Towards Adaptive Space Harnessing Systems through Wearable Soft Robotic Textiles

Jack M. Kalicak, Emma V. Brown, Krishma Singal, and Vanessa Sanchez

***Abstract*—Exercise is a primary countermeasure used to reduce the negative health effects of microgravity that occur during spaceflight. To substitute the gravitational loading found on Earth, space exercise often relies on harnesses to produce loading; however, they are often uncomfortable and are not easily adjustable, especially during exercise. As a step towards addressing these challenges, this paper explores 3D knit, pneumatically actuated straps, as a component in space exercise harnesses. We explore how engineered textile design affects anchoring performance of the straps, demonstrating the impact material choice has on strap inflation and anchoring force. This investigation lays the groundwork for future feedback-controlled systems that adjust based on harness anchoring data to enable new exercise and training routines in space, while maintaining harness comfort.**

I. Introduction

Long duration spaceflight enables groundbreaking scientific discoveries beyond Earth, but also results in microgravity induced changes in the body [1]. Particularly concerning are reductions in cardiovascular fitness, muscle strength, and muscle size that occur in extended partial and microgravity [2], [3]. Beyond neuromuscular and cardiovascular changes, astronauts experience significant changes to bone density that may accelerate the onset of osteoporosis [4]. These changes result from a reduction in gravitational loading and the corresponding decrease in mechanical loading on the body, which not only impacts crew health but can lead to crew performance decline that may impair mission success [5], [6], [7], [8], [9], [10]. Current long-duration spaceflight takes place on the International Space Station (ISS), where the effects of low gravity are combated with resistive training and aerobic exercise countermeasures [11].

Exercise requires loading [12]; however, microgravity environments lack the 1 G gravitational load present in most Earth-based exercises. To simulate Earth's gravity, astronauts attach themselves, often with harnesses, to ISS exercise equipment including the Advanced Resistive Exercise Device, T2 treadmill, or Cycle Ergometer with Vibration Isolation and Stabilization System [9]. While exercise countermeasures reduce the detrimental physical effects of microgravity, the harnesses can create discomfort such as bruising, chafing, and scarring [13], [14]. This tissue damage creates sore spots that cannot be loaded as forcefully as healthy skin, requiring a reduction in applied load and, therefore, exercise effectiveness [14], [15]. The most recent major harness upgrade, the New Glenn Harness, reduced T2 treadmill harness discomfort, but it still takes multiple sessions for crew members to get comfortable [14], [16]. Furthermore, half of the tested group supplemented the harness design with the "comfort kit," composed of three different padding types, suggesting further changes can be made to increase comfort for a wider range of astronauts [16]. Beyond comfort improvements, new harnessing strategies could enable the next generation of space exercises, especially improving comfort during extended exercise periods and reducing performance limiting changes from microgravity to astronauts during long duration spaceflight [11], [17].

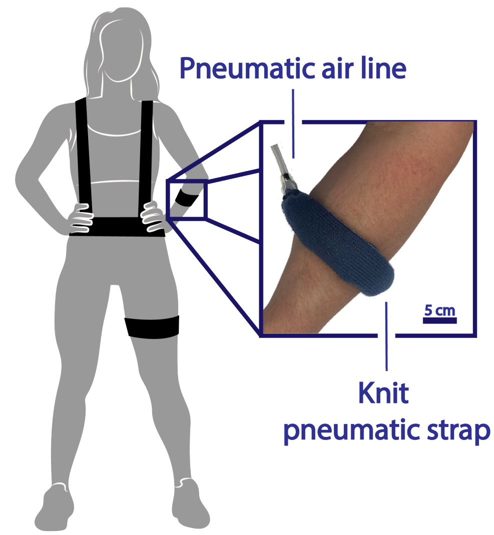

Fig. 1. The 3D knit pneumatic straps, shown in black, can be affixed to the body in a number of locations including the thigh, forearm, and torso. These straps would then fit directly to the exercise loading device or to a larger harness network on the individual.

This paper presents an initial step in designing new harnessing strategies for improved comfort and performance, such as those shown in Fig. 1, taking inspiration from the recent soft robotics boom which has resulted in a plethora of wearable devices [18] for rehabilitation [19], assistance [20], [21], and haptics [22], [23]. Leveraging these soft robotic strategies, newer approaches have explored "shrink-to-fit" mechanisms made from soft actuators such as series pouch motors (SPM), [24], a combination of auxetic structures and pneumatics [25], and fabric pneumatic artificial muscles (fPAM) [26]. These soft actuators promote wearability as they are easily donned deflated and are subsequently inflated to reduce their

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circumference around the wearer's limb [26], rather than manually tightening straps or hook and loop. This contraction generates an anchoring effect between the device and limb. The applied pressure can be regulated by a microcontroller, allowing fine tuning of the pneumatic straps' inflation to the wearer's preference or in response to harness sensors.

While effective at anchoring, current strategies depend on textiles that are heat sealable and can hold air. Within this actuation methodology, there has been minimal structural or material evaluation of these actuators to optimize anchoring. The fabrication methodologies of heat sealable actuators also create barriers to more complex design. As these actuators are made with cut and sew type processes, integrating complex designs, body conforming panels, or regions of graded stiffness would rely on tedious manufacturing tweaks or new processes, limiting design scalability.

This work proposes the use of 3D knit pneumatic straps within space exercise harnesses, to increase fabrication efficiency, improve wearer comfort, and explore structural design. 3D knitting is an additive manufacturing technique capable of fabricating textiles with variable stiffness and fine-tuned shaping that conforms to the body [27], traits that can be used to optimize pneumatic actuator performance [28]. Additionally, compared to other additive processes, 3D knitting allows for the simultaneous inclusion of a wide range of materials to create integrated devices that not only are optimized for comfort but can also add functional and conductive properties [28], [29], [30], [31]. Working towards this vision, we first discuss how to construct 3D knit pneumatic straps. Then, we illustrate how material variation influences the anchoring performance of the straps, exploring the relationship between textile design, radial expansion during actuation, and pull off force. These findings can potentially extend to improve astronaut comfort and exercise countermeasure outcomes.

II. Materials and Methods

The 3D knit pneumatic strap is composed of two layers as shown in Fig. 2; an inner sealed bladder and a tubular knit outer layer that constrains its deformation [28], [32]. Selectively varying the stiffness through differing knit architecture and materials within the outer fabric layer dictates actuator deformation, generating motions including extension, bending, and twisting [28], [33]. For pneumatic harnessing, the material of the outer sleeve also affects the friction between the skin and device, and can be designed to maximize user comfort and conform to fire safety and offgassing standards [34].

A. Pneumatic Actuator

The inner bladder was constructed from a stretchable thermoplastic film (Fibre Glass-Stretchlon 200), which was cut into a 23 cm by 18 cm piece, folded along its longer axis, impulse sealed (ULINE: 500), and trimmed, leaving an enclosed structure of 23 cm by 6 cm. To improve its strength, the bladder was inverted. A nylon barb fitting and plug, each fit with a 1.5 cm piece of latex tubing, were connected to either side of the bladder. Cable ties were then looped around the tube ends and fastened on top of the bagging film. A cable tie gun was used to tighten the tie, gripping into the latex tubing which acts as a gasket around the plastic fittings to seal the bladder.

B. Knit Outer Sleeve

Following construction of the inner bladder, the outer knit layer was fabricated with a v-bed manual knitting machine (Brother KH-940 with Ribber). This machine was chosen for its ability to create 3D tubular structures, without post processing methods like sewing, decreasing both fabrication time and waste. Future iterations of the sleeve would be moved to computer numerical control (CNC) knitting machines, enabling one-shot manufacturing of complex knit sleeves. The full-needle, jersey tubular structure was knit to 4 cm in diameter and 30 ± 1 cm in length. This structure was repeated with three materials: cotton (Yeoman Yarns), polyester (Unifi: 2/150/34 REPREVE®), and conductive polyester (Schoeller: 2/50).

To maintain yarn diameter consistency between samples, we varied the number of yarn ends knit in the sample for different yarn types: one for cotton, three for polyester, and three for the conductive polyester (two conductive polyester and one non-conductive to reduce material costs). To increase strap strength, enhance structural rigidity, and confine the actuator's deformation for a low profile form factor [35], additional, reinforced, cotton and polyester samples were made with two ends of monofilament (Hiten 0.27 mm) as modeled in Fig. 2a.

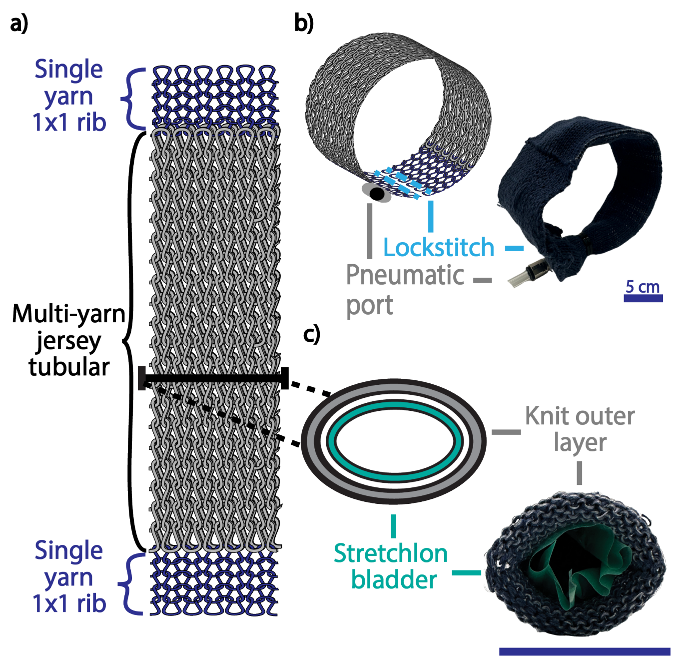

Fig. 2. Fabrication details for knitted pneumatic straps. (a) A schematic of the knit structures for the outer textile layer of the strap. The diagram illustrates a multi-yarn configuration, such as cotton and monofilament, for the tubular jersey section. (b) The flat strap is sewn together, transforming it into a sleeve worn around a limb. (c) Cross sectional view of the knit strap illustrating the device's inner bladder, and outer knit layer that programs the actuation profile.

For all five configurations, 5 cm sections of 1x1 ribbing were fabricated at the axial ends of the knitted tubes to prevent fabric curling and stitched together using a lockstitch (Juki DDL-5550N), shown in Fig. 2b, transforming the long tubular band into a sleeve that could anchor to the body. While a lockstitch was used for this process, future iterations will knit the tubular band into a sleeve on a CNC knitting machine, resulting in a one-shot manufacturing outer layer. A bladder was inserted into each of the tubular knit sleeves, as shown in Fig. 2c and a push-to-connect fitting was attached to enable easy strap inflation with pressurized air, inducing actuation.

C. Mechanical Characterization

To evaluate the varying material effects on the pneumatic strap performance, a tensile pull off test was performed with a universal testing machine (UTM) (Instron 68TM-10) to simulate exercise loading response (Fig. 3).

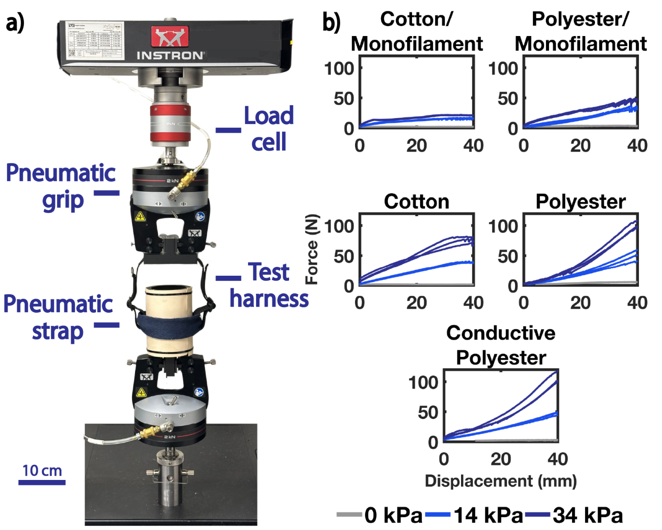

Fig. 3. The testing methodology for the pneumatic straps using the UTM a) The components of the test setup used to pull the pneumatic strap with webbing. b) The force and displacement outputs of the pneumatic straps for a variety of different outer layer materials.

Each of the five pneumatic straps was donned onto a 3D printed test cylinder, representing a limb. The cylinder had a diameter of 9 cm and featured a bottom face extrusion to directly interface with the UTM. To more closely mimic human skin friction, a rubber skin analog (Gospire: Tattoo Practice Skin) was bonded to the 3D printed base with epoxy adhesive (J-B Weld).

Two webbing straps were looped around the pneumatic strap, mimicking a harness attachment and inserted into a fixture clamped between UTM's pneumatic grips. While the webbing reduced contact between the skin analog and the pneumatic actuator, the webbing size and location was consistent for all tests, allowing for comparison. Future test methodologies would use a more transparent strategy to pull on the strap, improving resolution on strap material selection performance.

Each sample underwent testing at a rate of 100 mm/min for three trials, both unpressurized and pressurized to 14 kPa and 34 kPa, to one strap width (40 mm). These pressure levels were selected based on prior studies that identified them as values relevant to lower and upper bounds of user-reported comfort, acknowledging that perceived comfort may vary with device design [24], [26], [36].

III. Results

Our testing demonstrates that material choice impacts strap anchoring force (Fig. 3). We show that the maximum pull off force decreases when switching from polyester to cotton. Furthermore, we observed a dramatic decrease in pull off force for the polyester and cotton samples when combined with monofilament

To examine the potential causes for the force differences, we used a Hirox digital microscope to zoom in to 30x on the plain and monofilament reinforced samples and visually characterized surface roughness (Fig. 4 a-d). This initial qualitative assessment revealed little apparent surface roughness difference, but showed highly stretched stitches in the non-reinforced samples. These observations prompted an examination of the inflation diameter differences as shown in Table I. Quantitative surface roughness analysis may be pursued in future work.

TABLE I
Average inflation diameter at 14 and 34 kPa

Material	14 kPa [mm]	34 kPa [mm]
Polyester	47.0 ± 1.0	54.3 ± 1.2
Polyester/Monofilament	33.7 ± 0.6	37.0 ± 1.0
Conductive Polyester	48.3 ± 2.1	52.7 ± 1.5
Cotton	47.7 ± 0.6	51.3 ± 0.6
Cotton/Monofilament	31.3 ± 0.6	36.3 ± 0.6

Adding monofilament to the samples increased their outer layer stiffness, constraining inner bladder inflation and reducing overall inflated strap diameter and strap constriction around the limb analog. We used the inflated diameter of each sample to normalize the force data (Fig. 4e), investigating if the anchoring force of the strap is dominated by increased contact area. As the conductive and plain polyester straps exhibit similar inflation, force, and diameter responses, conductive polyester is shown in Fig. 4e, but excluded from the analysis. The increased inflation leads to a significant holding force increase, however does not fully explain the differences in holding force between materials, warranting further investigation.

IV. Conclusion and Future Work

Material selection is a powerful tool for controlling the inflation and anchoring force in pneumatic straps. Inserting stiff yarns, such as monofilament, reduces both inflation diameter and anchoring force. This approach can be used independently or with pressure adjustments to optimize anchoring performance for specific applications, and should be considered alongside engineering initial strap geometry. Additionally, 3D knitting enables a variety of fabrication options, supporting a wide range of materials.

While this paper explores the role of material choice in one of the simplest 3D knit structures, tubular jersey knitting,

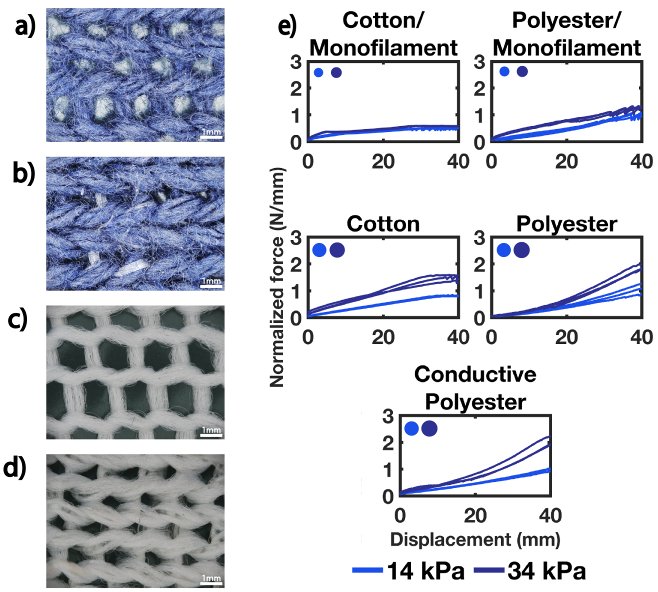

Fig. 4. To further investigate material effects we imaged a) cotton, b) cotton and monofilament, c) polyester, and d) polyester and monofilament straps pressurized to 14 kPa with a digital microscope. e) Shows the normalized pull off force for the materials, excluding the uninflated (0 kPa) case. Each figure includes to-scale dots representing strap diameter at 14 kPa (lighter) and 34 kPa (darker).

additional knit structure parameters could be modified to further tune the straps' mechanical properties. A microcontroller and solenoids could also be used to control the inflation of the straps and therefore their fit. These customizations provide opportunities to further tailor space exercise harnesses, informing the design of future exercise countermeasures that promote astronaut health.

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