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Peristaltic (PS) Suit: Active Bioelectronic Sensing-Compression Spacesuit for Microgravity Adaptation and Cardiovascular Deconditioning

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It is known that prolonged exposure to microgravity induces various acute health risks, including osteoporosis, skeletal muscle atrophy and fatigue, and cardiovascular deconditioning. Providing continuous medical check-ups and interventions for astronauts throughout their journey in outer space and after their return to Earth is, therefore, imperative. Without the influence of gravity, hydrostatic bodily fluid pressure gradients vanish, and blood distribution shifts from the astronaut's legs towards their upper body. The Peristaltic (PS) Suit is an active bioelectronic intra vehicular activity spacesuit that can simultaneously perform multi-modal, distributed physical and physiological sensing, as well as exert spatiotemporal and peristaltic pressure across the body to normalize cardiovascular flow. The integration of both wireless biosensing and pneumatic actuation systems in the PS-Suit facilitates a closed-loop and timely response to astronauts, and enables researchers to correspondingly study the direct influence of active-dynamic compression during relevant environmental conditions, such as microgravity, on various physiological markers.

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I. Nomenclature

AGS	=	anti-gravity suit
BLE	=	Bluetooth low energy
BP	=	blood pressure
BPM	=	beat per minute
DBP	=	diastolic blood pressure
ECG	=	electrocardiography
GCG	=	gradient compression garment
GUI	=	graphical user interface
HR	=	heart rate
I^2C	=	inter-integrated circuit
IMU	=	inertial measurement unit
IR	=	infrared
ISS	=	international space station
IVA	=	intravehicular activity
LBNP	=	low body negative pressure
LOE	=	low earth orbit
OI	=	orthostatic intolerance
PAT	=	pulse arrival time
PPG	=	photoplethysmography
PTT	=	pulse transit time
SBP	=	systolic blood pressure
SMA	=	shape memory alloy
TPU	=	thermoplastic polyurethane

II. Introduction

More than 60 years after the first man in space Yuri Gagarin aboard the Vostok 1 and completed one orbit of the Earth, long-duration spaceflight and missions in which astronauts live and work at the International Space Station (ISS) have become a routine [1]. The ISS provides an equipped platform where research and experiments on the effects of space environments, including microgravity and long-duration spaceflight, on human physiology can be conducted by scientists and astronauts with the latest operational procedures, systems, and technologies that we expect to evolve further across future missions to the moon, Mars and perhaps beyond.

The early crewed space program Gemini (1965) concluded that prolonged microgravity exposure induces various significant acute health risks, including reduction of red cell mass, osteoporosis, skeletal muscle atrophy and fatigue, cardiovascular deconditioning, and orthostatic intolerance [2]. More recently, Marshall-Goebel *et al.* (2019) found that exposure to microgravity results in a chronic reverse headward blood and tissue shift that can lead to complications like thrombosis or blood clots [3] (this study was done by measuring the internal jugular vein, which collects blood from the brain and runs down to the neck, from 11 healthy astronauts before, after, and during spaceflights on a 6-month mission). Providing continuous medical monitoring and intervention for astronauts throughout their journey in microgravity and after their return to Earth is therefore imperative. Indeed, cardiovascular health will become increasingly important in long-term missions outside of the LOE such as a journey to Mars (at least a 1.5-year return trip from the Earth). To this end, we have developed a Peristaltic Suit (PS-Suit) by embedding an array of soft, textile-based actuators and physical and physiological sensors into a full-body intravehicular activity (IVA) suit with miniaturized wireless sensing-actuation physiological and pneumatic control hardware. The incorporation of both sensing and actuation systems in an IVA suit enables us to perform closed-loop intervention and study the direct influence of active compression on various physiological markers, particularly for cardiovascular health.

III. Background and Related Work

A. Cardiovascular Performance and Monitoring in Space Physiology

One critical transition that disrupts flight operations and crew safety is landing day orthostatic intolerance (OI). Astronauts who have orthostatic intolerance cannot maintain adequate arterial blood pressure and have decreased brain blood levels when upright. Around 60 to 80% of astronauts experienced OI during a 10 min of 80° head-up tilt research study 4–6 h after landing from a long-duration spaceflight [4]. While we now have a better understanding of human physiology in space environment, it is vital to continuously monitor the health and performance of astronauts during and after both extra- and intravehicular activity so that we can provide appropriate countermeasures to reduce the likelihood of OI and to ensure astronaut's health and safety during their operation, travel, and landing.

Currently, astronauts perform health monitoring and check-up routines using several devices such as an electrocardiogram (ECG), BP cuff, and vascular sonogram. The process can take hours daily and is sometimes painful and inefficient for them [5]. With future missions to the moon, Mars, and beyond, astronauts will require the ability to more seamlessly monitor and analyze their health and performance in order to determine and maximize their ability to perform their operations safely and effectively. Wearable technologies, electronic textiles, and smart clothing developed for personal health, physical activity, and safety applications on the Earth can be adapted for space applications [6–11], like the Astroskin smart shirt that was initially launched with SpaceX CRS-16 in 2018 and measured multitude physiological parameters, such as blood pressure, electrophysiology, breathing rate, temperature and blood oxygen level as an example [12,13]. The continuous advancement of these technologies illustrates the burgeoning potential of the development and integration of new sensing modalities and actuation systems for personalized telemedicine and seamless medical intervention in outer space [14,15].

B. Countermeasure Technologies and Compression Suits

A lower body negative pressure (LBNP) chamber (commonly known as Chibis suit) provides an effective cardiovascular countermeasure by pulling fluid down to the legs in a vacuum chamber and expanding veins and tissues of the lower body [16]. However, the system immobilizes astronauts as they need to submerge their body from the hip down in a chamber. Several wearable countermeasures have been designed and tested for spaceflight, including the Skylab Cardiovascular Counter Pressure Garment, the Shuttle AGS, the Kentavr, and the more recent gradient compression garment (GCG) suits.

The Skylab Cardiovascular Counter Pressure Garment, employed inflatable tubes that can be pressurized manually through a single bulb [17]. The mechanism was applied in partial-pressure suits for jet pilots prior to the development of full pressurized suits ("G-suits" have also long been used in jet fighters to prevent pilots from losing consciousness during high-G maneuvers). Upon inflation, the tubes expand and tighten the circumference of the leg, applying pressure mechanically. The garment was patterned such that the applied pressure was greatest at the ankles, and progressively less pressure was applied to the top of the thigh. The AGS, a more advanced example, is a pneumatic partial pressure system made up of five interconnected pressure bladders that cover from lower abdomen to the ankle [18]. Adapted from its use for military and jet pilots in the 1980s, the AGS is an active garment that can be controlled through a pneumatic system and inflated to give pressure in the range of 26.9 to 129.3 mmHg. The primary disadvantage of AGS is that it requires the wearer to be stationary. It is not optimized for wearability and mobility, as the air pipe is wired to a bulky pneumatic system. The pressure in the inflatables is also used as a control and does not represent the actual pressure exerted on the body, making it less effective as a compression suit.

The Kentavr and the GCG, on the other hand, are made of a passive elastic fabric with the form-factor of a pant and a suspender overall, respectively. The Kentavr is adjusted using lacing panels on each component, allowing for a customizable fit to each subject and providing approximately 30 +/- 5 mmHg of compression [18,19]. The GCG is tailored to the individual from the lower abdomen to the foot, and is designed to produce a fixed gradient compression force of 16 mmHg in the abdominal region to 55 mmHg around the ankle [20]. However, compression garments are difficult to don/doff and are not able to exert dynamic or controllable pressure on the body. They also do not adapt to the physiological and physical changes of the astronauts. Several efforts have explored smart materials such as shape memory alloy (SMA) to develop morphing or dynamic compression garments [21,22]. Their practicality is still under research, as they are stiffer and require high temperature or electrical current through Joule heating to actuate. Consequently, there is a need for a smart compression garment that offers a closed-loop dynamic and spatiotemporal control based on physical and physiological changes (*i.e.* BP that informs cardiovascular health) of the astronaut with a wearable and light-weight system designed for practical use during long-term space travel.

IV. Active Compression System Design and Development

To develop our active compression device based on soft textile-based pneumatic actuators, we used thermoplastic polyurethane (TPU) film, typically implemented in hot-melt adhesives (e.g., HM65, Perfectex). An inflatable bladder was fabricated by thermally-welding two layers of TPU film with an impulse sealer (FS400, Fuxury). A hole was then punctured for the pneumatic tubing opening (1.5mm, uxcell) and sealed with soft silicone rubber glue (RTV 732, Dow Corning). A two-terminal textile pressure sensor for quantifying the compression force was developed by sandwiching a piezoresistive knit fabric (LTT-SLPA-60k, Eeonyx) in between two conductive knit fabrics (Stretch Conductive Fabric, Less EMF) and connecting TPU-insulated conductive threads (117/17 dtex silver-coated nylon, Statex). The textile pressure sensor leverages the piezoresistive effect, in which a force exerted onto a functional fabric compresses its conducting molecules, forming more electrical network, and thus, reduces its resistance [23].

Figure 1a illustrates a design of an active compression sleeve with an array of five fabric bladders. An outer woven fabric and an inner 4-way stretch fabric are patterned with openings in which to embed the inflatable pouches. The mechanical properties of these fabrics restrict and provide positive compression force toward the limb as the inner bladders are inflated. We also realized that integrating free-standing TPU bladders inside a textile sleeve, instead of fusing or melting them onto a textile with a heat press machine, is the most reliable approach, since we can easily access and replace the bladder in the case of a damage or puncture. A two-terminal textile pressure sensor for quantifying the compression force is developed by sandwiching a piezoresistive knit fabric (LTT-SLPA-60k, Eeonyx) in between two conductive knit fabrics (Stretch Conductive Fabric, Less EMF) and connecting TPU-insulated conductive threads (117/17 dtex silver-coated nylon, Statex).

We fabricated an active compression calf (Figure 1b-c) and arm (Figure 1e) sleeve by embedding five inflatable pouches into a customized textile structure and connecting it to a miniaturized pneumatic system (FlowIO Platform [27]). As shown in Figure 1d, we can program the air flow, provide a controlled compression, and sequentially inflate each chamber to mimic peristalsis movement**,** which is the propagation of contraction and relaxation of muscles in our gastrointestinal tract. Figure 1f shows the compression pressure data of each chamber as the active compression arm sleeve is inflated and deflated sequentially or simultaneously. A force exerted on each fabric pressure sensor reduces its resistance, which is shown as a drop in the ADC value.

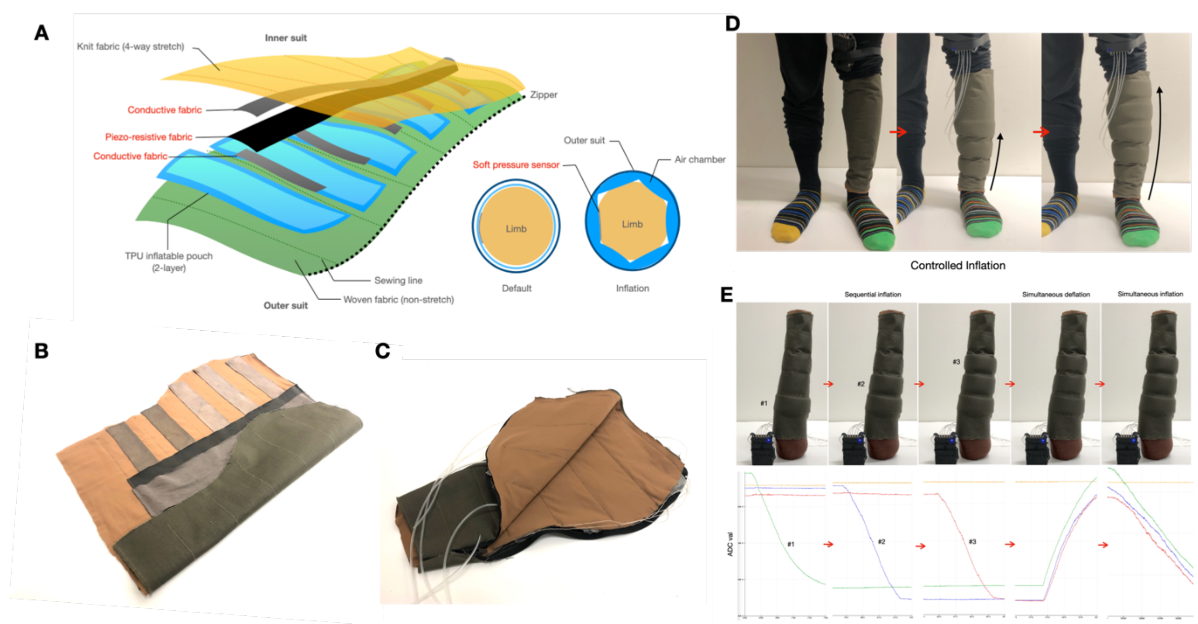

Fig.1: a) Exploded view and illustration of an active compression sleeve prototype, b) Internal textile pressure-sensing array layer and c) final prototype of a calf sleeve integrated with air tubing. d) Demonstration of a peristalsis dynamic compression movement from ankle to knee. E) Arm sleeve prototype actuated sequentially and simultaneously with real-time compression pressure sensing.

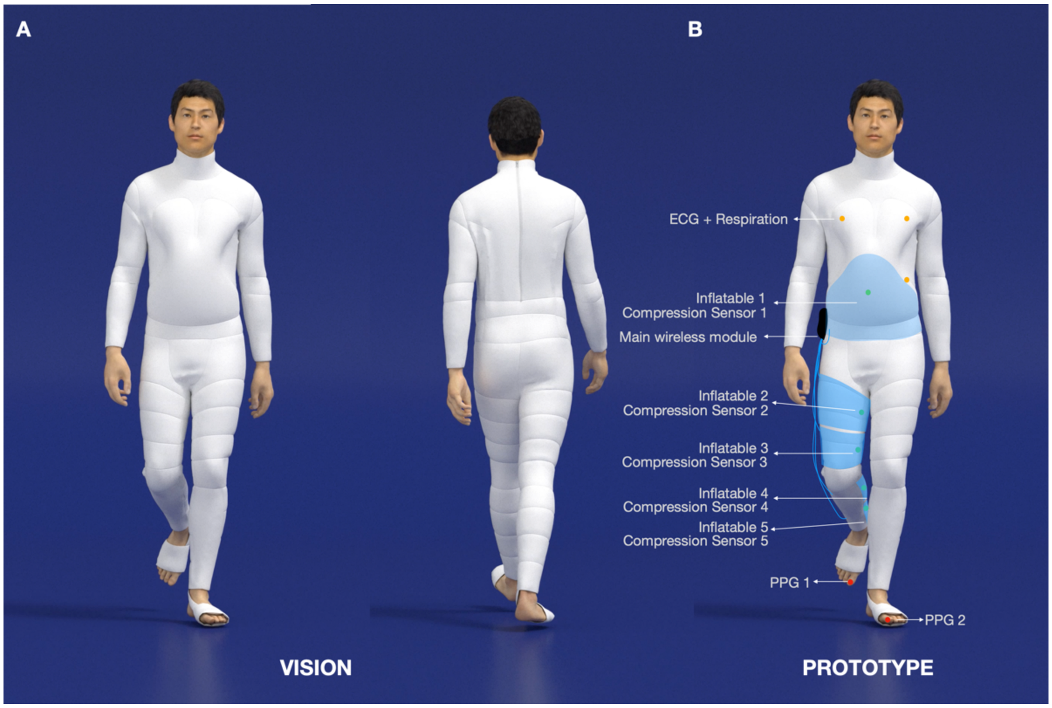

Fig.2: a) PS-Suit concept and b) illustration of our recent prototype flown in a zero-gravity flight showing all the main component of the system

V. The Peristaltic Suit System

The final prototype of the PS-Suit, as shown in Figure 2, consists of an array of inflatable chambers (five chambers distributed from the lower abdomen to the ankle) with a physiological and physical activity sensing system and a pneumatic actuation system that enable both multi-modal physiological sensing and active-dynamic compression. The PS-Suit outer layer (Figure 3c) is adapted from a high-performance Nomex racing suit (Profox) with a combination of knitted Nomex around the joints and a double-layer quilt woven and tailored based on the wearer's body circumferences. Nomex can be found in the outermost layer of spacesuits. It is a high-performance fiber with excellent temperature and mechanical resistance; this ensures protection, mobility, and comfortability while wearing the PS-Suit.

A. Physiological and Activity Sensing System

The physiological and activity sensing module (Figure 3a) comprises a set of skin-contact physiological sensors (MAX30105, Maxim Integrated and ADS1292R, Texas Instrument) with their central processing system (Feather Sense nrf52840) embedded in multiple locations across the PS-Suit (Figure 2b). It includes three biopotential and bioimpedance electrodes around the upper left chest (LC), right chest (RC), and lower left (LL) region of the body to monitor the heart's electrical activity or electrocardiography (ECG) and respiration. The respiration sensing in ADS1292R is done through impedance measurement from these electrodes [24].

Two blood-flow sensing nodes are also distributed around the left toe and right toe. The blood flow sensing mechanism is based on photoplethysmography (PPG), in which a light-emitting diode (red, infrared/IR, and green) illuminates the skin and a photodiode captures the reflected signal and light absorption caused by the blood circulation [25]. In addition, blood oxygen saturation level can be derived from PPG based on the ratio of red and IR light absorbance. By processing the ECG and PPG data, we can measure pulse arrival time (PAT) that correlates to the participant's blood pressure without any inflation cuff that could interfere with the circulation [26]. Inertial measurement unit (IMU) for gravity data analysis and physical activity sensing is also integrated in this module. We have developed a GUI to visualize all the compression, physical activity, and physiological sensor data continuously in real-time (Figure 3b).

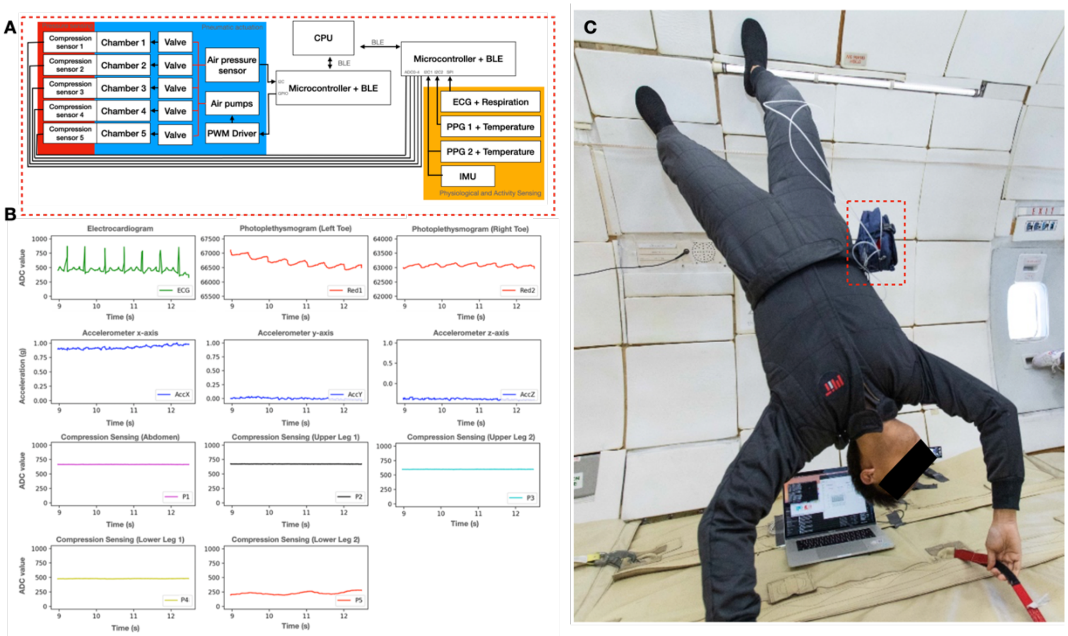

Fig.3: a) System schematic of the physiological and activity sensing module and pneumatic actuation module, b) Our GUI that shows recording of wireless sensing unit, including physiological sensors (ECG and PPG on both toes), accelerometers, and compression sensors (showing pressure gradient), and c) a test subject wearing tailored PS-Suit in a zero-gravity flight.

B. Pneumatic Actuation System

As shown in Figure 4, the pneumatic system (FlowIO) consists of miniature motor pumps, circuits, and valves that can be wirelessly controlled through BLE and a microcontroller (Feather Sense nrf52840) to control a set of five air chambers distributed throughout the PS-Suit. A fabric pressure sensor is integrated on every air chamber for feedback and control of the compression mechanism. As illustrated in Figure 5a, compression pressure in mmHg rises as the inflation time increases, and it is inversely proportional to the pressure sensor's resistance. Based on the ADC data of every inflatable pressure sensor (Figure 3b), which correlates to the resistance value in Figure 5b, we can estimate a gradient compression in the PS-Suit of around 18 mmHg in lower abdomen to 50 mmHg around the ankle (comparable to a pressure gradient in a GCG suit [20]).

The main module of FlowIO features up to 5 pneumatic I/O ports, each port supporting the actions of inflation, vacuum, release to atmospheric pressure, pressure hold, pressure sense, and flow-rate variability. It contains 7 normally-closed solenoid valves in a manifold configuration, of which two are for inlet and outlet, and the remaining five for the I/O ports. Besides the standard configuration, our system supports 4 additional configurations, where the pumps can be connected in series or in parallel, and used either for inflation or for vacuum. A series configuration achieves higher pressures, while a parallel configuration achieves higher flow rate. We used a Li-Po battery with a high C-rate (45C and 7.4V, AWANFI) to run our 3V DC air pump (RK-528TB, Skoocom) that can provide flow rates of up to 4.5L/min and a pressure range of -60 to 150kPa.

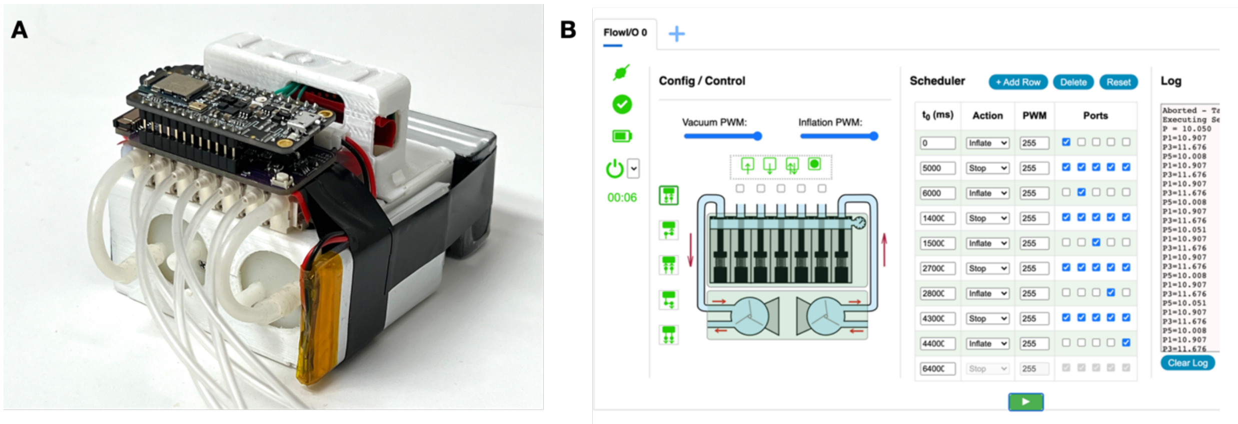

Fig.4: a) FlowIO Pneumatic System that controls all the air chambers for peristaltic pressure and gradient compression in the PS-Suit and b) GUI for controlling the five air flow valves and scheduling the time of inflation and vacuum/deflation.

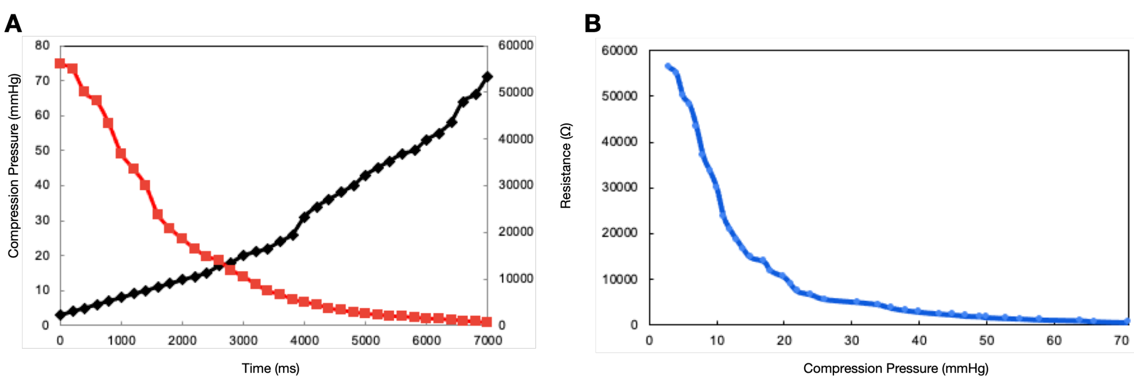

Fig.5: a) The relationship between actuation time of an embedded bladder (~15 x 20 cm) and compression pressure with Kikuhime pressure monitor (mmHg) and the integrated piezoresistive sensor (Ω). b) Resistance of the piezoresistive sensor vs compression pressure.

VI. Conclusion

We have developed the PS-Suit, an active sensing-compression intravehicular activity spacesuit that could simultaneously perform multi-modal, distributed physical and physiological sensing, as well as exert spatiotemporal and peristaltic pressure across the body. The integration of both wireless biosensing and pneumatic actuation systems in the PS-Suit facilitates closed-loop and timely response to astronauts' circulatory health, and enables our upcoming research to correspondingly study the direct influence of active-dynamic compression and microgravity on different physiological parameters. The PS-Suit platform could not only allow better regulation of blood flow and cardiovascular health to support better circulation of body fluids, but also augment astronaut's physical training through active muscle compression, and provide emotional support through comfort and telepresence communication with haptic transfer. The design and control framework of the suit will also be applicable in other health, rehabilitation, exercise, or soft robotics applications, not only in outer space, but also on the Earth, in the form of anti-gravity suits, athletic or lymphedema compression garments, shapewear, corsets for exoskeleton and posture correction, and surgical tourniquets.

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