Date: Fri, 7 Dec 2001 01:10:23 -0600
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Article1: Design and testing of an advanced pressure suit glove
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Source1: AIAA PAPER 84-0067
Date: Jan 01, 1984

REMOTE_ADDR: 24.70.160.2
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AIAA'84

AIAA-84-0067

Design and Testing of an Advanced Spacesuit Glove

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AIAA 22nd Aerospace Sciences Meeting

January 9-12, 1984/Reno, Nevada

DESIGN AND TESTING OF AN ADVANCED PRESSURE SUIT GLOVE

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A84-17856

ABSTRACT

A lightweight pressure suit glove, made of an elastic material, was designed and constructed to apply a mechanical counterpressure to the human hand equal to the pressure of the air that a human would breathe in a conventional pressure suit. An interface was also built, allowing the lightweight glove, called a skinsuit glove, to mechanically pressurize the hand in a partial-vacuum chamber while the rest of the body remained exposed to normal atmosphere conditions. The skinsuit glove allowed the hand to be more mobile and dextrous than did a conventional pressure suit glove from an Apollo A7L-B pressure suit. The skinsuit glove also afforded better tactile feedback than an A7L-B glove, and was less fatiguing to wear. Adverse health effects on the hand due to exposure of the human skin to partial vacuum were not observed.

I. INTRODUCTION

When astronauts venture out into space, they must be protected from the hostile environment they find there. To do this, engineers have developed several types of protective garments for astronauts, called pressure suits. Pressure Suits of all designs have in common that they protect the wearer from extremes of temperature, reject the heat produced by the metabolism of the wearer, and provide him with a steady supply of air to breathe. They also have in common that they restrict, often severely, the ability of the astronaut to move around, to handle objects, and in general to interact with his environment.

Two diferent approaches are primarily used to provide a comfortable environment around the astronaut's body. The first, "hard" pressure suits, are most appropriate for high breathing pressures, on the order of 8 psi. A hard suit has rigid cylinders to contain the air along the more-or-less rigid limbs of the body, and joints to allow motion of these limbs. The challenge to the designer of such a suit is to make the joints "constant-volume", so that the astronaut does not have to compress his air every time he moves, performing thermodynamic work upon the air. The second sort of pressure suit, the "soft" suit, encloses the astronaut in a flexible airtight bag of roughly manlike shape. Soft suits are common at lower breathing pressures because, like any pressurized bag, they tend to seek a maximum volume, and lower pressure reduces this tendency of a soft suit to assume a spread-eagle posture. Although soft suits such as the NASA A7L-B are designed to be nearly constant volume, an astronaut wearing a soft suit does perform thermodynamic work on the air around him every time he moves, and often soft suits require cables and other restraints to restrict the motion of the pressure suit to a region where the wearer is most comfortable.

The shortcomings of both soft and hard pressure suits are especially acute in the gloves. To design a constant volume joint as small as a human knuckle is difficult, making a hard suit glove difficult to use. Similarly, cables and other restraints are not easily incorporated into something as small as the hand. Since both types of gloves require the wearer to handle objects through a layer of material strong enough to contain from four to eight psi of air, not counting the added clumsiness of any thermal, micrometeoroid, or radiation protection he might have, it is hard to see how the astronaut can perform manual tasks of any delicacy at all.

A better pressure suit glove would allow the wearer to be much more dextrous. It would be lightweight, have a much wider range of motion than today's gloves, and would provide better tactile feedback. If such a glove were also significantly less fatiguing to use, and were inexpensive as well, then it would allow more sophisticated tasks to be performed in EVA, and increase the safety of the missions by allowing emergency repairs of a more delicate nature. As an important step toward the utilization of space, then, a better pressure suit glove is definitely needed.

One idea for such a glove derives from a pressure suit which was first developed by Dr. Paul Webb of Webb Associates in the late 1960's (Ref 7). The reasoning is that a steady supply of air is important to the lungs, but the skin is not so particular. Mechanically speaking, the air to which the human skin is exposed, whether on the earth or in a pressure suit, performs no function except to apply an inward pressure to the skin. This pressure is exactly balanced by the pressure of the tissues inside the skin, which is hydrostatically applied by the air in the lungs. If the counterpressure, which is normally provided by the air against the skin, were instead provided by some other means then mechanical equilibrium could be preserved and the astronaut could function normally.

Dr. Webb constructed what he called a "Space Activity Suit" based on this principle, and tested it at some length. It was his finding that a subject wearing such a suit enjoyed a substantially reduced energy cost of activity compared to a conventional pressure suit. However, he did encounter difficulty with blood pooling, resulting from uneven pressurization of the body. Application of Dr. Webb's basic approach, combined with an analysis of the human hand's various motions and a set of design requirements for eventual operational use, permits one to build a glove of a type similar to that used by Dr. Webb, and which allows the wearer to enjoy many of the advantages described above. The improved glove, called a "skinsuit" glove, was tested against a conventional pressure suit glove from an A7L-B pressure suit.

This report describes the tests performed, instruments used, and results obtained. It demonstrates that the skinsuit gloves used in this research were in general superior to the conventional pressure suit gloves. It also examines the errors inherent in testing the concept of elastic pressurization and offers suggestions for further research into the skinsuit glove.

II. THEORETICAL BASIS FOR THE SKINSUIT GLOVE

At first examination it is difficult to see how the human skin might be protected from vacuum by an elastic fabric. Any such fabric is woven from many small elastic fibers and therefore has a finite mesh size. Small areas of the skin, depending in size on the density of the weave, are directly exposed to vacuum when a subject is wearing a skinsuit glove in space. One must consider whether the skin is strong enough to support the internal load imposed on it by the air the subject is breathing. Also, we must examine the question of whether skin directly exposed to vacuum under such a scheme will diffuse a significant amount of air to space. Finally, the counterpressure on the skin must be maintained at a constant level, which requires that the elastic fabric supply an even pressure to the body.

Research performed by Bancroft and Dunn (Ref. 1) indicates that exposure of the body to total vacuum for two or three minutes is possible, as verified by experiments with apes and dogs. The limiting factor on such an exposure is hypoxia, or lack of oxygen, rather than blood gas effects. Furthermore, a study by Wilson (Ref. 2) exposed human hands, in the laboratory, to vacuum conditions, placing a pressure gradient of a full atmosphere across the skin. Swelling caused by the subcutaneous collection of gas was not observable in Wilson's study until two to eight minutes after exposure, depending on the subject. This indicates that the human skin is strong enough to support a load of a full atmosphere for a short period of time. It also shows that the human skin is relatively impermeable to air under the test conditions.

Studies on the subject of the tensile strength of normal human skin were performed by Rothman (Ref. 3) and by Yoshimura (Ref. 4). They separately determined that the tensile strength of human skin, mostly due to the strength of the tough collagen fibers under the dermis, was a minimum of 2100 psi. Further research by Rothman examined the gas diffusion characteristics of skin. He showed the oxygen loss through the skin was negligible, if in fact it existed at all, under an applied load of a quarter of a standard atmosphere, or 3.7 psi. He also showed that diffusion of carbon dioxide takes place under the same applied load, at a rate of 100 ml/hr/sq. meter, at standard temperature and pressure. Figuring the skin area of two human hands conservatively at 0.1 sq. meter, we see that the skin would pass 10 ml of carbon dioxide every hour through the hands, or about the amount of carbon dioxide exhaled in one lungful. The rate of carbon dioxide loss is thus negligible under these conditions, which are close to those which might be experienced by an astronaut wearing skinsuit gloves. This is important because we must insure that there is no disruption of the breathing reflex, which is controlled by the concentration of carbon dioxide in the blood. The rate of the diffusion of nitrogen is unimportant for skinsuit applications, since the astronaut would be required to purge all the nitrogen from his blood before suiting up at the pressure levels being considered. However, it was shown by the same author to be only 7.5 ml/hr/sq. meter. It appears, from the data mentioned above, that the human skin is quite impermeable to the three major gases found in the bodies of human beings. Losses of these gases through the skin could of course be made up from the breathing supply, water or an electrolyte drink during regularly scheduled rest periods.

From the available data, it would appear that the human skin is not only very strong, but also relatively impermeable to gas. This suggests that the skin itself may be exposed to vacuum for some length of time. The realization that the human skin is in itself almost an ideal pressure suit is the starting point for the elastic pressurization concept. Yet the designer of such a suit must come up with some means of applying pressure to the body so as to avoid the collection of gas underneath the skin, as mentioned above. In an elastic pressure suit, this is accomplished by the application of mechanical force with an elastic fabric.

In order to sustain life, the lungs must always be filled with oxygen, at a partial pressure of at least 3.0 psi. At pressures less than this, the oxygen will not diffuse into the blood at the rate necessary to keep the brain alive. To sustain any sort of reasonable physical activity, there should be more than the bare minimum of oxygen available, and a figure of 3.5 psi is usually accepted as a reasonable value for the partial pressure of oxygen in the lungs. (In practice, NASA pressure suits run at higher pressures, with pure oxygen, the presence of other gases in the lungs being immaterial insofar as they do not reach toxic concentrations. The Soviets have operated their pressure suits at the 3.5 psi level (Ref. 5)). The air in the lungs assures that the alveoli and the other surrounding tissues are at a pressure of 3.5 psi, assuming the astronaut is breathing pure oxygen at that pressure. The blood in the capillaries that service the alveoli is also at that pressure. As it flows from the lungs into the pulmonary vein, it remains at nearly 3.5 psi until it reaches the heart, where the pumping action of the heart causes the pressure to rise on an oscillating cycle with an average value of about 1.93 psi. The blood flows in the arteries to the various tissues, and its pressure decreases steadily as it moves away from the heart due to pumping losses. When it reaches the tissues, its pressure has decreased to 3.5 psi. The tissues, which are nourished by the blood, are pressurized by the air surrounding the body to effectively the same pressure as the blood (Ref. 6).

If there is no air surrounding the body, then the pressure gradient at the tissues will cause the smallest veins to become engorged with blood, since their walls are less strong than those of the arteries. If there remains a pressure gradient of a very modest .19 psi across the venous walls, then the blood will be forced through these walls and will accumulate in the surrounding tissues. The resulting swelling, known as edema, is not particularly uncomfortable, but the reduction in circulating blood volume can put the subject at risk of fainting. The risk is slight at 200 ml of blood lost, but fainting is almost certain at four times this value. The situation is analogous to that experienced by a blood donor. The lightheadedness he feels is also due to a reduction in circulating blood volume.

To prevent the onset of edema, a counterpressure must be applied to the skin equal to the pressure of the breathing gas. In a shirtsleeve environment or in a conventional pressure suit, this is done by immersing the astronaut in the same air he breathes. In the skinsuit glove, however, the applied pressure comes from the fabric mesh. This mesh has gaps in it of about half a square millimeter, on the average, across which the skin is directly exposed to vacuum. It must contain a maximum load of 3.5 psi in our example, and must further restrict the flow of gas across its surface. We have seen in the preceeding discussion, however, that the skin is several orders of magnitude stronger than is required, and can also restrict the flow of gas to effectively zero. Thus a hand wearing a skinsuit glove enjoys the same mechanical equilibrium as does a hand in a normal atmosphere. The edema does not form and the hand may function normally.

Two final considerations are how the elastic garment pressurizes the skin and how the counterpressure is maintained at a constant level when the hand moves. As to the second problem, if the elastic fabric used to make the skinsuit glove were a linearly elastic one, then the designer would have a problem. But most fabrics used in garment manufacture are nonlinear; they allow a variety of elongations at a given stress level because of the way they are woven, and the inherent stress characteristics of the polymers from which they are woven. According to anthropometric data (Ref. 7), no linear dimension on the hand elongates more than 51 percent nor shortens more than 32 percent, even under the most extreme manual contortions. If the designer chooses a fabric with a stress-strain curve similar to the one in Figure 1, then he may assure constant counterpressure under motion as long as he designs in the linear region shown.

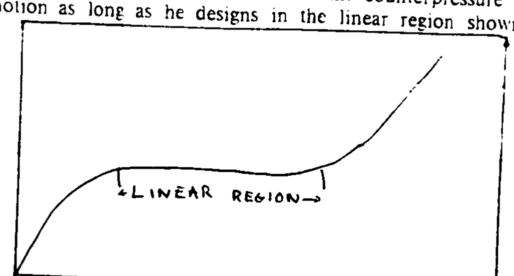


Figure 1: Stress-Strain Curve For A Fabric Suitable For Skinsuit Use.

For an understanding of how elastic garments pressurize the body, one may model a typical limb section, such as a finger, as a thin-walled cylinder. Let the increment of force opposing the tension be:

$$dF = (PLD / 2) \sin a \, da$$

The total force is thus:

$$F = \int_0^{\pi} (PLD / 2) \sin a \, da$$

$$= [(1/2) PLD (\cos a)]_0^{\pi}$$

$$= PLD$$

Since the tension is half of the applied force, and the radius is half the diameter, then we solve for the pressure in terms of the tension per unit length, t, and the radius, r:

$$P = t / r$$

The important thing to note is that as the radius of a body part increases, the pressure applied to it decreases if we wish to stay in the linear design region at a constant tension per unit length. For body parts of larger radius, therefore, we must add several layers of fabric.

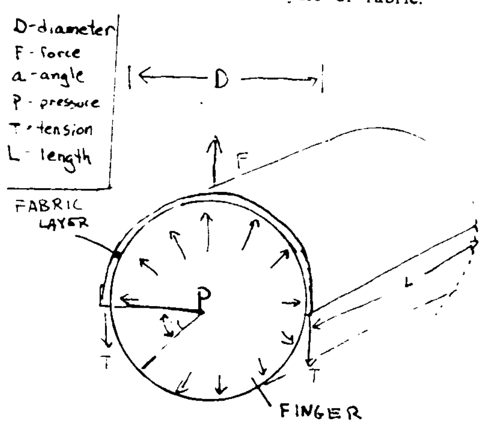


Figure 2: How Elastic Fabrics Pressurize The Skin

This theoretical analysis has examined some of the problems inherent in the elastic pressurization scheme. Most of these are of a physiological or medical nature. With the theoretical feasibility of the skinsuit glove established, we may now consider the construction, testing, and performance of such a glove.

III. DESIGN CONSIDERATIONS

The primary consideration that the designer of a skinsuit garment must bear in mind is that the garment in question must fit the subject exactly. This is necessary because the level of counterpressure must be constant over the entire surface of the hand, in the case of a glove, to prevent the onset of edema. Because the counterpressure varies inversely with the radius of the part being pressurized, as noted above, the tension per unit length must also vary so that an even counterpressure is maintained. The radii of the various bones, joints, and so forth of the human hand varies according to an arbitrary pattern which is unique for every person. How, then, might a garment be tailored to squeeze evenly on the hand at all times?

As it turns out, the problem of applying an even pressure to the hand has already risen in the medical profession, in the treatment of people who suffer from severe burns. To avoid the uneven regeneration of the skin, burn victims must have their dressings pressed into the affected area at a steady even pressure, which depends on the severity of the burn. If this does not happen, the scar tissue will grow in a haphazard fashion that is not only unsightly but restrictive of motion as well. To counteract this problem, a technology for making elastic pressure covers of good precision has been developed by a medical supply company known as the Jobst Institute, in Toledo, Ohio. Their elastic pressure covers are tailored to fit the patient exactly, and they supply the necessary counterpressure to the burn dressings to prevent runaway scarring.

Jobst Institute pressure covers are typically tailored to apply to the skin a counterpressure of approximately 0.5 psi, this being the level of pressure appropriate to the treatment of burns. For skinsuit application, however, a higher level of pressure is necessary, at least 3.5 psi. To supply the extra pressure needed, a material was chosen which was capable of supporting a high tension per unit length of fabric. Normally, such a material would be used on a limb section of greater radius, such as the upper arm or thigh. By using the high stress fabric on the hand, however, the need for having many layers of fabric was eliminated.

Tailoring of the skinsuit glove was performed by Jobst's patented technique of taking a careful series of measurements of the circumferences of the joints of the hand. An outline drawing of the hand was also made to determine how the radius of the fingers varied between joints. Using this information, Jobst Institute fabricated two skinsuit gloves. One of these gloves had a natural rubber elastomer core, while the other had a Spandex fiber core. This was done to determine which of the two elastomers, Spandex, a DuPont synthetic, or rubber, was more appropriate, in terms of pressure level, tear resistance, and vacuum induced brittleness from outgassing.

The gloves were also tested with a number of configurations. The use of zippers was tried, to aid in donning and doffing the glove. A gauntlet, a second fingerless glove fitted over the primary glove, was required to increase the counterpressure over the palm and the back of the hand to the design level. The gauntlet was first tried with the four fingers emerging through the same hole, and later with webs of fabric in three places to separate the fingers. A velcro closure was also used on one gauntlet. Finally, a number of foam rubber pads were made in the early stages of the research to prevent gapping of the skinsuit fabric across the concave areas of the hand. In general, the seams necessary to hold the glove together were kept clear of the fingers to maximize tactile feedback.

The elastic pressure gloves in Dr. Paul Webb's study (Ref. 8) of the late 1960's differed in some respects from the ones used in this research. First of all, Webb's gloves supplied a counterpressure of only 3.1 psi to the hand, even though the breathing system of his subjects was at the same pressure. It was Dr. Webb's intent to reduce the counterpressure distally on the limbs; he did this to improve circulation and to reduce the difficulty associated with breathing with the positive pressure breathing system he used. Unfortunately, his subjects experienced an unacceptable amount of blood pooling, especially in the sinuses of the elbows, wrists, and ankles. Since the potential breathing and circulation problems Webb feared are not applicable in the testing of a glove, the glove used here was designed for the full 3.5 psi. Webb also felt the need for rounding pads to prevent the gapping of the elastic pressurizing fabric across concavities of the skin. Some pads were made early in this study, but were not in general used, for three reasons. Improvements in tailoring technology over the past decade resulted in a fit much better than that enjoyed by Webb's subjects. Also, the higher counterpressure levels of the gloves used in this research induced a greater degree of rounding to the hand than did Webb's gloves, making the cylindrical model more close to the actual situation. Finally, a superior material, the Spandex fabric, was available here, while Webb used the natural rubber fabric. It must be remembered that Webb's research was based primarily on developing an entire elastically pressurized suit, reducing the energy cost of activity to the astronaut, and proving the elastic pressurization concept. The research decribed here was specifically intended to improve the technology of elastic pressurization gloves, to exploit the advantages afforded by improvements in the basic fabric and tailoring technologies, and to prove the concept of a hybrid suit – a suit which pressurizes some of the body by elastic means and some of the body by means of conventional pressure suit technology.

To accomplish this final goal, an interface between the mechanically pressurized glove and the atmospherically pressurized body was built. This originally took the form of a neoprene rubber tube clamped to an aluminum ring, which was machined to fit the wrist seal of a standard NASA A7L-B pressure suit. Later the design was improved to eliminate the clamp by machining male and female wrist ring segments and trapping the neoprene cuff between them. The neoprene was sealed against the arm by the pressure differential forcing the cuff against the skin. A loose cotton overglove was added to prevent the arm from being sucked into the glove by the pressure differential. The interface was designed throughout to be compatible with existing NASA hardware, and thus eventually to allow testing of a skinsuit glove by a subject in a conventional pressure suit

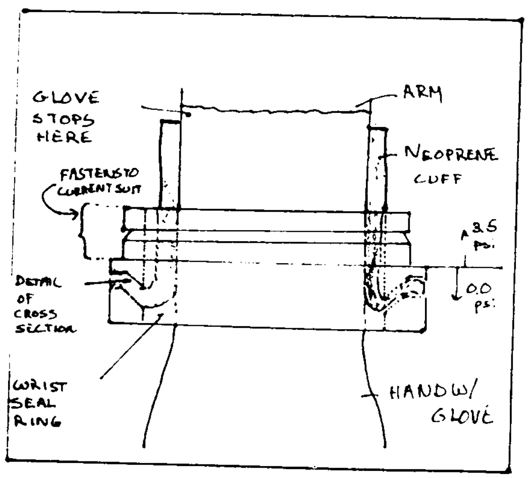


Figure 3: An Interface Between The Skinsuit Glove And The Arm

IV. TESTS PERFORMED AND APPARATUS USED

The main thrust of the study described in this report was the evaluation of the usefulness of the skinsuit glove at reduced pressures. To determine its usefulness as a potential addition to present pressure suit technology a number of different experiments were performed. For testing purposes, the experimental environment was produced by means of a small partial vacuum chamber which placed the same pressure differential on the hand with the skinsuit glove that the hand would feel under actual service conditions. The tests were performed with the skinsuit glove, the NASA A7L-B glove, and the naked hand. The A7L-B glove was tested both in a pressurized and unpressurized state, to separate the effects of pressure work from those of inherent glove resistance. The naked hand was tested as a control.

The areas of inquiry were divided into several groups, according to the nature of the variable being measured. The first group, mobility and dexterity measurements, was designed to lead to a quantitative idea of the range of motion and manual dexterity of the subject in each type of glove. The second, strength tests, to measured the extent to which pressure suit gloves fatigue the hand under repetitive exercise. Tactile feedback, the subject of the third test group was measured in order to determine the level of touch sensitivity in each type of glove. Physiological tests examined the health effects associated with wearing of skinsuit gloves. Finally, materials tests analyzed the stress-strain characteristics of the two fabrics used in glove manufacture, to develop the characteristics of an improved fabric for glove applications.

Two gloves were used by the subject. They were designed to supply a counterpressure of 3.5 psi, and were equipped with zippers to facilitate their donning and removal. One glove was made from a synthetic Spandex fiber, while the other was based on an elastomer fiber of natural rubber. The gauntlets were also zippered, and had a single large hole through which the fingers emerged.

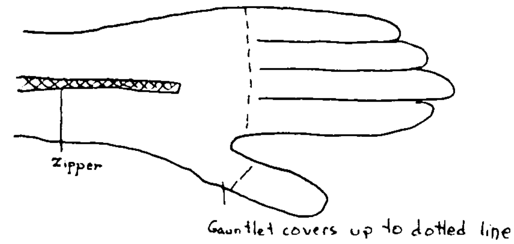


Figure 4: Glove used in testing

The environment in which the gloves were tested was a small partial vacuum chamber called a "glove box". The glove box designed was a Plexiglas cylinder sealed at each end by a square plate. One of these bulkheads was fitted with a hole large enough to accept the wrist seal assembly; this formed the interface between regions of atmospheric and elastic pressurization on the body. The cylinder was some nine inches in diameter by a foot long. When assembled, the subject could reach into the cylinder through the wrist seal and perform various tasks inside the box, which was pumped down to 11.2 psi, giving an atmospheric pressure differential of 3.5 psi across the hand.

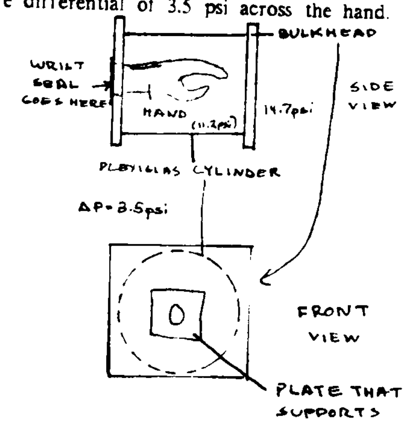


Figure 5: Apparatus Used In Partial Vacuum Testing : The Glove Box

The largest and most important test category was the mobility and dexterity category, where the greatest amount of data were compiled. The variable of interest in the mobility category was the angular range of motion of each joint in the hand. The mobility data were gathered by contorting the hand through a prescribed sequence of motions, shining a bright light through the glove box, and measuring the angles of deflection of the resulting shadow with a transparent protractor.

The dexterity of the hand was measured with a modified version of a standard test of manual dexterity, the Purdue Pegboard test, developed at Purdue university in the late 1940's. The test requires the subject to place as many pins as possible into matching holes on a board in thirty seconds, and allows the subject to move his arm freely with respect to the board. Because the glove box did restrict the motion of the arm with respect to the contents of the box, the Purdue test was modified in this study. A seven inch square wooden board was drilled with 36 quarter-inch holes in a six-by-six pattern, separated by one inch clearance between the grid points. The subject placed as many five-inch-long aluminum rods in these holes, which were an inch deep, as he could in a thirty second interval.

Strength tests were performed to arrive at some idea of how fatiguing it would be to wear each type of glove in space, to what extent the glove works against the hand, and with what strength an astronaut might expect to be able to hold onto things in space. A tennis-ball sized bulb was squeezed into a pressure gauge. The pressure reading was multiplied by the surface area of the bulb and thus converted to a force. The right and left hands of the subject were exercised so that the ungloved hand could be used as a control. This technique assumes that the right and left hands appreciate in strength by equal amounts under equal exercise.

To be able to measure the touch sensitivity of the gloved astronaut, a series of tactile feedback tests were performed. These were semi-qualitative in nature. American coins of various sizes were felt by the subject. The object was to determine, by feel, whether a coin was heads or tails, based on the slightly greater degree of roughness of the tail side. For more quantitative results, an improved tactile feedback test was used based on the Braille alphabet for the blind. If a "touch-chart" of random Braille letters of varying sizes were arranged in the manner of an eyechart, then the tactile analog of visual acuity, or "tactile acuity" could be determined. Since most sighted people, however, are unfamiliar with the Braille alphabet, a simplified technique was used. Raised hemispherical dots were arranged in a T-shaped pattern, and the subject was required to determine by feel which side was the base of the T.

The physiological tests which were performed were more qualitative in nature. Mainly, the level of edema which was present in the hand as a result of any uneven pressurization by the skinsuit gloves was noted. Lacking a quantitative means of measuring the level of edema, it was classified as nonexistent, mild, or severe. Mild edema is characterized under the definition used here as being a visually detectable swelling. Severe edema is defined as being a swelling greater than one-eighth of an inch outward, or any swelling accompanied by pain or discoloration. The physiological test category also included qualitative estimates by the subject of glove fit, discomfort, pinching, soreness, and so forth.

Finally, the material properties of the skinsuit fabrics were examined The stress-strain characteristics of the Spandex and Rubber fibers were measured by a spring force gauge, using the gauntlets as fabric samples. Because the variation of the counterpressure across the skin depends directly on the properties of the material supplying that counterpressure, the data have some medical significance as well. Also, the identification of the characteristics of a fabric that performs well in the skinsuit glove application could lead to a prescription of an improved skinsuit glove material.

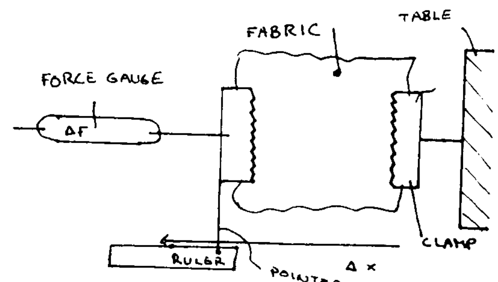


Figure 6: Measuring the elastic curve of skinsuit glove material

V. RESULTS

In general, the results of testing the skinsuit glove were fairly encouraging. Compared with the A7L-B glove, the skinsuit glove offered a considerable increase in both mobility and dexterity. Tactile feedback was also significantly improved. The degradation of strength as a result of exercise took place at a much slower rate in the skinsuit glove than in the A7L-B glove. Best of all, the skinsuit glove proved to be free of the physiological difficulties which might conceivably be associated with its use. The skinsuit glove was comfortable to wear, in fact, more so under a partial vacuum than under normal pressure.

The data here are expressed as percentages of the naked hand score, where applicable. However, the raw scores for the naked hand are given so that the raw scores for the other cases may be recovered from the percentage scores given by any researchers wishing to reproduce this work.

The mobility tests measure the angle of deflection of the joints of the hand. These were averaged in three groups - finger mobility, thumb mobility, and wrist mobility. This is done because there is no obvious weighting function that assesses the relative usefulness of, for example, the angles of deflection of the first and second joints of the index finger. Also, the fingers, wrist and thumb are separate design problems for the engineer designing the conventional pressure suit glove, and the data given here offer an indication of the skill of these engineers. Table 1 expresses the results of the mobility tests.

TABLE 1 : Mobility of Pressure Suit Gloves

	finger	thumb	wrist
Naked hand	100	100	100
A7L-B (3.5 psi)	32	30	52
A7L-B (0 psi)	61	65	52
Skinsuit Spandex	90	93	85
Rubber	92	93	85

The pegboard which was used to measure manual dexterity required the subject to place as many pins as possible in thirty seconds, as described before. Good control and mobility retention were observed. The raw score for the unpressurized pressure suit glove was five pins placed in 30 seconds.

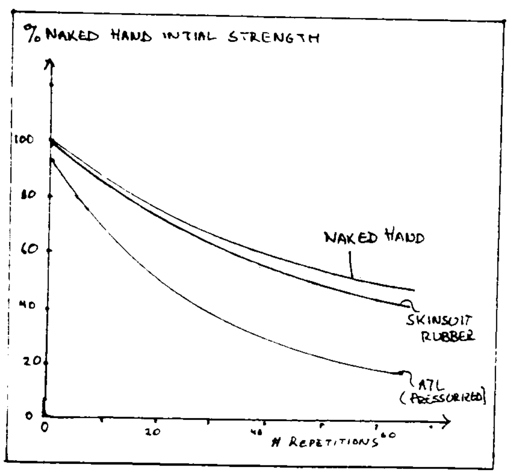
TABLE 2 : Dexterity of Pressure Suit Gloves in the Pegboard Test

Naked hand:	100
A7L-B (3.5 psi):	17
A7L-B (0 psi):	27
Skinsuit:	
Spandex	71
Rubber	77

Score is expressed as percentage of naked hand raw score, or 17 pins in 30 seconds.

High dexterity retention by Skinsuit

The strength test measured the types of fatigue associated with two different types of grips, one for each subject. The subject exercised his hand in a "ball" grip, by squeezing a bulb filled with air. His strength was determined by measuring the pressure to which the air inside the bulb rose with a manometer. A measurement was taken after every ten repetitions of exercise, and the results of the test are given in Graph 1. Note that the initial strength of both sorts of grip is similar in both cases, suggesting that once the wearer of a conventional pressure suit glove overcomes the glove's internal resistance, he is able to exert nearly as much strength as he would be able to exert without it. The faster decay rate for conventional gloves, however, indicates that he will tire more quickly if he must perform repetitive exercise.



Graph 1 : Strength Degradation with Fatigue

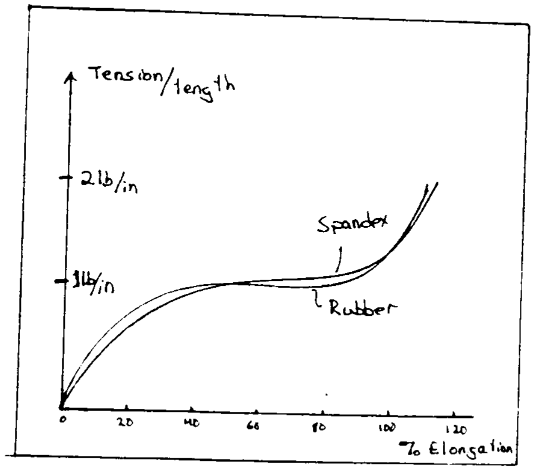
The tactile feedback test at first was qualitative in nature, examining the ability of the gloved subject to determine whether a coin was heads or tails. It was determined that the subject could do this reliably with the naked hand or the skinsuit gloves, but not at all well with the A7L-B glove. Accordingly, an improved tactile feedback test entailed the feeling of a pattern of raised dots, as described above. The subject was not permitted to rub the fingers along the dots, and only allowed to determine the pattern from the information that was able to propagate through the material of the glove. Table 3 describes the results of this test with dots of two different sizes in the configuration shown; the numbers represent the percentage of correct guesses averaged over several trials. The difference in tactile feedback between a pressurized and unpressurized A7L-B glove was negligible, so only the data for the unpressurized case appear below.

Table 3 : Tactile Feedback of Pressure Suit Gloves

Glove:	2 mm	4 mm
Naked hand	100	100
A7L-B (0 psi)	30	75
Skinsuit (Spandex)	90	100

Percentage of correct guesses

The materials test measured the stress-strain characteristics of the two fabrics used in skinsuit construction. These fabrics were woven from either Spandex or rubber elastic cords bound together by Dacron threads. The fabrics, similar to those used in foundation garments, were designed to provide high counterpressure to the body over a wide region of elongations, without major change in stress. It was observed that the Spandex fiber was more resistant to wear than was the rubber one. Also, the rubber tended to exert slightly less pressure while providing slightly greater mobility. Using a force gauge, measurements of the elongation as a function of the applied force were taken, and are shown in Graph 2.



Graph 2 : Stress-Strain Relations for Skinsuit Fabrics

Physiological observations were made throughout the study, during two special test runs of thirty minutes each. These two special tests were aimed at determining the degree of severity of any health problems associated with the use of skinsuits. Each skinsuit glove was worn in a partial vacuum of 3.5 psi for thirty minutes. Small amounts of edema, barely detectable by vision, were observed in the webs of the fingers, and a somewhat greater amount, causing a swelling of perhaps one-sixteenth of an inch, in the palm. There was no indication that the edema caused any loss of joint function, or any pain. The edema was also reduced when the gloves were repositioned on the hand, suggesting that the swelling may have been due, at least in part, to some misalignment of the glove during the initial donning. Also, upon removal of the glove, a small red mark was observed on the hand, caused by the zipper. This was not uncomfortable, and the mark disappeared after about three minutes. In general, the skinsuit gloves appeared to be more comfortable to wear in partial vacuum than at atmospheric pressure, probably due to the relief of the mechanical constriction of the glove.

VI ANALYSIS OF ERRORS

Because human factors research is a statistical science, and because the program of testing described in this report was prone to certain errors, it is important to detail the possible error sources. In general, the errors are mostly observational. They could be minimized with the use of better equipment and technique. In some cases, however, the error is intrinsic, and a very subtle or sophisticated experimental program would be required to improve the quality of the data.

Probably the worst of the errors has to do with the sensitivity of any test of manual dexterity and of hand mobility to the fit of the glove. The skinsuit gloves used in this study were exactly tailored to the subject by the methods discussed in section III. The A7L-B glove that was used, however, was tailored to astronaut Owen Garriott. This error could be removed by obtaining a series of exact measurements of the hand of the astronaut for whom the A7L-B glove was originally tailored, or by obtaining a new A7L-B glove tailored to a local test subject.

Another source of error derives from the fact that a hand working in a pressure suit performs thermodynamic work on the gas in the suit, while a hand moving in a pressure suit glove in a glove box does not compress any gas, because the gas immediately vents to the atmosphere. The volume of the hand was determined by water displacement measurements to be, however, within 80 ml of the internal volume of the glove for the subject, and so the amount of compression is not great. The stiffness of the glove, which is aggravated by the pressurization, dominates the thermodynamic work done. Although this effect might distort the data obtained from testing skinsuit segments designed to protect larger segments of the body, the difference is relatively small for the case of a single glove.

One big problem in human factors testing of any sort is the worry that the subject might affect the data due to some bias on his part. This difficulty is especially likely to appear when the investigator and the test subject are the same person. One way often used to defeat this difficulty is a technique called "blind testing", which means not letting the subject know how well he is doing on any test, not letting him watch his performance, and, in general, maintaining the subject in a state of relative ignorance so that his biases affect the data as little as possible. The subject in this study could always tell which glove he was wearing, so the testing was not truly blind. In other respects, though, a level of relative ignorance on the part of the subject was maintained. People who were not actually being tested recorded the data, and the information was withheld from the test subject until after the test was completed. In this way, the effects of the biases of the test subject toward the skinsuit concept were diminished.

VII. CONCLUSIONS

In general, the evaluation of the skinsuit glove was fairly encouraging. It offered a considerable advantage over the conventional pressure suit glove in mobility and dexterity. Tactile feedback was enormously improved, and the skinsuit glove proved to be much less fatiguing to wear. Although the wrist seal interface could still be improved somewhat, the system as a whole functioned well. Best of all, the physiological problems observed by Webb in his research were not present in this study.

The mobility and dexterity advantages of the skinsuit glove may largely be ascribed to the lighter material of which they are made. Offering similar protection to the hand without having to be tough enough to retain the pressure and the breathing gas, a skinsuit glove allows the retention of a much greater percentage of the naked hand's mobility and dexterity. There is no effort to make the skinsuit glove gas-tight, and it can thus have very lightweight construction and open mesh. This lightweight construction and open mesh probably also help explain the improved tactile feedback of the skinsuit glove. Small patches of skin on the order of half a square millimeter are exposed directly to whatever object is being handled, and a corresponding increase in sensory accuracy is obtained. In the A7L-B glove, on the other hand, the skin is separated from the object by as much as three millimeters of rubber. Improved tactile feedback probably also explains the improvement in pegboard scores as well, since performance on the pegboard involves both tactile feedback and mobility. Even the lower strength degradation may also be attributes to the lighter construction of the skinsuit glove. Of course, an operational skinsuit glove would require a thermal and micrometeoroid protection garment (TMPG), such as that fixed in place on the A7L-B glove. The TMPG is fairly lightweight, but probably degrades the mobility and dexterity of the A7L-B glove and accounts for some of the mobility advantage of the skinsuit glove.

The effects on the hand of using the skinsuit glove are evidently not harmful. A small amount of edema is considered acceptable by most doctors, and the levels observed in this study were always very mild or nonexistent. There was less swelling of the hands of the subject in this tests than there was in Webb's original study, probably because of the higher counterpressure used in this study (4.1 – 3.5 psi at the fingertips, vs. 3.1 psi). One area of concern, induced swelling in the concavities of the hand, proved to be less acute than expected. The higher counterpressure levels used caused the parts of the hand to be persuaded into a more cylindrical configuration, and this induced rounding probably helped stave off the edema.

The wrist seal used was rather poor. It had a pronounced tendency to suck the subject's hand into the glove box, and the additional effort which he had to expend to overcome this tendency may have affected the data to some extent. An improved wrist seal was designed, and equipped with a cotton overglove that restricted the forward motion of the hand past a certain point. The increased load in the web of the fingers was not uncomfortable, but the presence of the glove may have restricted the motion of the wrist and certainly hid the hand from vision. The new wrist seal did not pull as much as the earlier version, because it had a slightly smaller area exposed to the atmosphere for the pressure differential to act upon. Nevertheless, this tendency was sufficiently annoying that the overglove was needed, and it improved the ease of use of the skinsuit glove by a great degree. A better wrist seal is still needed, however, and one approach is to dam up the inside of the neoprene with rubber or plastic, transferring the force to the wrist ring better, but making the glove much harder to put on and take off.

REFERENCES

1. Bancroft, R.W., and Dunn, J.E. *Experimental animal decompressions to a near vacuum environment.* Aerospace Med. 36:720-725

2. Wilson, C.L. *Production of gas in human tissues at low pressures.* Report No. 61-105 School of Aerospace Medicine, Brooks Air Force Base, Texas

3. Rothman, S. **Physiology and Biochemistry of the Skin** University of Chicago Press, Chicago, 1974

4. Yoshimura. Hideki *Organ Systems in Adaptation: The Skin.* Chapter 8 in Section 4. Adaptation to the Environment: **Handbook of Physiology.** M.B. Visscher, et al., eds. American Physiological Society. Washington. D.C. 1964.

5. Oberg. James. **Red Star in Orbit** Stackpole Books. Philadelphia. Pa., 1981.

6. Haldane. J.S. **Respiration** Yale University Press. New Haven. 1920

7. Webb. Paul. and Annis. J.F. *Development of a Space Activity Suit* NASA CR-1892. 1971

8. Humanscale (A human-factors design tool). MIT Press.

9. Gray. J.S.. **Anatomy. Surgical and Physical.** Doubleday. London. 188