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Development and Evaluation of a Glove for Extravehicular Activity Space Suit without Prebreathing

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Abstract

The current United States space suit, called an extravehicular mobility unit (EMU), is pressurized with 100% oxygen at 0.29 atm (4.3 psi or 29.6 kPa) in the vacuum of space. This pressure is much lower than that on the earth or in the International Space Station, and prebreathing is required to avoid decompression sickness (DCS). Higher pressure can reduce the risk of DCS, but mobility would be sacrificed due to larger pressure differential between the inside and outside of the suit. To solve the issues regarding mobility, we employed elastic material. If high mobility is acquired, higher pressurization can be employed. Thus, we developed an elastic glove pressurized at 0.65 atm, which is the minimal pressure to avoid decompression sickness without prebreathing.

Range of motion with the nonelastic glove at 0.29 atm, which is simulated current EMU, was similar to that of the elastic glove at 0.65 atm. However, the required force evaluated by electromyography during finger flexion using elastic glove at 0.65 atm was smaller than that using the nonelastic glove at 0.29 atm. These results will encourage further development and investigation of a new extravehicular activity suit.

Keywords: Decompression sickness; Injury; Range of motion; Electromyography

Abbreviations: EVA: Extravehicular Activity; EMU: Extravehicular Mobility Unit; MCP: Metacarpophalangeal; ROM: Range of Motion; PIP: Proximal Interphalangeal; EMG: Electromyography

Introduction

In space, working outside of a spacecraft and lunar surface exploration are called extravehicular activity (EVA). For EVA in the vacuum of space, astronauts must wear a space suit or EVA suit. From an early point in the space program, hand and upper-extremity demands during EVA were recognized, and many astronauts prepared for their missions with hand and upper-extremity exercises. During EVA, astronauts must use of a variety of tools and move large pieces of equipment, which lack weight in the zero-gravity environment but still have mass and velocity. As the number of EVAs increases, attention to hand and upper-extremity problems also increases. Many EVAs are performed primarily by the upper extremity because the lower extremities are free-floating in the zero gravity of space or are locked into a large remote manipulator system positioning arm [1]. To develop a new space suit, we focused on the glove, which is the most important and complicated part of the suit.

Pressurization of the EVA suit

With low application of pressure to the body, astronauts are exposed to the risk of decompression sickness, which is caused by gas bubble formation within tissues due to inert gas supersaturation and gas embolism caused by entry of gas into the blood vessels [2]. The current United States space suit, called an extravehicular mobility unit (EMU), is pressurized with 100% oxygen at 0.29 atm (4.3 psi or 29.6 kPa) during EVA [3]. According to the law of partial pressure, the oxygen pressure is 0.21 atm (3.1 psi or 21.3 kPa) on Earth and in the International Space Station because the partial pressure of oxygen is 21% in the air, and normal atmospheric pressure is 1 atm. Thus, at least 0.21 atm of oxygen is needed for breathing and living. The inner pressure of the EMU is lower than the normal atmospheric pressure, and prebreathing or denitrogenation is required before EVA to avoid decompression sickness (DCS) especially due to eluted nitrogen in the blood and interstitial tissues [4]. Lowering breathing pressure, gas in the blood especially nitrogen, diffuses from the blood in the capillaries into alveoli, and is expired. Lowering gas pressure in the blood induces diffusion of nitrogen from the interstitial tissue into the blood. Prebreathing reduces the nitrogen content in the astronaut's body which prevents the formation of nitrogen bubbles in body tissues and surface vein, and avoids DCS. The oxygen pressure is sufficient for breathing because the EMU is pressurized with pure oxygen as described above. Even with this low pressure, the suit is stiff, restricts movement, and is fatiguing to work in because of expansion; i.e., the pressure differential between the inside and outside of the suit [5]. If the inner suit pressure is the same as the atmospheric pressure of 1 atm (101.4 kPa or 14.7 psi) on the earth surface or cabin pressure of the International Space Station [6], decompression sickness is not induced. However, the larger pressure differential prevents flexibility of the suit and therefore mobility [5]. Considering the pressurized space-suit glove, the structure surrounding the finger joint can be approximated by an inflatable fabric tube subjected to a bending moment from the hand. With the simple model, the maximum bending resistance of the glove is equal to πpr^3, where p is pressure differential between inside and outside of the glove, and r is the radius of the radius glove section [7]. Thus, higher pressurization and glove size are dominant factors in glove mobility if the material and the length are the same. From the standpoint of protection from DCS, a higher inner suit pressure is better, but from the standpoint of mobility, a lower inner pressure is favorable. Conversely, if high mobility could be obtained, the inner pressure would not have to be lowered.

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Physical Injuries

Astronauts experience hand and upper-extremity overuse and repetitive injuries during EVA [1,8,9], including traumatic onycholysis, fingertip abrasions, bruised and painful knuckles, subungual hematoma, paronychial and fingertip infection, frostbite, dislocations, and compressive neuropathies. Because hook-and-loop fasteners are routinely used to secure supplies and instruments in a zero-gravity environment, a number of astronauts have noted abrasions and minor cuts of their fingertips from disengaging supplies and instruments from the plastic hook section of the Velcro. Without pressure differential between inside and outside of glove, the glove is soft and deforms easily during movement. However, the pressure differential makes the grove stiff as described above, and the glove do not deform according to the shape of the joint. Additionally, the hard palm bar lies distal to the fifth and fourth metacarpophalangeal (MCP) joints in many astronauts' hands; consequently there is limited MCP joint flexion. Flexion of the fingers results intermittent friction of the dorsal aspect of the finger joints against the dorsal inner aspect of the gloves. This can lead to MCP joints pain as well as redness and thickening over the dorsal aspects of the MCP joints. Elbow problems also occur and include suit contact problems and medial or lateral epicondylitis.

Development of a New Glove for EVA

To solve the issue regarding mobility and injury, we employed elastic material. On the flexion side of the joints, the contractile force of the material helps with muscle contraction and joint movement. The material itself shrinks and does not disturb the joint movement with folding. On the extension side of the joints, the contraction force may disturb the joint contraction. However, the deformed material should match for the extension side, and it does not abrade the joint.

We recently demonstrated that a gas-pressurized elastic glove and sleeve improved mobility compared with a nonelastic, size-matched glove and sleeve similar to those in the current EMU [10,11]. The elastic glove was constructed with elastic polyurethane string and showed a wider range of motion (ROM) of the proximal interphalangeal (PIP) joint and a greater grip strength compared with the nonelastic glove. The nonelastic textile or stitching in less mobile areas, such as the sides of the arms, did not affect mobility.

These studies clarified that higher mobility can be acquired using elastic material for gloves, which are the most important part of the suit for EVA. As described above, if mobility is high, the suit pressure can be higher. As a next step, we developed a higher-pressure glove that does not require prebreathing. Lower pressurization is still better for movement; thus, the question is how much pressure is needed to avoid decompression sickness. To determine the threshold of decompression sickness, healthy subjects were exposed to low ambient pressure. While breathing air, which has the same nitrogen and oxygen contents, the threshold was considered to be 0.7 atm or 9.7 psi [12]. However, the use of 100% oxygen lowered the threshold to 0.65 atm or 9.5 psi [13,14]. No venous gas was detected in any subjects at a pressure higher than the ambient pressure. Venous gas was detected earlier or at a higher pressure than the pressure that induces symptoms of decompression sickness, and 100% oxygen was safer than a mixture of nitrogen and oxygen. With regard to EVA, carrying and applying mixed gases make life support systems heavier, larger, and more complicated. Thus, we employed a pressure of 0.65 atm with 100% oxygen to evaluate the new EVA suit that does not require prebreathing.

For development of the new suit, we hypothesized that elastic glove would improve the mobility, and studied the mobility of the elastic glove, which has a pressure differential of 0.65 atm between the inside and outside. The glove has three components: a gas-tight elastic layer, an elastic restraint layer, and a compression device for the palm (Figure 1). The gas-tight elastic layer is made of latex rubber. The restraint layer is made of polyurethane, and stitches are placed at the lateral parts of the finger and palm. The compression device comprises a hard wire over the line of the palm and flat plates, which are parted to the right and left on the dorsum of the hand. The parts of the palm and dorsum of the hand are connected by the wire and compress the glove to avoid ballooning [15].

Mobility Tests

To evaluate the mobility of the glove, we measured ROM in the finger and amplitudes of electromyography (EMG) during the finger movement. 10 right-handed healthy subjects (9 men and 1 women; mean ± SE for age, height, and weight: 21 ± 0.2 years, 171.6 ± 2.6 cm, and 60.0 ± 2.3 kg, respectively), and their right hands were used for the study. The study was approved by the institutional review board of Gifu University of Medical Science. Written informed consent was obtained from all subjects after they were thoroughly acquainted with all aspects of the experiment. To compare the mobility of the newly developed glove with that of the current EMU glove, we evaluated the ROM and EMG amplitudes in the same subjects using nonelastic gloves, the material of which has properties similar to those of the material of the EMU glove.

The right hand was positioned at heart level inside a clear acrylic chamber that was connected to a vacuum pump and pressure gauge. Subjects were asked to flex their finger for three times (Figure 2).

Figure 1: Photograph (upper panels) and illustration (lower panels) of the elastic glove. The restraint layer and compression device of the glove for the right hand (left: palm side, right: dorsal side). For the restraint layer, stitches are placed at the lateral parts of the finger and the palm. The compression device comprises a hard wire over the line of the palm and flat plates, which part the right and left dorsal aspects of the hand.

Measurements were performed at normal ambient pressure with no glove and with the nonelastic and elastic gloves under negative pressure. Subjects donned the glove, which was attached and sealed to the chamber at the wrist. The chamber pressure was set at 0.29 atm below ambient pressure with the nonelastic glove and at 0.65 atm below ambient pressure with the elastic glove. Thus, the combination of the pressure differential and elasticity was similar to that in the current EMU and our concept. The sizes of the gloves were designed to match when inflated. All measurements were performed and finished within an hour.

The ROM of the PIP joint was measured using a video system (HDC-HS350; Panasonic, Osaka, Japan). The video camera was set at the level of the hand at a distance of 1 m. Images of the index finger during maximal flexion from the extended neutral position of the finger were captured, and ROM was analyzed after the measurements. The angle of PIP joint during maximal flexion of each condition was analyzed using image analyzing software (Image J, ML, USA).

The EMG amplitude of the flexor digitorum superficialis muscle during flexion was simultaneously measured using an electrode and built-in bioamplifier (DL-141; S&ME, Tokyo, Japan). The EMG signal was monitored and recorded continuously at a rate of 1000 samples/s using an analog-to-digital converter equipped with data acquisition and analysis software (MacLab; ADInstruments, Sydney, Australia). The amplitude or root-mean-square values of the EMG during three times flexion were averaged for each glove condition. Measurements were analyzed using one-way ANOVA. When any significant effects were observed, Scheffe's post-hoc test was applied to compare the conditions. All data were expressed as means ± SE, and significance was set at $p<0.05$.

Figure 3 shows the ROM of the PIP joint of the index finger. With no glove, the joint flexed 106 ± 3 degrees from an extended neutral position. The motion was restricted while wearing the nonelastic and elastic gloves in the underpressure chamber; the ROM with the nonelastic glove at 0.29 atm and with the elastic glove at 0.65 atm was significantly narrower than that of the bare hand. However, the values with the gloves were similar regardless of the material and pressure differential (Figure 3).

The EMG amplitudes during finger flexion are shown in figure 4. The amplitude was 1.3 ± 0.1 mV with the bare hand at normal ambient pressure. The amplitude significantly increased 4-fold when the nonelastic glove was used with a pressure differential of 0.29 atm (5.2 ± 0.4 mV). With the pressure differential of 0.65 atm of the elastic glove, the amplitude (3.3 ± 0.1 mV) was significantly smaller than that of the nonelastic glove at 0.29 atm. Thus, the ROM of the nonelastic glove at 0.29 atm and that of the elastic glove at 0.65 atm were similar, but the EMG amplitude with elastic glove showed smaller amplitude of the EMG during similar range of finger flexion (Figure 4). The results suggest that the elastic glove is easier to bend and has lower risk of DCS compared with the current nonelastic glove. As a perspective, an EVA suit which no prebreathing is required can be developed without sacrificing mobility when elastic material is employed.

The study focused only on mobility in the presence of a pressure differential between the inside and outside of the gloves. Thus, those other problems are not considered, and the study has some limitations. Protection from stressors in space, such as cold, heat, meteoroids, and radiation, were not considered in this study because the elastic glove was not designed for space use in the immediate future. Volunteers were not astronauts, and their training statuses and ages differed from those of current astronauts [16]. If any concept of the present study is adopted for practical use, further investigation with body type- and age-matched volunteers using a new suit with full layers should be planned.

Figure 2: Experimental condition using the elastic glove. The hand with the elastic glove was inserted to the chamber and sealed. The inner pressure was set at 0.65 atm below the normal ambient pressure.

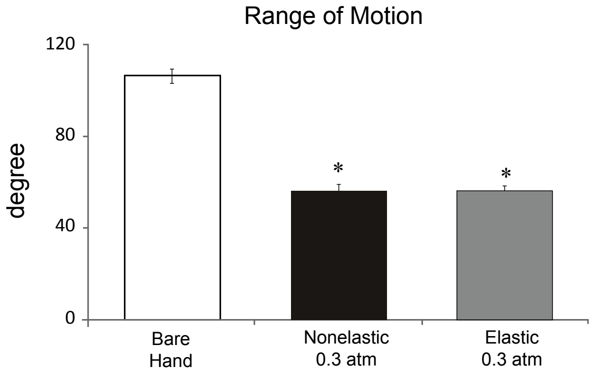

Figure 3: Range of motion of the proximal interphalangeal joint of the right index finger during finger flexion from the neutral horizontal position with a bare hand at normal ambient pressure, after donning a nonelastic glove with a pressure differential of 0.29 atm, and after donning an elastic glove with a pressure differential of 0.65 atm. $^{*}p<0.05$ *vs.* bare hand.

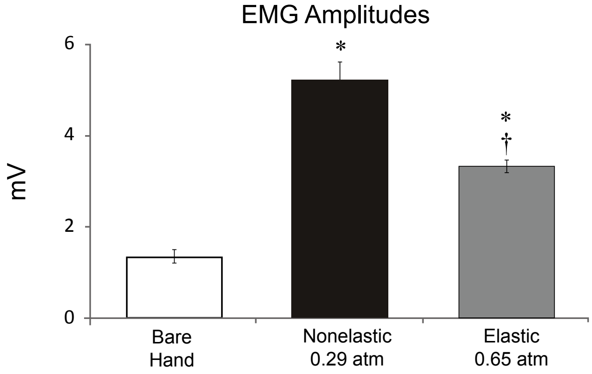

Figure 4: Mean amplitudes of surface electromyography (EMG) of the flexor digitorum superficialis muscle during finger flexion from the neutral horizontal position with a bare hand at normal ambient pressure, after donning a nonelastic glove with a pressure differential of 0.29 atm, and after donning an elastic glove with a pressure differential of 0.65 atm. $^{*}p<0.05$ *vs.* bare hand. $^{\dagger}p<0.05$ *vs.* nonelastic glove.

Furthermore, the mobility for a long period use, and the mobility of the whole body suit including the glove should be evaluated. However, the results of the present study encourage further development and investigation of a new EVA suit.

Future Studies

We are currently developing larger hinge joints (elbow and knee joints) and spheroid joints (shoulder and hip joints). The finger joints are also hinge joints; however, the larger joints require not only elasticity, but also a larger force for flexion. Furthermore, the large spheroid joints require another design. In the future, protection from stressors in space, such as cold, heat, meteoroids, and radiation, should be considered in the development of a whole body suit for EVA.

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