# Advancing EVA Suit Design: A Comparative Study of Mechanical Counter-Pressure Forearm Sleeves

Erin Fenderson[1]
Katelyn Gibbs[2]
Kaylie Sorrel[3]
Jessica Harder[4]
*Mississippi State University, Mississippi State, MS 39762*

**The development of mechanical counter-pressure (MCP) technology offers a promising solution to enhance astronaut mobility and flexibility during extravehicular activities (EVAs). This study presents the STATE Suit, an MCP forearm sleeve system designed to provide reliable compression while incorporating pressure monitoring and a thermal regulation system (TRS). Two distinct sleeve designs are explored: Design 1, which utilizes a pneumatically actuated compression layer to achieve uniform pressure distribution, and Design 2, which employs a tension-driven constrictive lattice structure composed of high-elasticity textiles to dynamically conform to the forearm under strain. Both designs aim to maintain a predetermined pressure threshold critical for astronaut safety while improving dexterity and comfort. By integrating real-time pressure sensors and thermal management strategies, this project seeks to address challenges in MCP implementation, with the goal of enabling more adaptable and effective EVA suit components.**

## Nomenclature

| | | |
|---|---|---|
| $\Delta x$ | = | change in spring length |
| *CAD* | = | Computer Aided Design |
| D | = | coil diameter |
| *kPa* | = | kilopascals |
| lb | = | pounds |
| *MCP* | = | mechanical counter-pressure |
| *NiTi* | = | Nitinol (Nickel Titanium) |
| $p$ | = | pressure |
| Pa | = | Pascals |
| *psia* | = | pounds per square inch (absolute) |
| $A$ | = | $X$ component of the resultant pressure force acting on the vehicle |
| $Fnet$ | = | Net Force applied by springs |
| $G$ | = | Shear Modulus |
| $K$ | = | spring constant |
| $Keq$ | = | equivalent spring constant |
| $N$ | = | number of active coils |
| $r$ | = | radius of the arm |
| $t$ | = | thickness of material layers |
| t | | |

[1] Erin Fenderson (Undergraduate), AIAA Member.
[2] Katelyn Gibbs (Undergraduate), AIAA Member.
[3] Kaylie Sorrel (Undergraduate), AIAA Member.
[4] Jessica Harder (Undergraduate), AIAA Member.

## I. Introduction

Human exploration of Mars presents unique challenges requiring innovative solutions in spacesuit design. Traditional spacesuits, while functional, impose significant limitations on astronaut mobility and adaptability. The STATE Suit project addresses these challenges by developing a modular arm system designed to provide effective mechanical counterpressure while maintaining flexibility and durability. The project explores two distinct approaches to achieving counterpressure. The first design utilizes pneumatically actuated compression, incorporating inflatable air bladders that regulate pressure dynamically. The second design employs a flexible biaxial weaving pattern with spring-attached cuffs, which create uniform counterpressure through passive mechanical tension. Initially, the project investigated the integration of Nitinol (NiTi), a shape-memory alloy, to enhance structural adaptability. The application was later refined to focus on core mechanical principles. The primary objective is to develop a modular arm system that optimizes both pressurization and thermal regulation, essential for long-duration missions in extreme environments.

## II. Methodology

The development of the STATE Suit has been guided by a systematic approach to optimizing mechanical counterpressure while maintaining astronaut mobility and comfort. Initially, the design concept focused on leveraging the unique properties of Nitinol (NiTi), a shape-memory alloy capable of deformation and recovery in response to temperature variations. NiTi was considered for enhancing both the forearm and glove system, providing dynamic adaptability to external conditions. As research progressed, a refined approach was taken to ensure precise actuation control while maintaining structural efficiency. This led to a strategic focus on developing a mechanical proof-of-concept for Design One, incorporating pneumatically actuated compression. In parallel, Design Two was introduced to explore an alternative counterpressure mechanism, utilizing a flexible biaxial weaving pattern with spring-attached cuffs. By evaluating both designs, the project aims to determine the most effective solution for achieving consistent pressure distribution and enhanced mobility in an extraterrestrial environment.

### A. Sensor Processing

The development of the STATE Suit integrates a strategic selection of materials, advanced design tools, and systematic testing methodologies to optimize performance and reliability. Nitinol (NiTi) was chosen for its exceptional flexibility, durability, and adaptability to microgravity environments. Initial testing focused on evaluating NiTi's response to controlled heating conditions, analyzing its behavior, and determining safe amperage levels suitable for human use.

To monitor pressure distribution across the forearm and hand, thin-film analog and digital pressure sensors were selected for integration with an Arduino-based data acquisition system, as illustrated in Figure 1. Mississippi State University's Athlete Engineering Department, having previously employed the Parker FlexSense Stretch Sensor in a separate project, provided access to FlexSense Pressure Sensors for this research. However, during preliminary testing, it was determined that the Arduino's resistor-based processing method was incompatible with the capacitance-based architecture of these sensors, preventing the collection of reliable data.

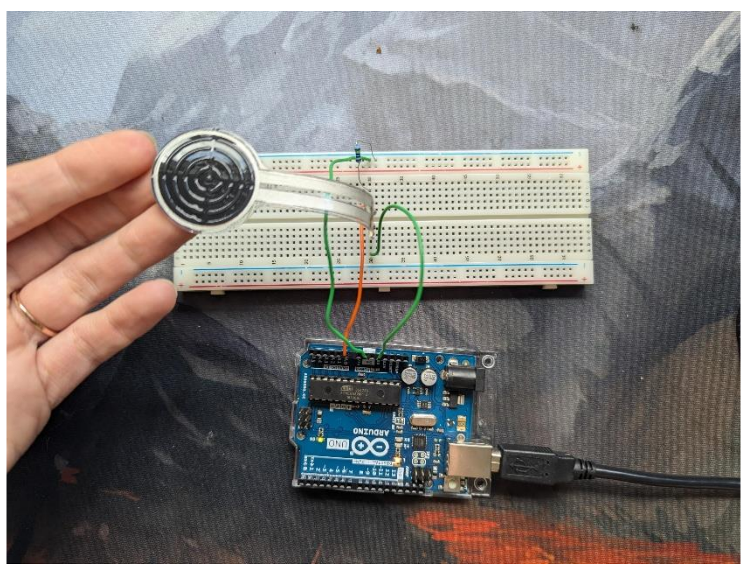


**Figure 1. Bread board wiring layout for sensor reading verification and calibration of sensors.**

Given the limited publicly available documentation on capacitance-based sensors, alternative solutions were explored. Further collaboration with Athlete Engineering led to access to their specialized software, which enabled accurate, real-time data acquisition from up to four sensors simultaneously, with output measured in picofarads. To ensure precision in pressure measurements, the sensors were calibrated using a range of known weights (1–5 pounds), establishing a correlation between applied force and sensor readings. For secure placement along the forearm, the sensors were embedded within a high-elasticity compression sleeve designed for uniform pressure distribution, ensuring consistent contact and reliable data collection. Figure 2 presents the experimental setup, including sensor placement and the data acquisition software utilized for processing.

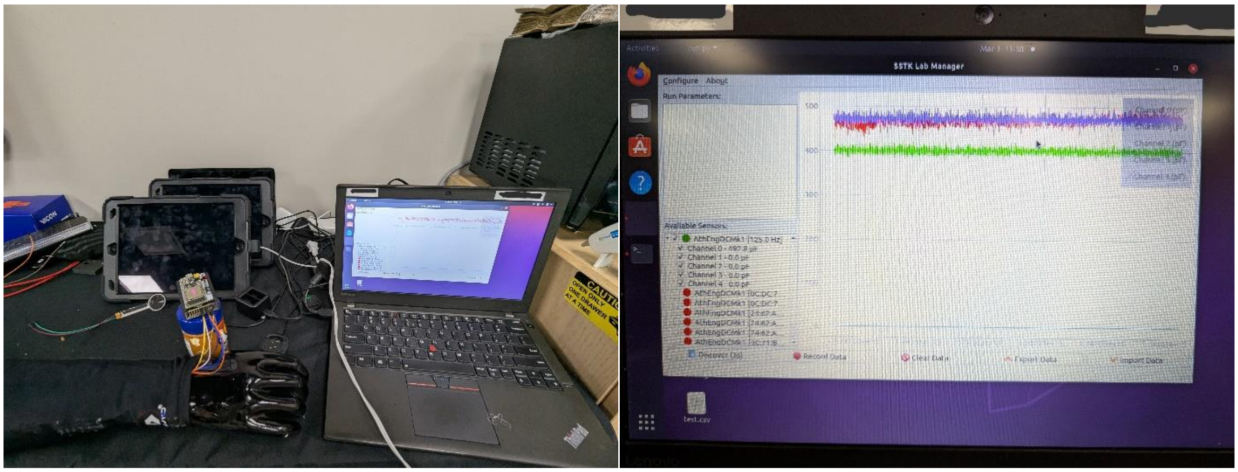



**Figure 2. Sensor setup and processing software.**

## B. Thermoregulation System

To enhance the thermo-regulatory performance of the mechanical counterpressure suit, an active cooling system has been integrated, incorporating a fluid circulation unit of 3/16-inch outer-diameter tubing. The tubing layout, as presented in Figure 3, has been designed to optimize both fluid distribution and coverage across the suit's internal surface. Although the system has been modeled in its entirety, thermal data related to its performance has not yet been incorporated into this study. However, the model demonstrates the successful integration of a dynamic cooling mechanism within the suit's overall architecture.

The primary objective of this cooling system is to support the compression layer by effectively managing the dissipation of heat produced by the wearer. By circulating coolants through the tubing, the system facilitates temperature regulation within the suit, preventing excessive heat buildup and contributing to the wearer's overall comfort. It is intended to work in conjunction with other subsystems, including the mechanical counterpressure layer. The cooling system is essential in maintaining the astronaut's body temperature, ensuring comfort and safety during strenuous physical activity in extreme environmental conditions.

Although real-time thermal feedback is not provided by the current model, future iterations of the design may incorporate sensors for the collection of thermal performance data. This would allow for a more refined and data-driven approach to cooling system optimization.

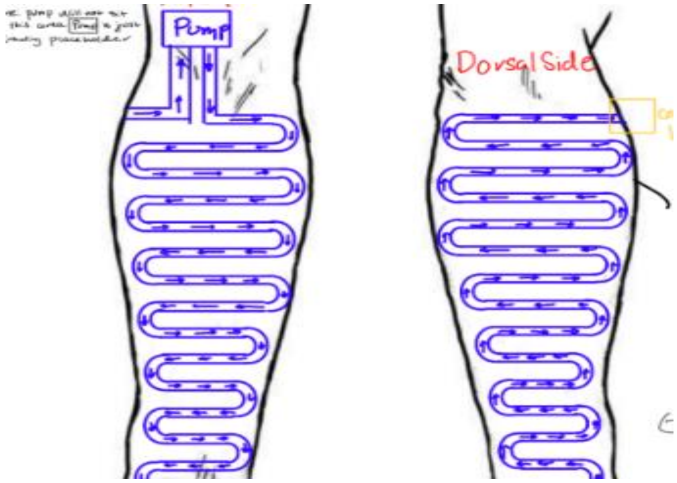


**Figure 3. Tubing pattern design selected for TRS.**

## C. Design One - Air Bladder Pressurization

The design utilizes a series of inflatable air bladders positioned within the suit to provide mechanical counterpressure. By inflating these bladders to a regulated pressure, the system aims to maintain adequate compression against the astronaut's body, reducing the need for a fully rigid or elastically constrictive material. The air bladders are constructed from a multi-layered elastomeric material, which offers both flexibility and durability. The bladders are strategically placed in high-mobility areas to ensure uniform pressure application without restricting movement. Each bladder is equipped with a micro-regulated valve system, allowing the astronaut to adjust inflation levels dynamically.

The inflation mechanism consists of a miniature air pump integrated into the suit, a network of pressure sensors that monitors and maintains uniform bladder expansion, and emergency pressure release valves to prevent overinflation in case of malfunction. The air pressure within the bladders is maintained at approximately 4.3 psi, matching the required counterpressure for EVA operations. The system is designed to be self-regulating, with manual override controls available through the astronaut's suit interface.

The standard required counterpressure for an EVA suit is 4.3 psi (equivalent to 29.6 kPa), which is approximately the minimum needed to support human physiological functions in a low-pressure environment. The volume of air required for the bladders depends on the surface area of the arm being covered, the thickness of the bladders, and the internal pressure needed to exert sufficient force.

$$V = A\ x\ t$$

To ensure adequate mechanical counterpressure, we calculate the force exerted on the skin. This force is distributed across the arm, ensuring that the suit applies sufficient compression to support bodily functions.

$$F = P\ x\ A$$

The bladder material must withstand internal pressure without excessive deformation. The hoop stress in the material is given by:

$$\boldsymbol{\sigma = \frac{Pr}{2t}}$$

The selected elastomer material should have a yield strength significantly higher than this value to ensure durability. To maintain proper inflation, the air pump must be able to supply the required volume flow rate. If pressure regulation is required over time, the flow rate is:

$$Q = \frac{V}{t}$$

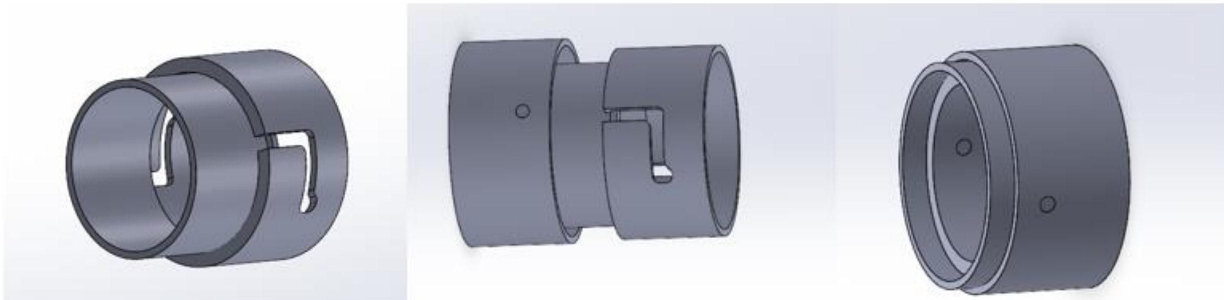
This sets the minimum required capacity for the miniature air pump integrated into the suit. The air bladder system is designed to be flexible, allowing free movement without excessive resistance. However, potential drawbacks include slight delays in pressure adjustment when moving rapidly, localized compression differences in areas with greater curvature and added bulk from the inflation mechanism, which may slightly impact maneuverability. To mitigate these concerns, the bladders are arranged in a segmented fashion, allowing for independent inflation zones that adapt to movement. In the event of a bladder puncture or rupture, the suit features multiple redundancies. Each bladder is isolated, so failure in one section does not compromise the entire system. A secondary manual inflation system allows astronauts to reinflate bladders if necessary. A fail-safe compression fabric layer provides a minimal level of mechanical counterpressure in case of system-wide failure. This ensures that the astronaut remains protected and functional even in emergency situations.

### D. Design Two – Braided Lattice with Axially Applied Tension

The creation of a woven or braided sleeve around the arm requires a precise balance of tension, pattern, and structural integrity to ensure both stability and flexibility. As depicted in Figure 4, the strands were interwoven in a systematic manner, with each pass carefully controlled to maintain consistent pressure against the arm. The tension was calibrated to avoid excessive tightness or looseness, ensuring an optimal fit. The weaving process involved an alternating pattern, with each section crossing over in a sequence, progressively spiraling or layering to enhance coverage. Throughout the construction, iterative adjustments were made to conform the material to the contours of the arm, thereby allowing for freedom of movement. The resulting structure is both functional and ergonomic, providing a secure yet comfortable fit that effectively accommodates the arm's natural range of motion.

**Figure 4. The flexible braided lattice.**

To facilitate the application of tension, connecting bands were designed using CAD software and subsequently 3D printed, as illustrated in Figure 5. The bands consist of three distinct layers: the inner (first) layer, which serves as the attachment point for the springs; the middle (second) layer, featuring grooves designed to accommodate a bayonet locking mechanism; and the outer (third) layer, which incorporates two pins that align with the guide rails of the middle layer. This layered configuration ensures precise functionality and stability during operation.



(c) Inner layer (b) Middle layer (a) Outer layer

**Figure 5. Inner, middle, and outer layer bands illustrating technique to create tension.**

When mechanically locked into place, tension is applied to the springs causing the biaxial woven pattern to create the expected counterpressure. The weaving method chosen contains constraining properties when tension is applied axially. These constraining properties are ideal in applying the uniform pressure that is needed. Additionally, alternative steel extension springs were employed to create the mechanically applied axial force needed for compression around the forearm. After calculating the forces and stresses needed to create counterpressure, the values were tested and evaluated for accuracy. This method is being implemented to achieve the target pressure of 4.3 psia.

Furthermore, the forearm was assumed to behave as a thin-walled cylindrical pressure vessel. This assumption facilitated calculations of stresses and spring forces needed for effective and safe counter-pressure or compression. 4.3 psia is the pressure value currently being used in spacesuits for astronaut safety during missions. The force that the thin-walled pressure vessel needs to apply to the wearer should be equivalent to the 4.3 psia currently in use. To achieve this many factors are considered- pressure needed, radius of the arm, thickness of the layers, Shear Modulus of NiTi when activated, diameter of NiTi wire, diameter of the coils in the spring, the number of active coils, net force applied by the springs, spring constants, equivalent spring constant, circumference of the wearer's arm, and lastly the change in the length of the spring when activated. The Pressure required, and Shear Modulus are known constants:

$$P = 4.3\ psia\ (29.6475\ kPa)$$
$$G = 28.8\ GPa\ (4180\ ksi)$$

Radius of the wearer's arm and thickness of the layers are approximate values and are also constant:

$$r \approx 2in$$
$$t \approx 0.16\ in$$

The diameter of the wire acts as a constant for each mathematical calculation. Further calculations were conducted to achieve optimality. However, continuous refinement would be fit as it would provide more suitable outputs. The adjustments made to the diameter must also maintain safe amperage levels to safeguard the wearer in the event of a failure. The diameter of the spring coil is tested using various sizes, from 1/16 (in) up to 13/64 (in). The number of active coils is based on the length of the compressed spring and the diameter of the wire:

$$N = \frac{Compressed\ Spring\ Length}{Diameter\ of\ Wire}$$

The spring constant for an individual spring utilizes the wire diameter (d), Shear Modulus (G), coil diameter (D), and number of active coils (N):

$$K = \frac{d^4 G}{8D^3 N}$$

The Net Force applied by the springs can be found in one or two ways. One way uses longitudinal stress (σ) and area (A) while the alternative makes use of the pressure required (P) and the radius of the arm (r). Both methods result in the same Net Force:

$$Fnet = \sigma A$$
$$Fnet = P\pi r^2$$

Where,

$$\sigma = \frac{Pr}{2t}$$

$$A = 2\pi rt$$

The circumference is found by:

$$C = 2\pi r$$

The maximum number of springs that can fit within the circumference found is:

$$\#\ of\ Springs = \frac{C}{D}$$

The equivalent spring constant for all springs combined is then found using the number of springs and the spring constant for each individual spring:

$$Keq = (\#springs)(K)$$

Lastly the change in spring length required to achieve the 4.3 (psia) is found utilizing Net force and equivalent spring constant:

$$\Delta x = \frac{Fnet}{Keq}$$

The application of the thin-walled cylindrical pressure vessel model to the forearm was essential for achieving effective mechanical counterpressure, equivalent to 4.3 psi. By incorporating key parameters such as pressure, arm radius, material properties, and spring mechanics, the analysis enables the determination of the necessary force and displacement for an optimized spring system. The calculated spring constant and corresponding spring length change form the basis for refining the design, ensuring both safety and performance. Future iterations can further enhance the system's efficiency, adaptability, and wearer comfort for practical applications.

## III. Discussion and Results

### A. Design One

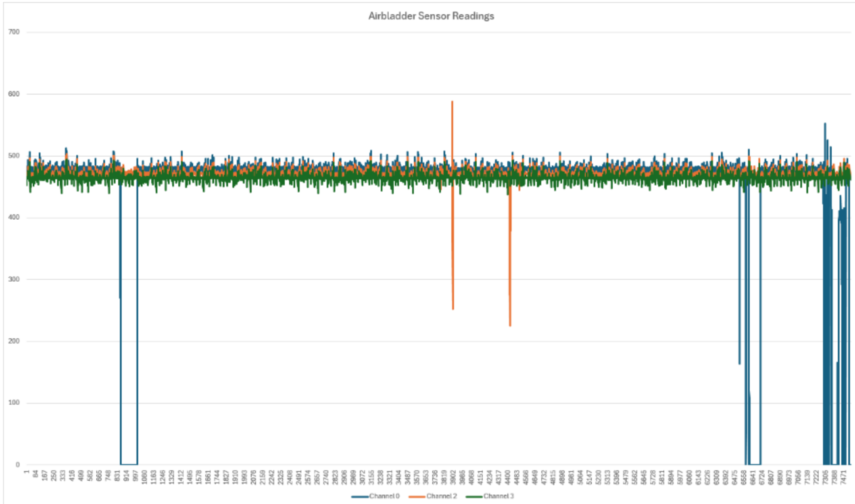



**Figure . Data fluctuations from sensors**

### B. Design Two

This analysis evaluates the effectiveness of a braided lattice counterpressure design in an MCP suit by examining sensor readings across multiple channels. The goal is to assess the uniformity and stability of the applied pressure, ensuring that the design provides consistent compression. By analyzing variations in sensor data, potential inconsistencies in the weave structure or material behavior can be identified, helping refine the design for improved performance and pressure distribution.

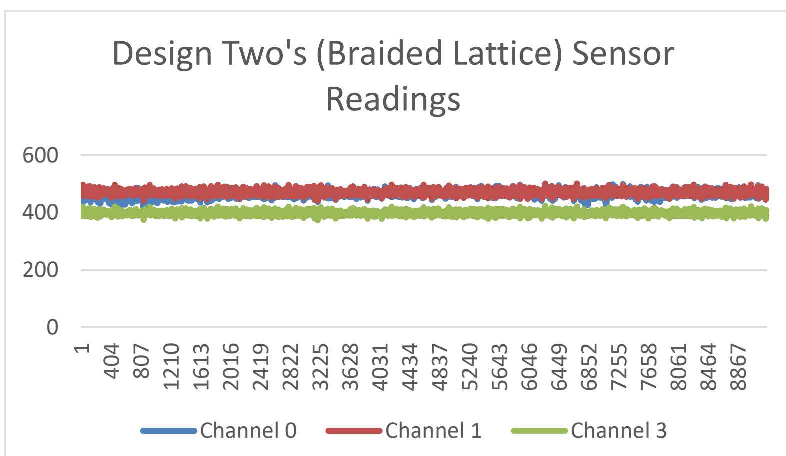



**Figure 9 2. Data fluctuations from sensors**

The sensor readings from the braided lattice counterpressure design show a generally stable pressure distribution across the three measured channels. Channel 1 (red) maintains the highest and most consistent readings, while Channel 3 (green) records the lowest. Channel 0 (blue), however, exhibits occasional fluctuations, including sharp drops, which may indicate localized inconsistencies in pressure. These variations could be due to factors such as material behavior, weave tightness, or sensor sensitivity. The fluctuations on Channel 0 suggest areas where pressure may be temporarily lost, which could impact overall performance. To improve uniformity, adjustments to the weave structure or sensor placement may be needed, helping to ensure more consistent and reliable counterpressure in the MCP suit.

## IV. Conclusion

The STATE Suit project explored two distinct approaches for achieving effective pressure in extravehicular activity (EVA) suits, focusing on both functionality and astronaut comfort during long-duration missions in extreme environments. Design One, utilizing pneumatically actuated air bladders, demonstrated the potential to provide precise and dynamic pressure regulation, offering a reliable method for maintaining the necessary pressure for human physiological needs in space. Despite its ability to maintain consistent pressure, challenges related to bulk, movement restriction, and the delay in pressure adjustment during dynamic movements were adherent.

On the other hand, Design Two, incorporating a woven sleeve with spring-attached cuffs, highlighted the advantages of a passive mechanical tension system that allows for greater flexibility and simpler integration. This design provided continuous counterpressure through the tensioning mechanism, offering superior freedom of movement and adaptability to the astronaut's natural range of motion. While this design faced challenges related to the long-term durability of the tensioning material, it presented a promising alternative to more complex pneumatic systems. In addition to counterpressure, the integration of a fluid circulation cooling system demonstrated the potential for effective thermal regulation, a crucial component for astronaut comfort and safety. The active cooling system, while not yet integrated with real-time thermal data, provides a foundational concept for future development, offering a comprehensive approach to managing heat dissipation and supporting the suit's overall performance.

Overall, both designs provide valuable insights into the trade-offs between complexity and functionality in spacesuit systems. Continued iterations will focus on improving system efficiency, mobility, and user comfort, with particular attention to miniaturizing components, enhancing material durability, and refining the cooling and pressure systems. These advancements will help ensure the suit's readiness for future EVA missions, with the goal of providing astronauts with the safety, flexibility, and performance required for extended space exploration.

## V. Acknowledgments

The team acknowledges the invaluable guidance and support of Dr. Craig Merrett and Dr. Jessica Pattison throughout the project. Additional thanks are extended to Mississippi State University's Athlete Engineering Department for provision of pressure sensors and industry experts who provided critical insights during design and testing phases and.

## VII. References


[1]Amjed, A. A., and Luma F. Ali. "Liquid Cooling Garment Configuration and Investigation: A Classifying and Comparative Review." International Communications in Heat and Mass Transfer, vol. 159, 2024, p. 108114, https://doi.org/10.1016/j.icheatmasstransfer.2024.108114. https://www.researchgate.net/publication/359686427_Shape_memory_textiles_for_smart_compression_management_for_chronic_venous_disorders_-A_review

[2]Anderson, A., Waldie, J., and Newman, D., "Modeling and design of a biosuit donning system," *40th International Conferenon Environmental Systems*, Jul. 2010.

[3]"Arduino - Force Sensor: Arduino tutorial," *Arduino Getting Started* Available: https://arduinogetstarted.com/tutorials/arduino-___force-sensor.

[4]Carruth, A. R. (2023, March 15). Spacesuits built to handle pressure - NASA. NASA. https://www.nasa.gov/humans-in-space/spacesuits-built-to-handle-pressure/

[5]*Development of smart textile materials with shape memory alloys for application in protective clothing*. (n.d.). PMC Home. https://pmc.ncbi.nlm.nih.gov/articles/PMC7040812/

[6]Graziosi, D. (2003, January). *I-Suit Advanced Spacesuit Design Improvements and Performance Testing*. University of Maryland. https://spacecraft.ssl.umd.edu/design_lib/ICES03-2443.I-Suit_tests.pdf

[7]Kumar, B., Kumar Maurya, S., Somkuwar, V., Garg, H., Mohanty, J., & Gupta, P. (2022, March). *Shape memory textiles for smart compression management for chronic venous disorders – A review*. Indian Journal of Fiber & Textile Research.

[8] *Mechanical counter-pressure space suit design using active materials*. (n.d.). DSpace@MIT Home. https://dspace.mit.edu/handle/1721.1/90602

[9]McFarland, Shane. "The Mechanical Counter-Pressure EVA Suits: NASA Outlook and Development Strategy in 2022." International Conference on Environmental Systems. 2022.

[10]*NASA's shape memory materials open doors for smart tech | T2 Portal*. (n.d.). NASA Technology Transfer Portal Home. https://technology.nasa.gov/Shape%20Memory%20Materials%20Open%20Doors%20for%20Smart%20Tech

[11]*Shape memory alloys*. (2024, February 15). SAES Getters. https://www.saesgetters.com/advanced-materials/shape-memory-alloys/