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How to cite: Rawal S, Madhubalan A, Manikandan P, Kanna J. Study on the Design of Space Gloves and EVA Suits with Future Challenges. Textile & Leather Review. 2022; 5:18-30.
<https://doi.org/10.31881/TLR.2021.25>

How to link: <https://doi.org/10.31881/TLR.2021.25>

Published: 5 February 2022

Study on the Design of Space Gloves and EVA Suits with Future Challenges

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Article

<https://doi.org/10.31881/TLR.2021.25>

Received 16 August 2021; Accepted 15 December 2021; Published 5 February 2022

ABSTRACT

The interaction of humans with space has increased tremendously. With the growing role of Extravehicular Activities (EVAs), the astronaut gloves in space suits require technological research and innovations. The gloves may seem insignificant to design, but it is practically the most tedious as all the tasks during an EVA require significant hand usage. A space glove should have strength and capabilities like dexterity, manipulability, and tactility. Its primary objective is to allow astronauts to move their fingers as efficiently as possible and aid with locomotion, restraint, and object handling. The present glove is cumbersome due to high torque requirements at the knuckles or metacarpophalangeal (MCP) joints. Also, astronauts suffer from a condition called fingernail delamination (or onycholysis) due to sustained pressure on the fingertips. The focus is on the main challenges of the given technology and scientific enhancements and how to use them to draw all their benefits. This paper provides a review study to determine the project's plausibility with gradual and substantial technological advancements.

KEYWORDS

EVA glove, spacesuit, effect on hand fatigue, materials, robotic hands

INTRODUCTION

Human interaction with space has increased tremendously. With the growing role of Extravehicular Activities (EVAs), the astronaut gloves in space suits require technological research and innovations. Astronauts working in space must wear protective, pressurized suits that allow them to manoeuvre quickly and without constraints while repairing satellites or adding solar panels to the space station. One of the vital elements of the suit is the glove. Designing a complete spacesuit including the gloves along with their appropriate fabrics is a highly demanding task. From the beginning of Extravehicular Activities, the glove has been considered a versatile, practical, and multipurpose tool intended for every task in space [1]. Apart from life support and protection systems that are considered a primary objective for an astronaut, it is crucial to have unrestricted hand movement, which minimizes the work required to flex the gloves. The glove's design should keep the following factors in mind: motion, comfort, and tactility [2].

Literature review

Numerous articles have been published in the field of the effect of gloves on task performance, along with the challenges faced by the scientists to make the glove. Mei-ying Kwan suggested that the gloves fit is essential because it affects the wearer's safety, performance, and comfort. Gloves that are currently constructed based on a splayed posture cannot provide a good fit [3]. Vishala et al. focused on minimizing the bending moment requirement for a finger in a pressurized EVA glove [4]. Shockey et al. described the damage observations and results of the laboratory tests, deduced how the damage occurred, and presented guidelines for designing more damage-resistant gloves [5]. Shirley L. Fleming indicated an increase in fatigue responses for the gloved condition versus the no-glove condition and an increase in fatigue responses for isometric grip versus the eccentric muscle action of the handgrip [6]. In 1958, Lyman and Groth reported that astronauts faced more force on their hands with gloves on rather than without them [7]. Wang et al. found out that astronaut gloves reduce strength capabilities, dexterity and manipulability. While reviewing "Space Suit Glove Design with Advanced Metacarpal Phalangeal Joints and Robotic Hand Evaluation", written by Southern et al., different patterning techniques and methods were introduced to reduce the pain and give more movement in the gloves [8]. Durgin et al. in the WPI Space Glove Design Project, discussed that the glove did not restrict the hand movement when it was kept under the pressure of 8 psi [9]. In a very recent study for Planetary Surface Exploration by Lluch, he presents an architecture concept of a spacesuit combining mechanical counter pressure (MCP) with gas-pressurization (GP). This conceptual idea increases mobility and safety through the pressure layer [10].

Given the appreciable work done by the scientific community, the primary work proposes a concept of power-assisted or robotic gloves to overcome the challenges faced by the astronauts. The study of the fundamental necessities to produce the prototype of a robotic astronaut glove is presented in this paper.

Glove history

The main focus was to change the material of the gloves rather than the design. The improvement started from the Mercury program and later led to the 1000 Series, the first shuttle EVA gloves. After the introduction of high technology services, such as stereolithography prototyping, laser cutting, laser scanning technology, 3D computer modelling, and CNC machining, the designers produced better designs. With the refinement of the bladder and restraint designs, the tactility of the fingertips was improved, and the designers achieved a better fit. The fit of the glove then provided minimum volume, decrease in torque and increase in fingertip tactility.

Over time, the designers started to make custom gloves for the astronauts, wherein a high-strength

palm bar was used, which segmented the palm of the pressurized gloves, eventually matching the hand's natural shape. Palm plate segmentation was introduced, which provided better locomotion and flexibility. The same concept was applied in Series 4000 gloves. A four-ring rolling convolute joint configuration was developed, providing a constant volume while manipulating low torque and stable motion [11,12].

The following change which was seen in the glove was the wrist joint. This change was seen in the Series 5000. Also, these new gloves required low torque to follow the wrist of an astronaut. The only drawback of this design was that it was made up of steel, which eventually increased the weight of the glove when compared to the Series 4000. New high technology services such as laser scanning, stereolithography prototyping, etc., were used in this Series. The production and the design of the glove were significantly enhanced in the Series 4000. With the advancement of the technologies, the design was improved, and better fabrication was possible. More accurate load testing and scanning data accurately with desired output was possible with the help of the Computer-Aided Design (CAD) software [11]. This phase of 3D modelling and CAD software was known as Phase V.

With the evolvement of the CAD software, more complex surface models were possible to design using 3D modelling and Uniform B-Spline capabilities. Titanium and Graphite/Epoxy composites were used instead of bushing assemblies. This ensured weight reduction in astronaut gloves. After using Phase V gloves, astronauts requested the designers to replace the wrist material with a softer material. This change led to the development of Phase VI gloves which are depicted in Figure 1. Overall, Thermal Micrometeoroid Garment (TMG) performance was increased by reducing unneeded insulation in the glove.

Figure 1. Phase VI ILC Dover Gloves; adapted with permission from Vincent Fournier, Phase VI Space Gloves (ILC) Dover, U.S.A., 2019, Centuri Gallery

Furthermore, with close fittings of hand and finger joints, the torque is reduced, and the aim of comfortability was achieved using lightweight fabrics. In 1988, when astronauts used Phase VI gloves, they seemed pretty satisfied with them. The changes made in gloves during the Mercury and Apollo programs remarked in the development of successful astronaut gloves.

EVA Glove technology has found its way from David Clark Co. (DDC) and ILC Dover. Phase VI gloves result from an improvement in Phase IV, Series 4000, Phase V gloves, and Series 5000. Hence, Phase VI gloves are used in all recent space missions.

EVA GLOVE DESIGN

A spacesuit is generally 3/16 inch or 0.48 cm thick. Early spacesuits were made of soft materials, but they combined hard and soft components to provide today's support, mobility, and comfort. The spacesuit is made up of 13 layers of materials, including an inner cooling garment (two layers), pressure garment (two layers), TMG (eight layers), and an outer layer (one layer) [13]. Nowadays, spacesuits are sewn or cemented together according to the fit of each astronaut. The glove and spacesuit layers are almost similar except that the cooling garment does not extend to the hand.

An astronaut glove consists of three layers, as depicted in Figure 2: the bladder, restraint, and TMG layers. The bladder layer keeps the air inside the spacesuit and maintains the pressure inside a glove. The second layer, the restraint layer, fits over the bladder layer and helps maintain the shape and the size of the glove. This layer was designed to be used in a space shuttle and the International Space Station (ISS). Finally, a TMG layer adds protection against fast-travelling particles and sharp objects. This layer also provides a buffer from thermal swings. Wrist movement is possible by using a rotary bearing at the wrist joint. Fabric joints are used for comfortable finger movements. To maintain the temperature inside the glove, small electric heating pads are installed on every fingertip. This system is originated as a 3-volt system designed to operate off a remotely located battery pack. A recent battery redesign has resulted in the evolvement of the heater system to a 12-volt design [11].

Figure 2. Layers of an astronaut glove; adapted with permission [5]

For the past few years, Phase VI gloves have been used for the space missions. Phase VI gloves are developed using computer-aided designs (CAD), making them different from the Series 4000 and 5000. These gloves are made with more accuracy and have a lower cost [11]. To develop the gloves of a perfect fit for the astronauts, ILC developed a laser scanner that provides a 3D scan of the hands of the crewmembers. Using the scanner, the gloves are made to use lesser volume, resulting in a better fit [11]. It features a lower torque wrist bearing and an enhanced rolling convolute wrist joint using a two-gimbal ring system tightly integrated into the wrist to reduce the astronaut's efforts. A recent study found that astronauts faced difficulty curling their fingers even in Phase VI gloves [11]. NASA designers and engineers provided various methodologies to overcome this problem. In a competition conducted by NASA, an aerospace engineer named Homer took notes about all the joint difficulties and designed a glove that would solve the problem of the finger movement. The solution which he gave is discussed further.

Materials used

Space gloves are designed to resist cutting, tearing, and puncturing and consist of multiple layers to provide contingency protection. As shown in Figure 3, the multiple layers used to make space gloves, along with their importance, are mentioned in Table 1. Gloves are particularly vulnerable to damage because they come in contact with the International Space Station (ISS) surfaces, tools, and parts being installed under gripping forces that can be 30 lbf or more [5]. Therefore, the materials used for making gloves should be designed to resist everything without any wear and tear.

Table 1. Materials and their importance [9,14]

MATERIAL/LAYER	FEATURES
Nylon	Nylon is used as a pressure-retaining bladder which creates an impermeable barrier between the inside of the suit and the vacuum of the space. This layer is further dipped in urethane (rubber) 6 times.
Nylon (Polyamides)	This layer is known for absorbing water-like substances from its surroundings. This layer is abrasion resistant which makes it perfect as a material for astronaut gloves.
Dacron	It is a type of polymer made from ethylene glycol and terephthalic acid. This layer is also used to retain pressure inside the glove. Due to its high abrasion resistance and resistance to heat, it is widely used.
Ripstop nylon	This material consists of a crisscross reinforcement. These small rectangles are designed to stop rips or punctures when there is a tear in the material.
Polyethylene	This layer is used for thermal insulation in the gloves. Being stiff, stable, and of high strength,
Terephthalate (PET)	PET forms the outer layer of the glove. PET is a blend of Teflon, Kevlar and Nomex.
Teflon	This material is lightweight, robust, durable and flexible. Being a non-combustible fabric, it is used as a layer in an astronaut glove.

Kevlar	Kevlar has the strength to resist bullets which makes it perfectly suitable for standing up to the impact from meteors and space junk. This material is also known for withstanding harsh space temperatures without getting damaged or changing its form.
Mylar	This material reflects the sun radiations and stabilizes the temperature of the glove.

*The layers are listed from the inner layer to the outer layer

The TMG is made up of neoprene and ripstop nylon. This layer maintains flexibility over a wide temperature range. The TMG layer protects an astronaut from solar radiation during EVAs. Teflon, mylar and chiffon have specific qualities which make the back of the fingers on the astronaut glove. These properties are listed in Table 1. Chiffon is a protective layer for Mylar. RTV 150, RTV 157 and nomex form the front of the fingers on the glove. The vulcanized rubber enhances tactility and gripping capabilities.

Figure 3. Multiple layers of an astronaut glove; Adapted from NASA Official gallery site (320; NASA-STD-3000 304)

CHALLENGES OF THE CURRENT EVA GLOVE

Among different parts of a suit, the glove has to perform various tasks in EVAs. Considering all the past missions, the astronauts want their gloves to allow locomotion, be comfortable and minimize the effort they put while gripping things. When designing gloves, hazardous extremes of heat and cold, meteoroid impact, radiation, abrasion, chemical exposure, puncture, high loads from suit pressurization, and task-induced loads must be addressed [15]. Much work has been done, and it is still going on, in providing the best for the astronauts for space exploration.

Gas-pressurized spacesuit gloves are bulky like stiff shells that limit astronauts' functions and capability of working in space [16]. A pair of gas-pressurized gloves were designed, developed, and fabricated. The glove theoretically satisfies all the requirements, but when tested, it degrades the mobility of astronauts' hands by 10% [17]. Moreover, some tests resulted in increased finger girth due to negative

pressure, probably due to blood shift toward the hand [18]. Other studies show that gas-pressurized glove induces fatigue during grip endurance with higher discomfort [19]. Traditional gas-pressurized suits are notoriously inflexible. Gas pressurization causes stiffening of the soft suit materials. Changes in internal volume and pressure caused by the deformation of the suit joints during movement force the astronauts to expend energy every time they bend the suit away from its equilibrium position.

Another problem that astronauts commonly face is onycholysis or fingernail delamination. In this problem, the fingernail detaches from the nail bed, causing the astronauts much pain. The present glove is cumbersome due to high torque requirements at the knuckles or metacarpophalangeal (MCP) joints [20]. Due to sustained pressure and the axial load on the fingertips along with the moisture present in the glove, astronauts' fingernails detach from the nail bed [21].

We are still researching to counteract this problem. Improvements can still be made to reduce the load on the fingertips as a nail takes approximately six months to regrow fully. Earlier research shows that a better flow of gasses near the fingertips can solve this problem [22]. Therefore, studies on the same aspect are under evaluation. ILC also studied this problem and has transitioned some of the research to actual life applications. At the same time, testing for this problem by adding layers showed that some layers could prevent harmful microbial growth inside the glove. Investigation on silver coatings as comfort liners is in progress, and this will need more investigation in the future for better results.

On the other hand, mechanical counter-pressure (MCP) spacesuits have great potential to improve astronauts' mobility. MCP suits differ from traditional gas-pressurized space suits by applying surface pressure to the wearer by using tight-fitting materials rather than a pressurized gas enclosure, thus representing a fundamental change in spacesuit design. By altering the pressurization mechanism, MCP suits avoid the pitfall of forcing the astronaut to work against the suit during movement; the suit acts as a conformal, wetsuit-like mobile garment rather than an inflexible balloon. MCP suits offer the added benefit of acting like a second-skin to the wearer, vastly reducing the suit's mass while simultaneously mitigating the risk of catastrophic failures due to puncture or depressurization. As a result, MCP suits represent a promising breakthrough technology for future exploration missions. The concept of MCP space suits was first proposed and explored in the 1960s and 1970s. However, the concept was rejected due to limitations in available materials, comfort, and donning and doffing challenges [23].

ROBOTIC EXOSKELETONS FOR HANDS WITH POWER-ASSISTANCE

After much research in this field by many scientists and from the experience of the astronauts, it was found out that the main problem lies in dexterity, manipulability, and tactility. An astronaut's journal stated that EVA in a gas-pressurized suit causes pain where the suit rubs against the body, and the

gloves are especially tough on the fingertips [24]. Therefore, to improve the future techniques of the glove, power-assisted or robotic gloves might be the future of space gloves. Along with that, gloves with better fittings according to each astronaut can be introduced. After studying all the literature, it was found that the glove region around the MCP joint can be widened for the manipulability of the hand. This will reduce the friction caused near the knuckles and will result in better outcomes from the astronauts.

Along with the area widening near the MCP joint, a NASA glove competition winner, Peter Homer, came up with the solution to crisscrossing one-eighth-inch craft ribbon into an "X" at each finger joint to create a hinge-like effect. The hinge helped to improve the fingers' dexterity [25].

Future gloves can be robust, wherein actuators will play a prominent role and solve tactility and manipulability issues [26]—physical sensors like Force Sensitive Resistors (FSR). Strain gauge, thermocouple, humidity sensor [27] are likely to replace human receptors. Astronauts usually have difficulty feeling objects through their gloves because of their thickness and 4.3 psi pressure difference [28]. These gloves will have low mass and inertia for better movements [29]. This robotic glove will be a complex structure, but it can provide 23 degrees of freedom in movement, as shown in Figure 4.

Figure 4. 23 DoF in a human hand; adapted with permission [29]

The choice of sensors and the proper use of kinematics play a significant role in designing these gloves. The most important thing is that they should have minimum weight and maximum strength. Two mechanisms can be kept in mind while designing the glove. One is the four bar mechanism, as depicted in Figure 5; this mechanism allows the rotation around an instantaneous centre that coincides with the operator's finger centre joint. Because of the parallelogram structure of the mechanism, the instant centre of rotation remains fixed during all movements. This means that the exoskeleton that uses this strategy should be customized to the wearer's hand. One advantage of this structure is that practically all elements are located on the back of the hand and do not hinder the operator's workspace. This

solution, however, has the disadvantage of being quite bulky. The other mechanism is the cable mechanism; in this structure, the movement is done through cables connected to motors that apply the desired torque on the joints. The advantage is that this technique does not involve a massive structure on the hand and that the engines that generate the actuation can be placed in less crucial areas, such as the forearm. A disadvantage of this structure is that the cables work only in traction, so it is necessary to place a couple of cables for each degree of freedom, one for the flexion and one for the extension of the finger [30,31]. The chances of making a robotically compatible anthropomorphic human scale hand have been increased with the development of resources in the past. NASA has already developed this type of hand at the Johnson Space Centre [32,33]. The robust hand needs more investigation soon in order to be a successful part of the EVA suit as it will strengthen the interactions with more precise and accurate methods [34].

a)

b)

Figure 5. (a) Four bar mechanisms; (b) Cable mechanism; adapted with permission [29]

CONCLUSION

This paper concludes that an astronaut would require light, comfortable, and robust gloves in a space-like environment. Many previous designs were successful and are still working. The robust astronaut gloves can be the future of the astronaut gloves. This glove will be able to solve maximum problems depending on the environment of the space and the working conditions of the astronaut. The MCP joint problem also has two solutions. The fingernail delamination problem is still under study. The scientists and engineers are trying to find the most appropriate and the best solution with proper testing as soon as possible. In the future, in our view, space glove design and the support of astronaut comfort in open space and while exploring planetary surfaces will likely be more effective [35]. The growing needs and human expansion in human-crewed exploration missions will demand more testing and development activities targeting EVA glove materials; thus, existing research is already taking

place with many perspectives for growth in the future. Finally, the complete hand prototype with the sensors and actuators will be realized.

Author Contributions

Conceptualization – Rawal S, Madhubalan A, Manikandan P and Kanna J; methodology – Rawal S, Madhubalan A; resources – Rawal S, Madhubalan A; writing-original draft preparation – Rawal S, Madhubalan A; writing-review and editing – Rawal S, Madhubalan A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

Acknowledgements

I wish to acknowledge the help provided by Vaayusastra Aerospace Pvt. Ltd. and SRM Institute of Science and Technology, Chennai. I would also like to show my deep appreciation to my supervisors, who helped finalize my research.

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