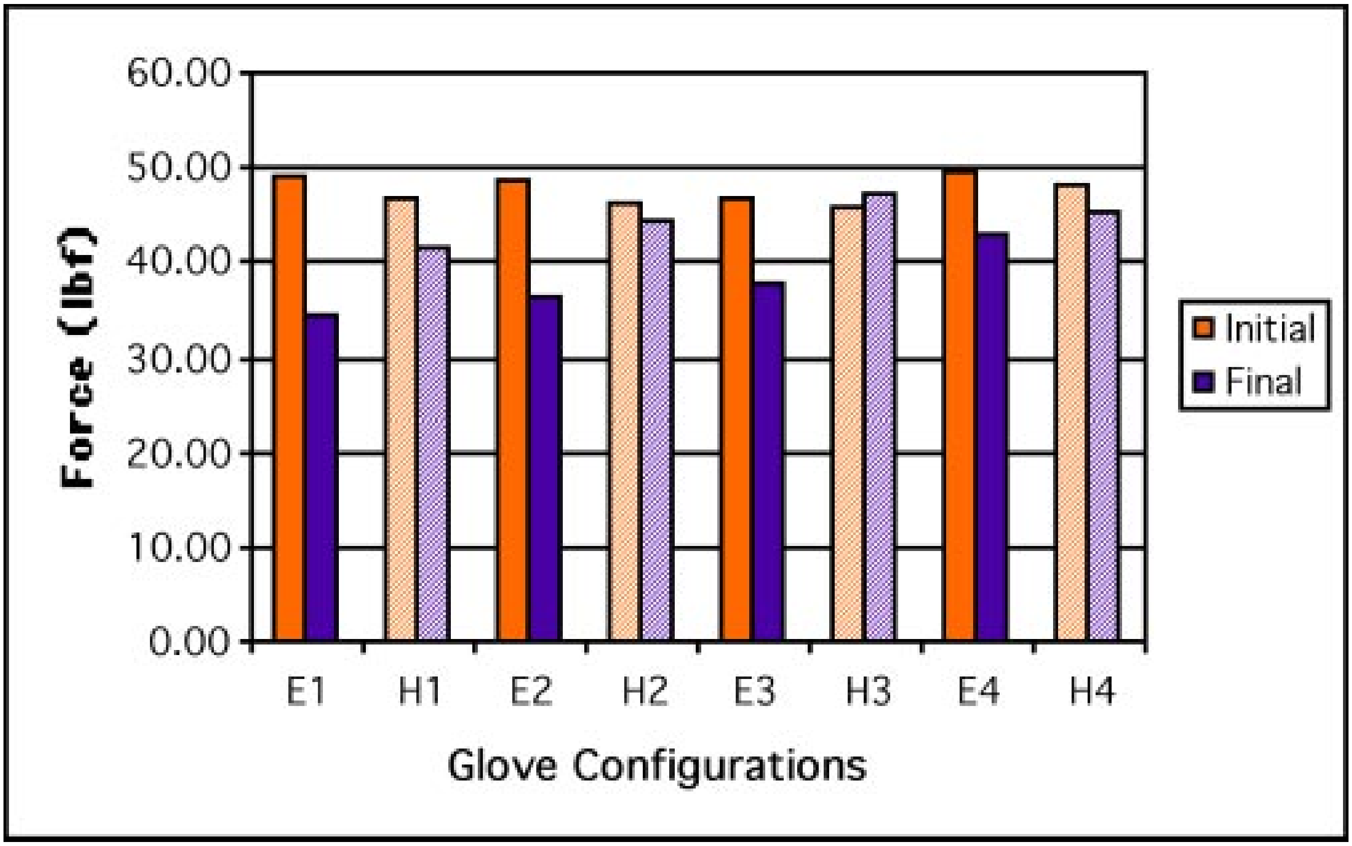

Figure 17: MS grip strength difference

The trend produced by the number of errors committed during each MPP test run was similar to both PSI and PSII. This trend is shown in Figure 16. The number of errors decreased with increasing familiarity with each glove, however the number of errors committed with the hybrid elastic glove was less than with the EMU glove for each grouping. The number of type two errors is fairly constant throughout all data groupings. The type two errors have been shown in PSI to be mainly a result of the addition of the TMG. The type one and two errors decrease for each glove at similar rates. The differences between the third and fourth group of data is fairly constant. This may indicate that the majority of learning has occurred prior to the fourth group. This allows the data from the fourth grouping to be used to compare the two glove conditions with minimal bias.

The differences between the initial and the final grip strength values produced similar results as in PSII. The strength data are shown in Figure 17. In each grouping, the average initial EMU grip strength is greater than the average initial hybrid elastic value, however the decrease in grip strength is substantially greater for the EMU glove. In the third grouping, the average final grip strength reading is actually greater than the initial reading. This may indicate a warming up period followed by a delayed fatiguing effect. It should also be noted that as the test subjects gain more experience in each grouping, the difference between the initial and final readings decreases significantly. This may be a result of increased muscular efficiency due to more familiarization with the glove.

In addition to gathering data on the difference in grip strength values at the beginning and end of the session, a third grip strength value was obtained prior to pressurizing the glove box at the beginning of the session. This value can be compared to the initial pressurized grip strength reading to obtain the decrease in grip strength due primarily to the 4.3psid of each glove. The decrease in grip strength compared to the barehanded condition for the EMU glove was 47.2% and 45.2% for the hybrid elastic glove. This is comparable to the decreases in grip strength observed by Bishu in 1993 and by Pelton in 2000.

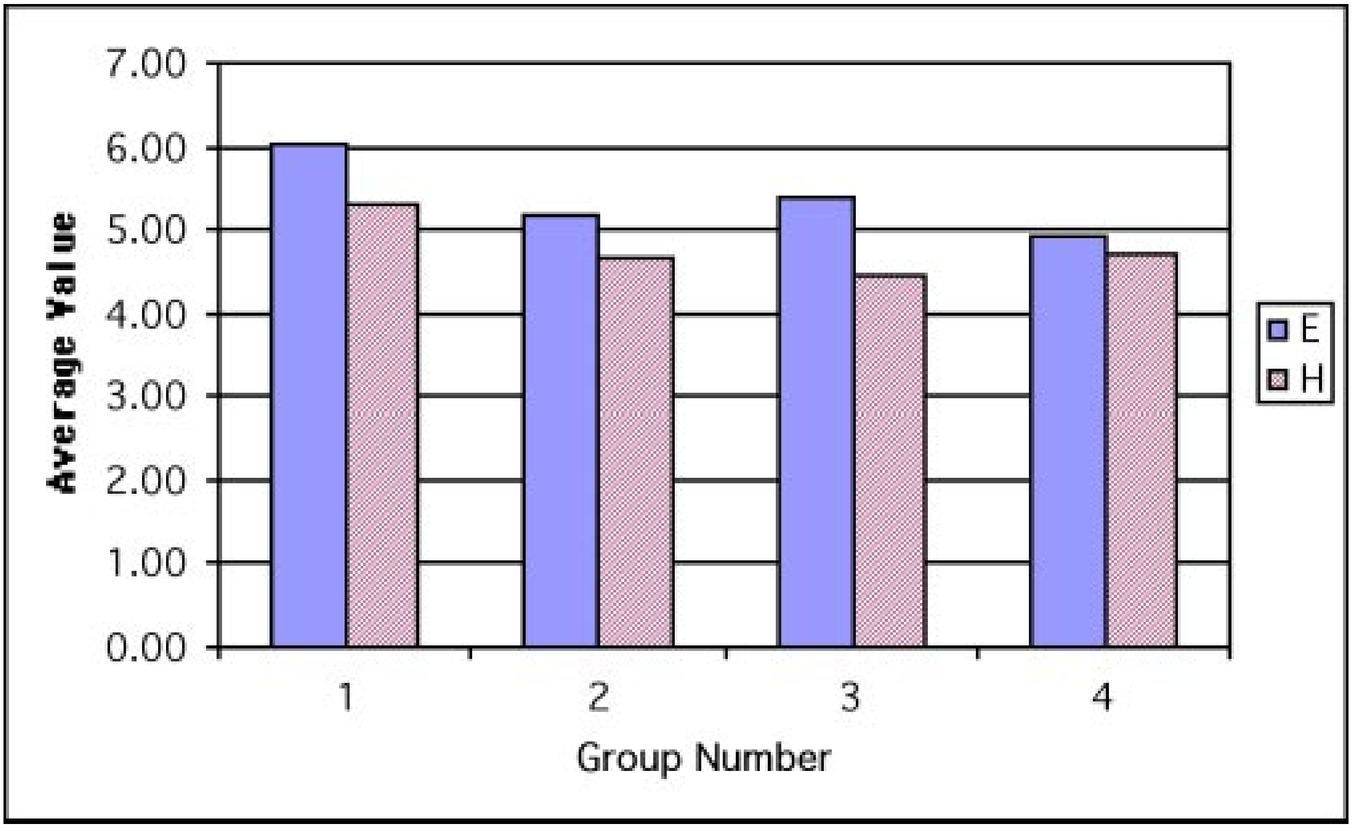

Figure 18: MS Average perceived exertion

The perceived exertion recorded throughout each test session suggests that the hybrid elastic glove is perceived as easier to use when compared to the EMU glove. The average perceived exertion values are shown in Figure 18. The perceived exertion values appear to decrease slightly with each grouping. This may be due to either increased familiarity with each glove or with the general ability to working the GSFC glove box at 4.3psid.

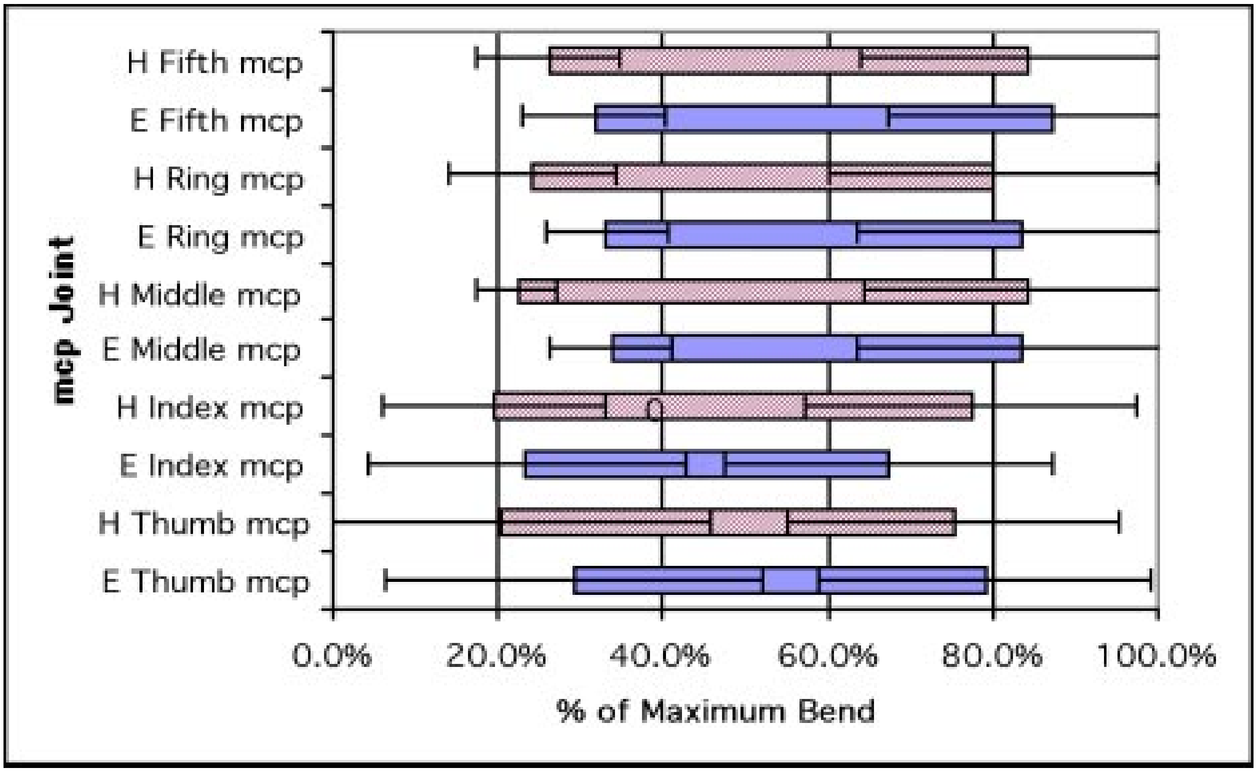

Figure 19: MS average mcp joint ROM

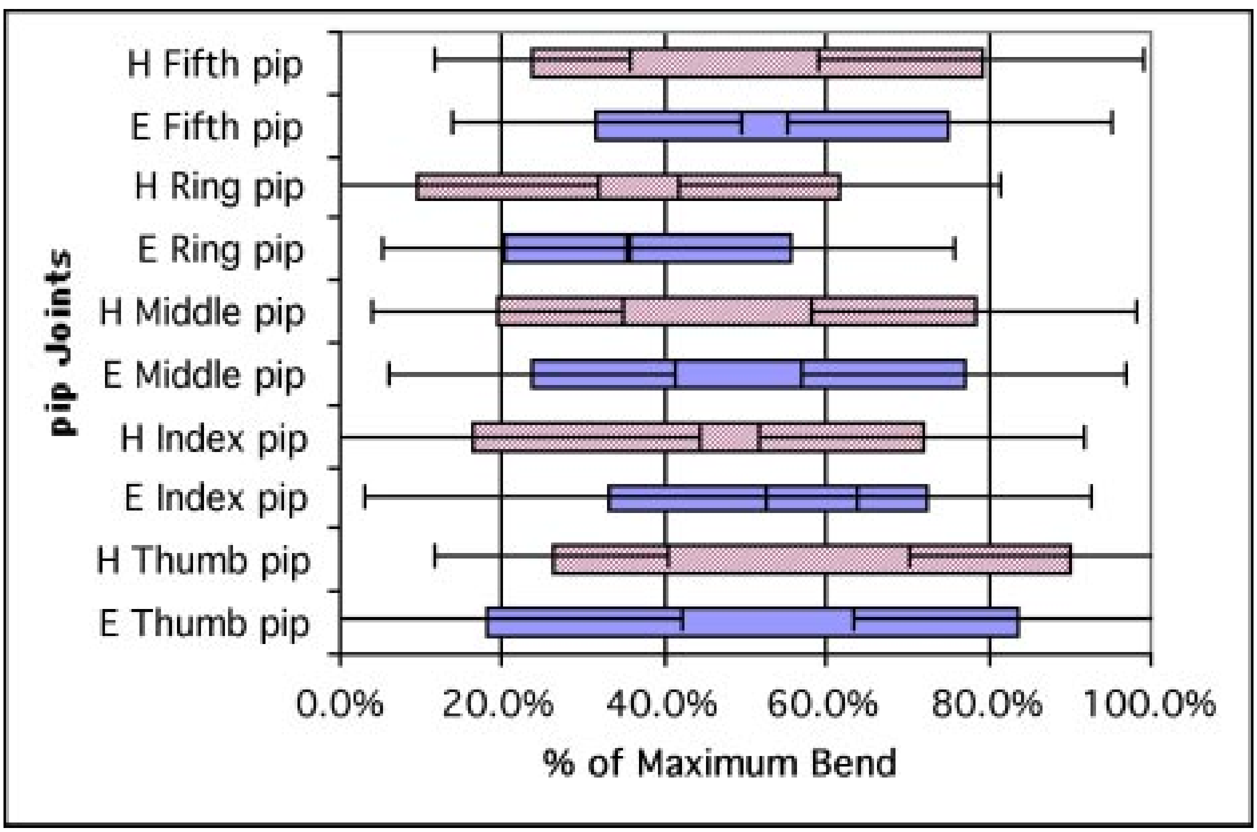

Figure 20: MS average pip joint ROM

The average maximum and minimum range of motion for each hybrid elastic mcp and pip joint appeared to similar to that of the 4000-series EMU glove. The average minimum and maximum mcp and pip joint range of motion for the hybrid elastic and EMU glove configurations are shown in Figures 19 and 20. The range of motion data for the barehanded condition was significantly different than both pressurized glove conditions and therefore was omitted from Figures 19 and 20.

DISCUSSION

The data collected in the main study tends to indicate that the hybrid elastic glove outperforms the 4000-series EMU glove in MPP performance times, errors performed, grip strength degradation and perceived exertion. This is most likely due to the elastic properties of the hybrid elastic restraint layer.

There is a noticeable difference between the MPP performance times of the first and last grouping. This is decrease in performance times is a result of a learning effect. Learning associated with simply performing the MPP test and using different gloves appeared to be significantly less than the learning associated with working in a 4.3psid environment. The learning associated with working in a pressurized environment had the greatest effect over the eight test sessions. The majority of this learning curve was overcome after five hours of pressurized glove box testing (after the fifth test session). Space flight operations require astronauts to train with pressurized gloves for much more than 8 hours prior to EVA, which makes the learning affect meaningless. However understanding the learning affect during early glove development is essential to compare different glove designs.

The order in which gloves were tested did appear to have an affect on performance times in the first four test sessions. When test subjects used the hybrid elastic glove in the first session, the performance times of the second session (E1) were varied. When test subjects used the EMU glove in the first session, the performance times of the second section (H1) were faster on average for every test subject. This would tend to indicate that the required learning time associated with the hybrid elastic glove is smaller than with the EMU glove.

Test subjects with greater grip strength had noticeably faster MPP performance times in the first pilot study. In the main study, only test subjects TS16, TS22 and TS24 had barehanded grip strength values over 110lbf. Test subjects TS16, TS19, TS24 and TS30 scored average MPP test completion times of less than 30 seconds in the last grouping (E4 or H4). This may suggests that there is some correlation between grip strength and performance times. Since grip strength is related to hand size and hand size was a controlled factor in this study, no substantial claims can be made to relate grip strength to performance times.

CONCLUSION

As the number and importance of EVA in the near future is expected to grow at a substantial rate, there is a need for a more dexterous pressure glove. This study has focused on the design, development and testing of a pressure glove with comparison to the 4000-series EMU glove. It should be noted that the Phase VI glove has replaced the 4000-series glove and ideally this test should be repeated to compare Phase VI performance.

The test subjects using the hybrid elastic glove recorded slightly faster completion times on average in the MPP dexterity test when compared to the EMU glove. Test subjects have also perceived the hybrid elastic glove as easier to use during each test session. The average number of errors performed during each MPP test run was slightly less for the hybrid elastic glove when compared to the 4000-series glove. It should also be noted that although the hybrid elastic glove is still considered an experimental glove, no major or minor failures, including noticeable degradations were observed during the last 128 hours of testing.

Due to the encouraging results obtained using the hybrid elastic concept, designs for full arm segments and standard EMU gloves incorporating only hybrid elastic fingers should be examined.

At this point in time, the hybrid elastic glove is comparable to (or slightly better than) the 4000-series EMU glove as the result of 2 years of design and development. The hybrid elastic glove should next be tested and evaluated against the Phase VI glove using similar test protocols and by completing simulated operational EVA tasks. Additional testing should include neutral buoyancy and thermal vacuum testing.

ACKNOWLEDGMENTS

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