3D Knit Spacesuit Sleeve

With Mulitfunctional Fibers and Tunable Compression

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1 3D Knit Spacesuit Sleeve Prototype

ABSTRACT

Textiles were among the first engineered materials to be used in protecting the human body from the harsh environment of outer space. Throughout history, these advances in soft material and garment manufacturing techniques have inspired scientists and engineers in partnership with designers to create adaptive solutions for extreme conditions. This research establishes a multi-disciplinary collaboration within a team of designers, engineers, and scientists to address current technical challenges associated with spacesuits' multi-layer fabric requirements.

This paper presents a novel approach to spacesuit fabrication and functionality using CNC knitting to enable precise material control throughout the 3-dimensional structure, creating higher functionality in a seamless and minimal textile architecture. We have developed a 3D textile framework consisting of a computational design workflow, multi-functional fiber integration and a highly customizable 3D layering method that can be adapted to the personalized dimensions of the body. This method includes designating regions for mobility, tunable compression, integrated sensing and quick donning and doffing within a single sleeve prototype as a first step toward a novel approach for spacesuit fabrication. While this work has focused on the spacesuit application, we imagine future applications in other textile architectures and next-generation apparel with integrated monitoring for increased performance, environmental regulation and improved comfort.

INTRODUCTION

Since the 1950s, spacesuit technologies have shown to be a continuous effort of negotiating between material capabilities, modes of fabrication, and the stringent requirements for survival in the extreme environment of outer space. The fabrication methods employed in spacesuit manufacturing have evolved with the technologies of material and textile production. Combined with manual fabrication techniques adopted from the garment industry, new technologies in soft materials influenced the spacesuit design solutions in earliest space expeditions, where new material layers functioned as reflective insulation, thermal lining, and gas-impermeable membranes (Thomas 2006; De Monchaux 2011). Following this history, we seek to propose a new approach to spacesuit construction utilizing the latest advances in material and textile manufacturing to create a seamless integration and minimal spacesuit construction (Figure 1). The extreme challenges of the space environment present a unique site for collaboration between science, engineering, and design, establishing technical requirements while imagining new adaptations of fabrication technologies. Through this cross-disciplinary team, we explore how CNC knitting, newly developed materials, and fiber-based sensors can address the unique technical challenges posed by spacesuits.

BACKGROUND

To protect the body from the vacuum of outer space, a spacesuit must provide breathable atmosphere and body surface pressure. Spacesuit designs differ in their technical strategies for maintaining pressure on the body surface in a vacuum environment. There is not a single solution to this problem, but rather different strategies that each negotiate a balance of trade-offs. The most common spacesuit type and the only type used operationally in human spaceflight thus far is gas pressurization. In this strategy, pressure is achieved by providing an airtight environment with non-permeable layers and gas-pressure. Alternatively, another type of suit has used a porous membrane, usually a textile, to provide mechanical pressure directly to the body (Webb 1968). Our approach pursues tunable mechanical counter pressure (MCP) through knit fabric construction.

Background to Traditional Spacesuits

Extravehicular Activity (EVA) spacesuits are highly familiarized in media imagery from the first lunar landing to recent spacewalks from the International Space Station. Though time-tested and highly reliable, these suits are extremely cumbersome because they require an atmosphere of pressurized air around the inhabitant. The suits' airtightness further necessitates many layers and mechanisms for temperature and moisture regulation since the body can no longer maintain these functions on its own in the absence of garment porosity (Thomas 2006). As a result, the necessary protective functions are performed by multiple layers of woven fabric in the suit's bulky assembly, and these materials are responsible for maintaining an impermeable membrane and regulating a steady interior thermal environment. Though the layers are individually thin and delicate, the airtight pressure requirements hinder astronaut mobility, and the motions of the joints are continuously at odds with the forces of pressure within the suit (Thomas 2006).

Background to Mechanical Counter Pressure (MCP) Suits

In contrast to this, MCP suits seek to alleviate the challenges of mobility and airtightness by providing mechanical pressure on the body through direct contact with the material. Though less well known compared to NASA's EVA suits, MCP suits have been in development since high-altitude flights were first made possible by advances in 1930s aviation technology, and MCP concepts were first explored for space flight applications in the 1950s (Figure 2a) (Webb 1968). MCP suits offer several proposed advantages over gas-pressurized versions, such as reduced bulk, improved mobility, and natural thermoregulation. These suits typically rely on elastic fibers which conform to the complex motion and geometry of the human body while maintaining the necessary pressure. Examples from NASA MCP Space Activity Suit prototypes in the 1960s and 1970s utilize elastic materials such as elastane and rubber cord in Bobbinet and Powernet textile constructions to provide mechanical pressure. These prototypes employed multiple layers of elastic mesh to generate the requisite level of elastic power to maintain pressure on the body (Figure 2b) (Mcfarland, Ross, and Sanders 2019). More recently, the MIT BioSuit™ research proposes a new version of the MCP suit concept, envisioning a future of lightweight, highly mobile, and individually adapted spacesuits (Figure 2c) (Newman 2007). The MIT BioSuit™ work has investigated methods to improve mobility, including Iberall's

2

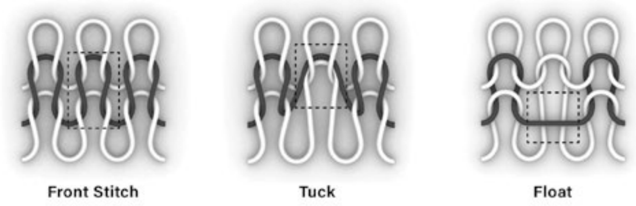
2 Evolution of Mechanical Counter Pressure (MCP) Suits including the David Clark MC-3 partial pressure suit for high-altitude flight (left), the 1960s Space Activity Suit (center), and the MIT BioSuit™ (right).

"lines of non-extension" (Iberall 1970) and skin strain mapping techniques (Obropta 2015, 2016, Wessendorf 2012), aiming to quantify skin movement to inform a "second-skin" garment.

Though MCP suits demonstrate a compelling alternative to the bulky traditional EVA suits, there remain multiple challenges that need to be addressed through alternative means of design and fabrication. Previous examples of MCP designs lack control of local fabric properties because they are assembled from layers of homogeneous sheet materials. In the early MCP suits that contained multiple layers of non-differentiated elastic mesh fabric, material that is easily compliant in thin layers becomes difficult to stretch when compiled into a high-power multilayer construction. As a result, convex bends in joints such as knees and elbows begin to experience resistance to mobility due to the thickness of the elastic fabric and inability to differentiate between circumferential and longitudinal strain in the material (Mcfarland, Ross, and Sanders 2019). Furthermore, the large amount of resistance in the elastic materials inhibits easy donning and doffing (putting on and taking off the suit), prompting the development of donning and doffing techniques and technologies (Anderson, 2010; Holschuh 2012, 2013, 2015, 2016). Our project addresses these challenges through CNC knitting which is capable of combining highly differentiated fabric properties into a single seamless assembly while maintaining the multilayered material functions required to support survival in space.

Background to CNC Knitting

CNC knitting is an ideal fabrication process to apply to these challenges because of its ability to combine multiple materials, designate localized fabric behavior, and integrate multi-layered geometry together in one seamless textile panel — functions that are absent in homogenous textile sheets. Knit fabrics are composed of rows of interlocking loops, called “stitches”, where various choices can be organize materials and properties on the fabric faces and in cross section. Other stitch types such as “tuck” and “float” can enable the placement of material within the fabric without looping (Figure 3) (Spencer 2001). The organization of stitches and stitch types controls the local knit structure, which can be leveraged to embed different fabric behaviors into different regions. In its simplest form, adaptive knit structure is ubiquitous in everyday garments and is visible in the ribbed cuffs of sleeves and socks, often differentiated from the plain body of the garment (Black 2012). There is widespread precedent for the application of knit structure both aesthetically and functionally, in garments and in architectural research (Ahlquist 2013; Popescu et al. 2020; Tamke et al. 2021). Deployed into more advanced configurations, knit structure can be leveraged as a tool to affect behavior and the form of a surface. Furthermore, knit structure can be organized along with material selections to differentiate and fine-tune every area of the fabric. Our knitting strategy seeks to move beyond simple surface-based application of knit structure and material integration, demonstrating a multi-layer three-dimensional seamless assembly where the properties of each layer can be independently manipulated.



3 Basic knit stitch types showing different configurations of inter-looped fiber.

FUNCTIONAL REQUIREMENTS

The proposed spacesuit prototype responds to a range of functional requirements, including pressure on the body, ease of mobility, speed of donning and doffing, potential thermal and radiation protection, and the ability to integrate fiber-based sensing systems. We manage these requirements through a seamless knit fabric construction that can integrate multiple materials, layers, and functions that are tailored to different regions of the body.

Compression

Though many factors affect the necessary amount of pressure to survive in space, 24 kPa has been proposed as a target pressure for MCP suits (Mcfarland, Ross, and Sanders 2019). However, solutions to pressure suit design can be studied at lower pressures during initial prototyping. Our sleeve seeks to develop a path forward for 3D-knitting in spacesuit pressure garments and to provide a minimum of 5 kPa to exceed the typical pressures (1.9-2.3 kPa) of flight socks (Belcaro 2003). Compression force is typically managed by manipulating the reduction factor of the elastic fabric relative to the corresponding circumference of the body. In contrast to a fluctuating reduction factor, our prototype applies a constant reduction factor across varying circumferences of the body and modulates the fabric power to maintain a uniform compression force. A reduction factor for the sleeve prototype was selected by testing a set of knit elastic cuff samples to determine the required amount of fabric power for different circumferences of the body (Figure 4). Furthermore, the surface of the body also contains many concavities, such as behind the knee or the inside of the elbow. These regions create additional challenges for fabrication, where pressure must be maintained through integrated padding to fill the concave areas. Here we demonstrate that this can be achieved through a combination of fiber materials and seamless knit construction.

Mobility

As a result of the high level of pressure applied to the body, enabling joint mobility while maintaining the required level of compression can present significant challenges. Our prototype seeks to provide at least 45 degrees of joint mobility in the elbow while maintaining the required mechanical pressure on the body. We aim to achieve this primarily through the manipulation of knit structure to provide a range of different elasticities embedded in different regions of the fabric through both elastic and non-elastic materials. In non-elastic layers, mobility is enabled through a region of higher surface area surrounding the outer elbow. In elastic layers, specific regions allow higher stretch in the longitudinal direction.

Donning and Doffing

The high level of pressure also creates challenges for the ease and speed of donning and doffing the suit. Simple garment closure mechanisms are not fully applicable in this scenario, often requiring significant assistance during the donning process. Rather than a single closure mechanism, we utilize the multilayered knit construction to separate the closure into different stages, distributing the compression forces into two closure sequences to speed the donning process to under one minute and enable an individual to put on the garment without assistance.

Integration with Sensing Systems

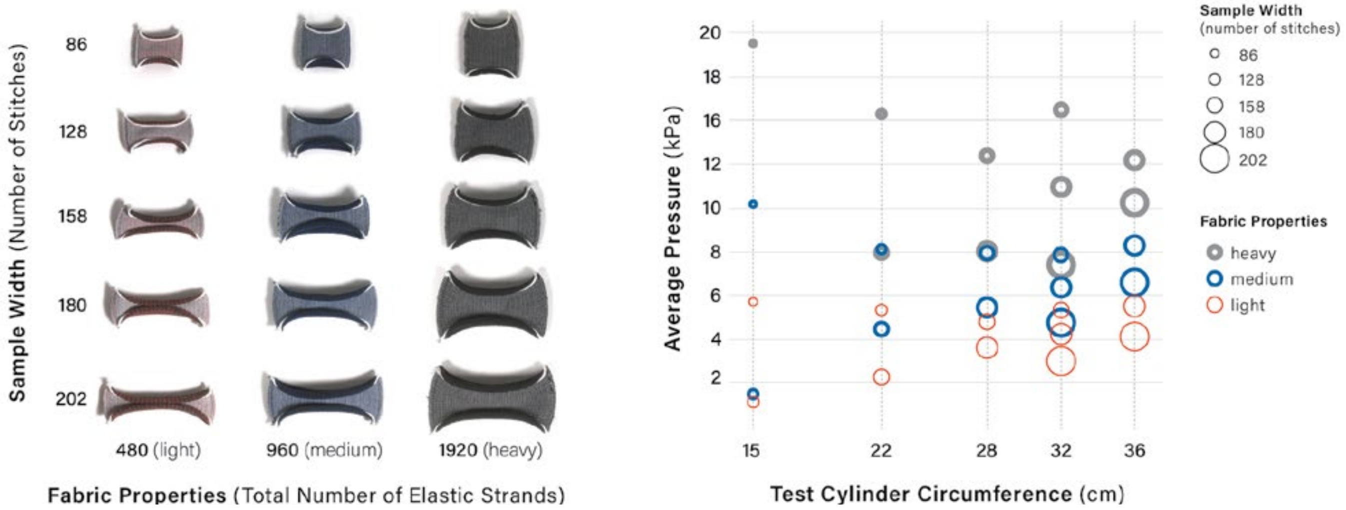
Finally, the system is designed to create a seamless integration of sensing systems to collect data about the performance of the suit (i.e., pressure) or the physical motions of the occupant. To match the mechanical and geometrical characteristics of the knit fabric, we use fiber-based sensors that demonstrate the potential for soft and stretchable sensing integration. The smart sensing is enabled by highly soft, flexible and stretchable fibers fabricated through thermal drawing, a scalable and non-expensive method for microfabrication. Here, we propose a built-in network of channels and pockets into which soft stretchable fiber-based sensors can be integrated. Our prototype contains two circumferential sensors for measuring pressure at the bicep and forearm as well as a longitudinal sensor across the elbow joint which measures joint movements using strain.

METHOD

To test our approach, we fabricated a prototypical spacesuit sleeve. Containing a range of conditions within the arm region, the sleeve prototype allows us to evaluate our fabrication strategy centered on CNC knitting and our material, pressure, and sensor integration. We begin by establishing a pattern for an individual's unique body shape and determining the distribution of zones, layers and components, with a set of specific fiber materials that serve unique functions in the knit fabric. The pattern is then developed into a knitting file that addresses the requirements through fine-tuned placement of materials and knit structures. Finally, a two-layer closure is installed on the longitudinal edges of the knit panel and assembled with the sensing components.

Situating the Requirements on the Body

We have developed a computational manufacturing approach focused on creating a customized fit of the knit spacesuit that is tailored to an individual's body scan. To create the custom sleeve, a person's scanned 3D arm was mapped into zones and



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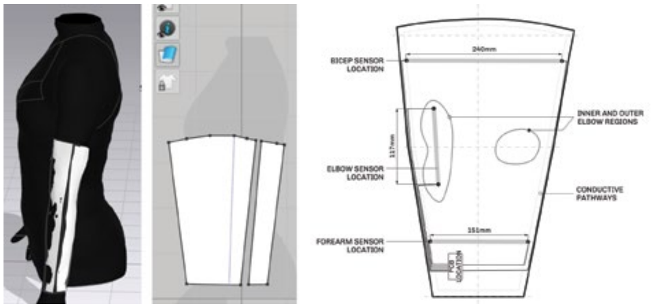
4 Knit cuff samples for collecting pressure data (left) and pressure measurements showing relationship between sample width, fabric properties, and reduction factor (right). As expected, pressure increases with a decreased sample width (i.e., an increased reduction factor), and pressure increases with heavier fabric properties, both due to increased fabric tension. These effects are consistent with the relationship defined by the hoop stress equation, which states that pressure is directly related to fabric tension and inversely related to cylinder radius (i.e., radius of the arm) (Schauss 2022).



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unrolled into a 2D pattern (CLO (version 7.0.228) 2022). The mapped pattern was then divided into segments to estimate mobility needs in the two primary regions, including the anterior and posterior elbow. The lower arm, elbow, and upper arm horizontal measurements defined the pattern reduction of the knit structure, while maintaining the scan's precise placement of the pattern. The pattern dimensions have unique zones on the arm which are then converted to a file for knitting.

Knitting

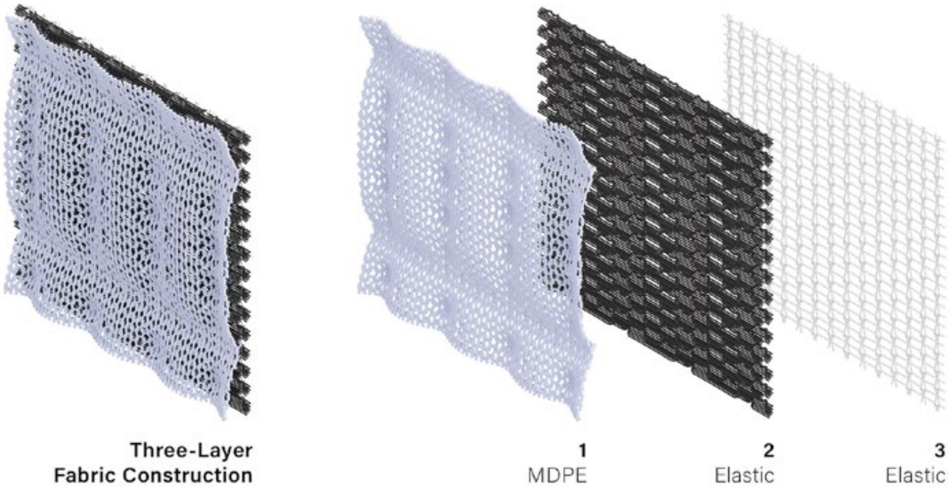
The textile panel is composed of multiple layers that are knit simultaneously: a thin elastic layer against the skin, a thicker transverse layer of elastic fibers in the central layer, and a protective polyethylene layer on the exterior (Figure 6). Each layer is independently capable of a range of variability in the pattern design, enabling the single textile sleeve to adapt to the dimensions of the body and the functional requirements of the spacesuit allowing properties of the fabric to be differentiated across the structure (Figure 7). In addition to the in-plane variation, the layers are capable of separating and merging with each other in cross section, enabling the formation of interior channels, pockets, and integrated plackets that accommodate assembly components. The pattern was developed in STOLL M1 Plus software interface and produced on a STOLL CMS 330 HP-W TT Sport 12-10 knitting machine (M1PLUS (version 7.2.037) 2021).

The central elastic layer is responsible for achieving the compression requirements of the sleeve. The prototype employs multiple spools, or “ends” of elastomeric nylon Lycra, but the method can potentially employ any knittable elastic material. To increase and decrease fabric power in different areas of the sleeve, the knit pattern is configured to customize how many cumulative strands are placed into different areas of the fabric. Formed from a series of horizontal tuck stitches, the density of horizontal courses of elastic fiber can be increased or decreased based on the desired compression force and body circumference. The pattern can be manipulated to adjust the number of elastic strands that are placed inside each knitting row. As a result, the prototype demonstrates a gradient of elastic fiber density as the circumference shifts from its smallest at the wrist to its largest at the bicep, containing twice as many elastic fibers per unit area as the wrist (Figure 8).

Mobility requirements are addressed through the interaction of the innermost and outermost layers of the knit panel. On the exterior layer, extra courses of stitches create a region with a higher surface area compared to the surrounding fabric, creating pleats and folds that expand and collapse with motion of the elbow (Figure 9a). On the innermost elastic layer, the elbow region is differentiated by adding twice as many rows of elastic stitches where the textile requires the greatest elasticity, increasing the potential for longitudinal strain (Figure 9b). Conversely, surface area and elastic stretch are restricted in the interior elbow region by adding fewer stitches within the same area of the pattern.

5 3D scan (left) converted to unrolled 2D pattern (right) with key regions for knit structure, locations of integrated sensors, and conductive pathways.

6 Detail of three-layered fabric construction.



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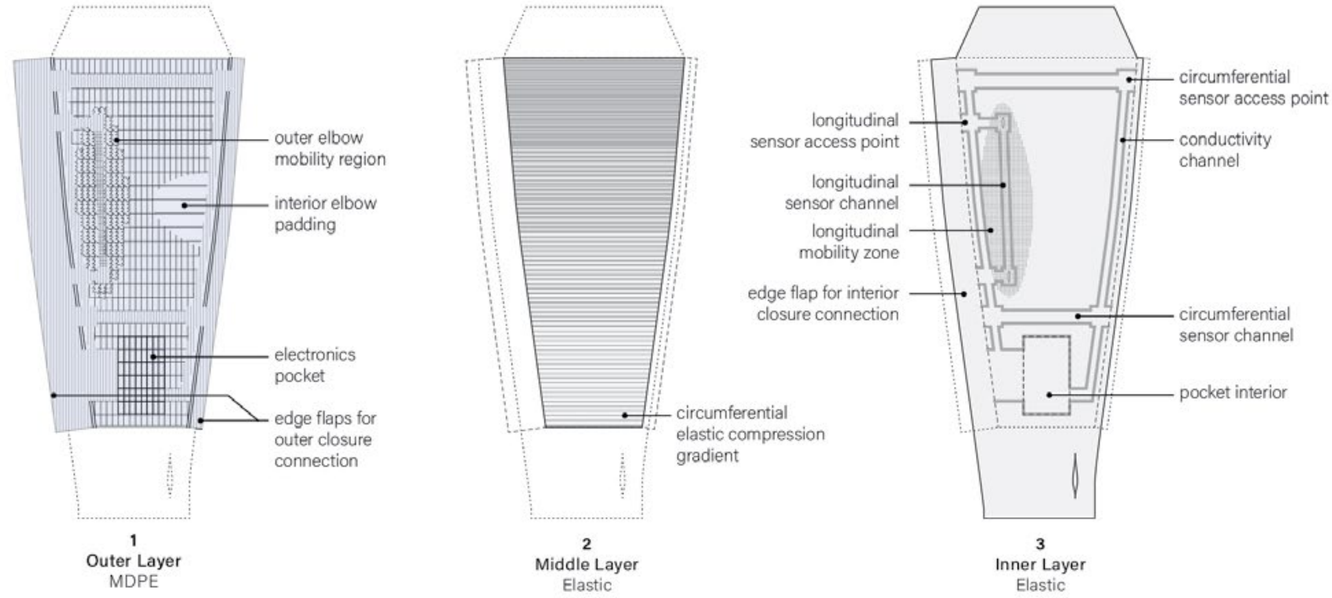
The exterior layer of the knit structure creates a continuous protective shell of 892-denier Medium-Density Polyethylene (MDPE) multifunctional yarn. The exterior shell is integrated with the padded regions, which consist of a heat-responsive bicomponent fiber. This outer layer seeks to create a continuous protective barrier with radiation shielding capability while maintaining the seamless integration for compression and mobility requirements. Initially soft and pliable, the MDPE fiber is heat-set at 85C after knitting which rigidifies the material and reduces the large porosity in the knit structure. The exterior layer is connected to the inner elastic layers through intermittent tuck stitches reaching to the opposite face of the fabric, forming a rectangular “quilted” appearance (Figure 10a). The rectangular pattern negotiates the surface area differences between the elastic inner layers and inelastic exterior layer, building enough slack throughout the inelastic material system that all the materials are able to flex together (Figure 10b). Padded areas are produced using a 72-filament, 290-denier, custom-made bicomponent fiber, containing both LLDPE and Nylon polymers in its cross section. Before knitting, the material begins as a smooth,



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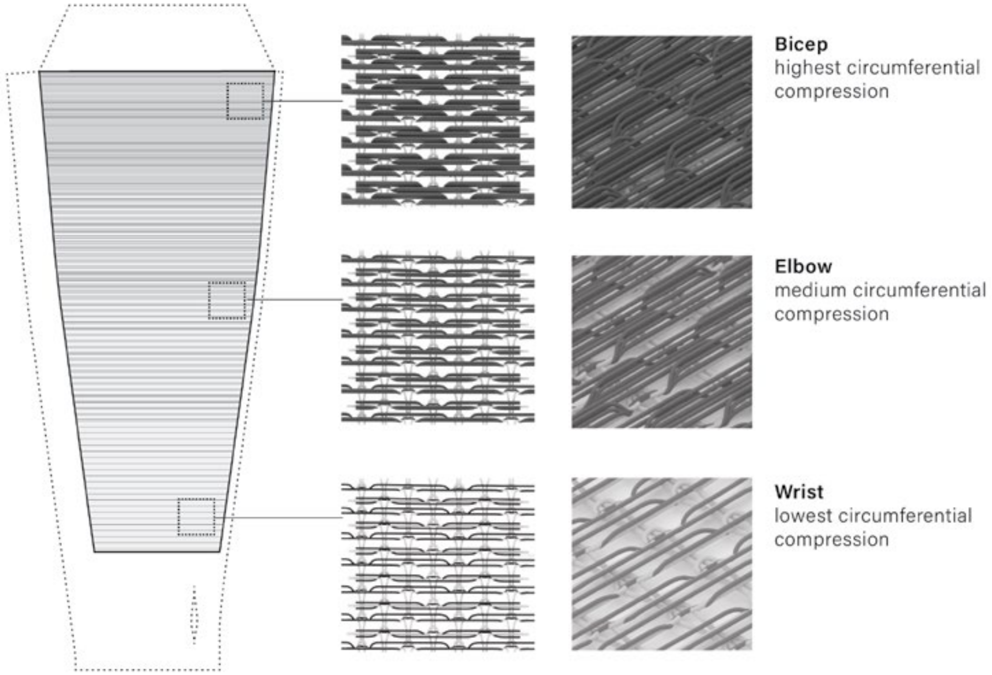

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7 Zones and functions within the three layers of seamless knit construction.

8 Gradient of elastic compression in the middle layer of the seamless knit structure.

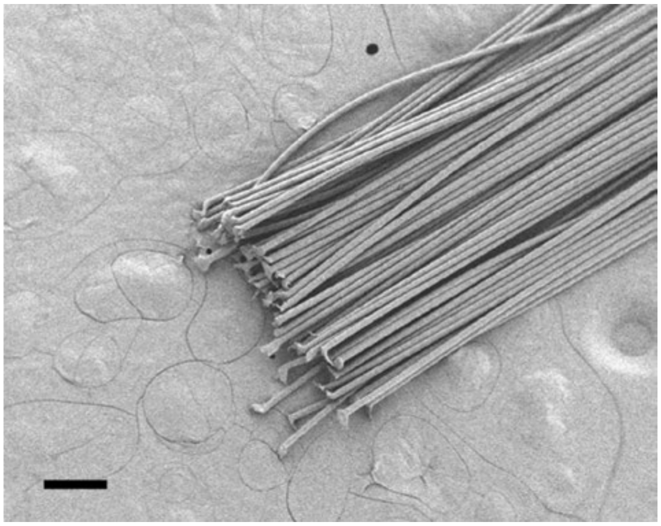
9 Knit zones enable longitudinal strain in the outer layer of non-elastic material (left) and innermost layer of elastic material (right).

10 Detail of typical exterior layer condition (left) and integrated padding in concave elbow region (right).

flat fiber, but responds to heat after knitting by becoming bulky and pillow-like. The fiber enables selective placement of padded areas directly in a knit fabric without any post-insertion or assembly.

Polyethylene is a versatile material with multiple functions related to space garments. PE molecules are composed of repeating units of two carbon atoms linked to four hydrogen atoms and have high hydrogen content to efficiently absorb and disperse harmful radiation (Narici et al. 2017; Barry 2005). PE is already being used to supplement radiation shielding of the sleeping quarters on the international space station. Existing research shows that polyethylene is 50% better than aluminum at shielding solar flares and 15% better at blocking cosmic rays (Narici et al. 2017). Padded areas that contain LLDPE material further enhance radiation protection properties of the sleeve. The multifunctional PE fabric platform also offers other unique advantages beyond shielding from ionizing radiation. These include stain-resistance, antibacterial properties, passive heat management and low weight in the spacesuit industry and beyond (Holschuh et al. 2012; Boriskina 2019; Alberghini et al. 2021). As can be seen, the diameter of yarn is commensurate with the conventional sizing of polyester, nylon or hybrid stretchable yarns thus making PE yarn immediately capable of being integrated into standard textile industry processes (Figure 11) (Holschuh et al. 2012; Alberghini et al. 2021).

Finally, the multi-layered CNC knitting approach can be leveraged to manipulate the geometric organization of the fabric. A network of interconnected channels was formed between the inner layer and the others, accommodating the strain sensors towards the skin and establishing the required pathways for electronic conductivity (Figure 12a). Junctures in the channel network are accessible through knit-in openings along the sides of the fabric panel, enabling the electronic components to be installed and maintained (Figure 12b). A pocket for additional electronic components was formed by separating the exterior surface from the inner layers with interconnection points between the pocket region and the channel network (Figure 12c). On the longitudinal edges of the panel, the materials were arranged to form a highly elastic inner membrane belonging to the interior closure, and a sturdier outer layer for attaching to the secondary ratchet closure (Figure 12d).



11 Scanning electron microscopy (SEM) image of a 72-filament PE yarn (~7 ° tilting view). Scale bar is 200 μm. Linear density of yarn is 892 denier. The PE yarn was fabricated via a melt extrusion process by a filament line machine at Hills Inc (Florida, USA). In a typical example, the pellets of medium density polyethylene resin were placed into the hopper with a screw rod that pushes them into the extruder barrel and then pumped through a die with 72 spherical holes. The extruded polyethylene fiber rapidly solidified in air at room temperature, forming a yarn with 72 filaments.

Assembly

The multi-layer knit fabrication was created to demonstrate a seamless and minimal structure while meeting the needs of the functional requirements and the integrated built-in sensing system. The final assembly of the spacesuit prototype was done by first introducing the two separated closure mechanisms and secondly, by integrating electrical components to the mapped knitted channels.

By dividing the closure mechanism into two stages, the multi-layer fabric architecture distributes pressure evenly over the arm while allowing the sleeve to be easily put on and off, spreading the compression forces over two closure sequences. The longitudinal inner membrane of the sleeve panel's edges was sewn onto a zipper. One side was made with a longer knitted length to allow the user to first zip the two edges into the arm in a "relaxed mode"; following this, the remaining pressure is applied with a magnetic boa ratchet system (Figure 13a, Figure 13b). The outside high-compression layer is sealed with an interwoven cord that was looped between closed-hook fasteners on both sides of the larger strip edges (Figure 13c). The ends of the fastening cord were attached to two boa ratchets on upper and bottom parts of the sleeve, allowing faster donning with adjustable tightening along the sleeve.

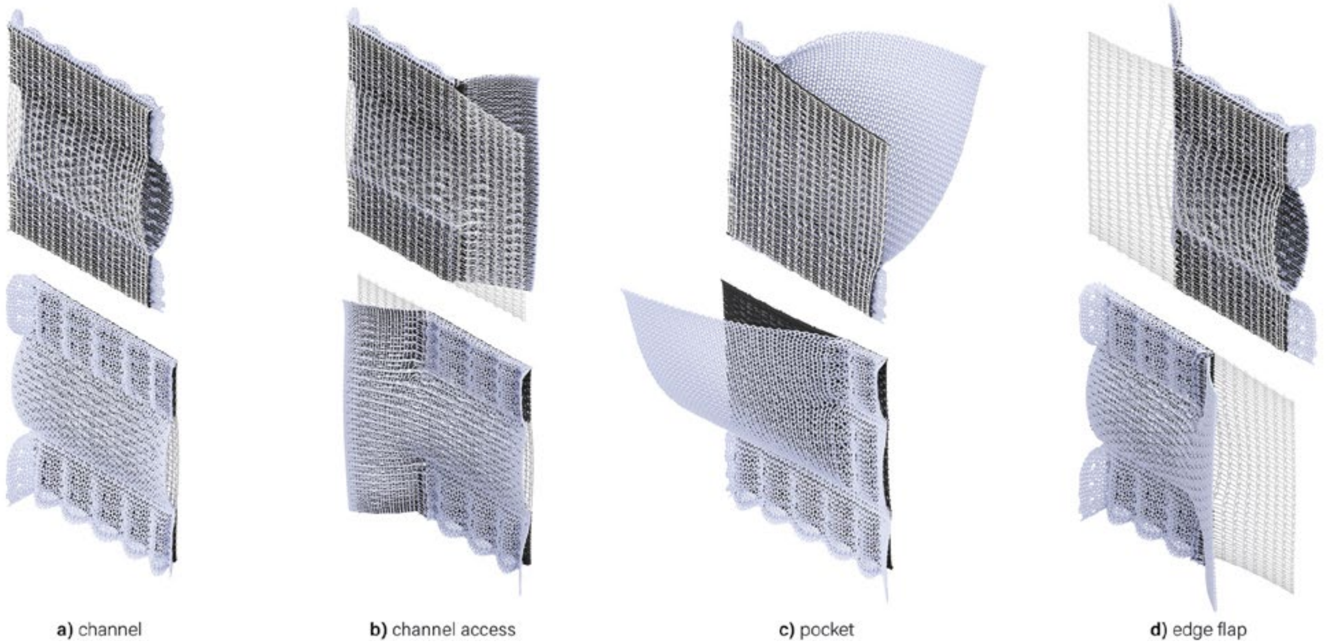
Internal knitted channels with conductive wires were routed to a knitted pocket with a PCB board, allowing the fiber-based sensors to communicate and perform signal conditioning, processing, and wireless communication via an Arduino Nano 33 BLE Sense. To enable modularity within the integration of the fiber sensor, we introduced a conductive snapping mechanism where one side was connected to the conductive wire system of the PCB and the other to the fiber-based sensor. For the internal wiring of the sensing components, our prototype contained two different stretchable conductive wires that were assembled into the elastic channels of the sleeve. One version produced an insulated connection by threading a stainless-steel yarn into a silicone tube, while the other produced an uninsulated connection by knitting a steel yarn with an elastic yarn to produce an expandable conductive cord (Figure 14a, Figure 14b).

The sensors themselves are fibers, composed of Styrene-ethylene-butylene-styrene (SEBS) and filled with liquid Gallium, allowing high stretchability (~100% strain) (Xu et al. 2017). The piezoresistive mechanism of these fibers is used to sense a variety of physical properties such as pressure and strain. Each fiber is encased in a thin layer of soft silicone (Smooth-On Ecoflex 00-30), creating a protective layer (1.2mm wide by 0.4mm thick) while maintaining the flexibility and stretchability requirements (Figure 15). The pressure and strain data for each sensor is communicated individually to the on-board system. Signals from these sensing fibers are used to monitor the amount of constant pressure on the body, as well as the strain generated by the wearer (i.e. through joint movements).

RESULTS AND DISCUSSION

Evaluation of Results

A final complete prototype was assembled and tested to evaluate its success relative to our initial goals of compression, mobility, ease of donning and doffing, and integration with



12 Various conditions of surface-to-surface connections and openings produced throughout the multilayer knit panel.

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13 Process of donning the sleeve showing inner zipper (left), ratchet cord (center), and ratchet mechanism (right) for tightening outer closure.

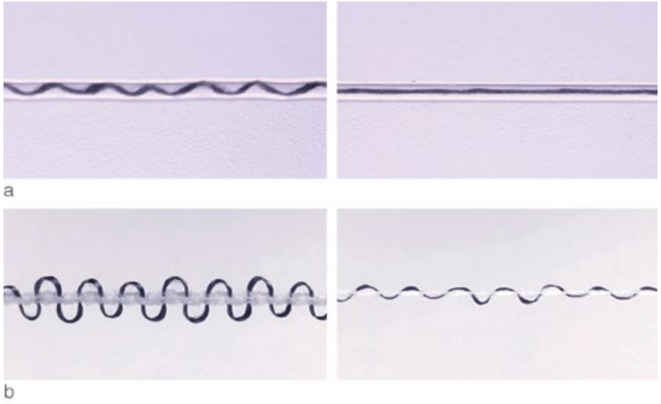
sensor systems (Figure 16). Overall, we believe the spacesuit sleeve shows significant variations in fabric behavior across the arm and demonstrates the overall viability of applying CNC knitting to achieve various regions of differing compression and mobility requirements. The sleeve pressure was evaluated by using the Pliance® pressure sensing system (novel 2022). Sensors (20 mm diameter) were placed on the inside and outside of the elbow joint to measure the consistency of pressure in different regions as the joint is moved and flexed underneath the fabric, and the sleeve was able to achieve pressures ranging from 4-8 kPa, meeting the minimum pressure goal for the sleeve. Smaller prototype samples were also able to achieve pressures of nearly 20 kPa, showing the knit technique can potentially be effective for generating the full amount of pressure required for a vacuum environment. The multi-layer surface geometry was able to accommodate the installation of sensors and corresponding layout of conductive connections and pathways, and successfully accommodated access points for connecting and adjusting sensor components. We believe our workflow is effective in enabling the design and fabrication of a functional spacesuit prototype that is able to meet multiple requirements in a single seamless system. This result likely could not be achieved with other textile fabrication methods, and our prototype establishes a new way forward for applying CNC knitting and novel material characteristics to future spacesuit development.

Next Steps and Discussion

Though successful as a first step, our initial prototype has limitations, requiring further refinement and testing to move forward as a truly viable spacesuit. First, additional prototyping is needed to calibrate and fine-tune the range of behaviors that exist in the fabric, particularly in how they respond in motion. Currently, an excess of rigidity in the interior elbow and excess material in the exterior elbow results in an uneven distribution of pressure along the circumference of the elbow region, lacking consistency during motion of the arm. Further improvements in the sleeve performance can be achieved through iteration and calibration of fabric properties. While we were able to reduce donning and doffing time to under one minute, additional refinements to the fabric tension are needed in the two-layer closure to further facilitate ease of the donning method. Improvements can be achieved through further iteration and refinement to the knit structures and pattern layout.

To more thoroughly integrate high-performance materials, PE yarns can be engineered to perform a wide range of mechanical properties and replace all the commercial fibers used in the current sleeve prototype. Furthermore, improved radiation shielding and abrasion resistance can be achieved through doping of PE fibers with nanomaterials such as metal-based powders (Alberghini et al. 2021; Blachowicz and Ehrmann 2021).

Immediate next steps include increasing compression levels to meet target pressures above 20 kPa, followed by testing in a vacuum environment. Additionally, future work will include fabricating tests for additional areas of the body, moving towards a full-body spacesuit prototype. Finally, our current testing procedures are heavily focused on evaluating pressure. While this was a primary goal in demonstrating the basic viability of our fabrication method, many other tests would need to be performed to prove that a prototype is prepared for space exploration. Ultimately, the ability to fabricate garments with customizable compression gradients and mobility zones has many potential applications not limited to space exploration; our continued work aims to translate this approach to other architectural textile applications in the near future.



14

CONCLUSION

The research presented in this paper proposes a new method for the design and manufacturing of spacesuits based on CNC knitting and a multi-functional 3-dimensional textile architecture. Through a unique collaboration between designers, scientists, and engineers, we have demonstrated a novel process for creating customized spacesuits, based on a scan of an astronaut's body, and embedded with tunable compression, quick donning / doffing, and integrated sensing. These capabilities enable a seamless and minimal spacesuit design without the reliance on bulky systems and complex layered assemblies. Our approach could offer better fit, increased comfort, greater range of motion and more information-rich interaction with the astronaut. The spacesuit sleeve prototype is one step towards this larger vision of fully integrating performance and functionality within an elegant, knitted architecture to allow for better human/space functionality and longer-term survival in the extreme environment of outer space.

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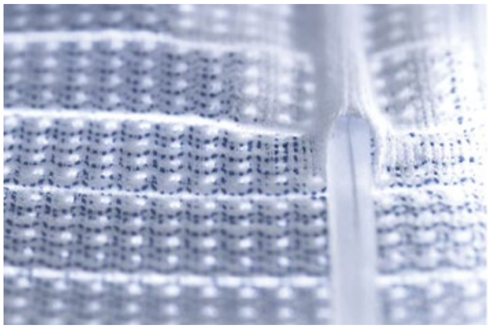
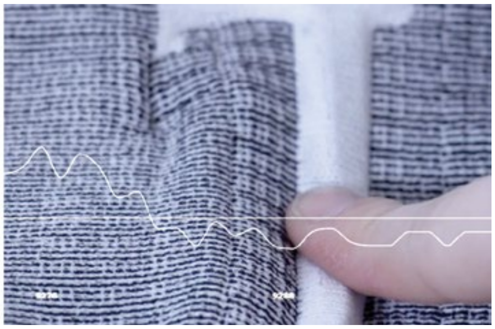


14 Stretchable conductors created from steel fiber threaded into silicone tubing (a) and by inserting as weft inlay into CNC-knit elastic (b).



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15 Details of soft sensors embedded in knit fabric.

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IMAGE CREDITS

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16 Completed and Assembled Sleeve Prototype.

16

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