Development of the Polipo Pressure Sensing System for Dynamic Space-Suited Motion

Allison Anderson, Yi˘git Mengüç, Member, IEEE, Robert J. Wood, Member, IEEE, and Dava Newman

Abstract—Working inside the space suit causes injury and discomfort, but suit assessment techniques such as measuring joint torques and ranges of motion fail to evaluate injury because they fail to distinguish interactions between the human and the space suit. Contact pressure sensing would allow a quantitative assessment of the nature and location of suit-body contact where injuries occur. However, commercially available systems are not well suited for measurement inside the confined environment of the space suit during movement. We report on the design of a wearable pressure sensing system, the Polipo. The Polipo dynamically measures between 5 and 60 kPa of pressure with ~1 kPa sensitivity, is within 10% root mean square error from a known loading profile during dynamic movement, and is a standalone system able to accommodate a 50th percentile female to a 95th percentile male upper body dimensions with near-shirt-sleeve mobility. This paper focuses on the upper body, but the methods may be extended to the full body as future work. It provides a pressure sensing system that could be applied beyond the field of aerospace to assess human–garment interactions, for example recommending armor protection for defense applications or to alleviate fall impacts for medical applications.

Index Terms—Astronaut injury, pressure sensing, space suit, wearable technology, soft sensors.

I. INTRODUCTION

CONTACT pressure sensing technology can enable investigations into a long-standing problem: astronaut injury and discomfort as a result of working inside the space suit. The US space suit is a difficult environment in which to work due to its stiffness and rigidity [1]–[3]. The causal mechanisms of injury have been hypothesized but little quantitative study has been done, primarily due to the lack of tools to assess injury [4], [5]. The interface where a person moves inside the space suit, pressing upon it to articulate the suit itself, has not been quantified. Previous studies have used a variety of techniques, such as photogrammetry, motion capture, and ergonomic strength measurement to evaluate suited performance [1]–[3], [6]–[11]. However, each of these metrics measure performance from the outside of the suit, thereby characterizing the human and space suit as a whole. For injury prevention, measuring human–suit interaction is needed.

A wearable pressure sensing system would provide insight into injury and discomfort, but a review of off-the-shelf technologies shows there is currently no viable solution for measurement inside the space suit [12]–[16]. Tekscan (Boston, MA) and Novel (Munich, Germany) are the most widely used commercially available sensors, but their inaccuracy during movement, high cost, and poor wearability make them unsuitable for measuring in the anticipated sensing regime: detecting pressures less than 60 kPa during dynamic movement in a confined space.

As an alternative to the limited commercial sensor options, there is a broad range of sensing technologies developed for research purposes. Sensors using physical principles for detection are commonly resistance and capacitance.

Resistance sensors are based on the change in resistance of various conductive materials in response to loading. Many sensor designs use fluids as the conductive medium [17]–[19]. Composite carbon particles may be used to alter the resistivity of the sensor, but the mechanism varies over time, making interpreting the output curve complicated [20], [21]. Another technique is to use a conductive fiber and measure resistance changes with strain, but issues with these techniques include hysteresis, large error, slow response time [22]–[25]. Finally, several methods use conductive materials separated by a thin medium in grid pattern, such that pressure completes a circuit [26]–[28].

Using changes in capacitance to detect pressure is a second simple and commonly studied method. Many designs consist of compressible foam sandwiched between conductive fabric whose capacitance varies as the material gets closer or further apart with changes in pressure [14], [29]–[32]. Capacitive systems trade off simplicity in design for greater variability in the response profile, as manifested with greater hysteresis and creep than in other sensor types [33]. Additionally, there is a limit to their effective size, since capacitance must change over an area [30].

There are several other pressure sensing concepts beyond using resistance and capacitance. Many robotic applications focus on developing a skin-like touch sensor [25], [34].
For example, piezoresistive fabrics and screen printed sensors are aligned in a grid of columns and rows [34], [35]. Fluid filled reservoirs may be used to detect pressure by measuring impedance or deflection of a diaphragm [36], [37].

Beyond the sensor itself, there are challenges in achieving a wearable electronic system suitable for the harsh environment of the space suit [38]–[41]. As electronics and sensor systems get smaller and more efficient, a great deal of research has been done on their applications for wearable human use in many fields. For space applications, requirements focus on safety, comfort, ease of use, operational simplicity, cost, electrical design, thermal, space environment (temperature, pressure, radiation), controls and displays, and operational life of systems [38]. Wearable electronics for the space suit has focused primarily in two areas: biomedical monitoring [41]–[43] and information display [38], [44]–[48]. Recent work has also evaluated electronic system design for a variety of sensor applications integrated to wearable garments [49] and wireless data transfer between sensor systems [50], but are generic platforms independent of the sensor itself. Contemporary with this work, sensor gloves for space suit applications are being developed [51].

From this review there is currently no solution for measuring the pressure at the interface between the human and space suit during movement over a large area of the body in the desired pressure range. Additionally, in-suit sensing is a relatively unexplored area, and few systems have been implemented in the pressurized suit environment. To address this need, a wearable pressure sensing system called the Polipo was developed to quantify the contact pressure between the person and the space suit during dynamic movement. This work focuses on the upper body with anticipated low-pressure (≈5-60 kPa) under fabric components and metal bearings of the space suit covering the arm. First, the sensor development and characterization is described, followed by the wearable electronics system in which the sensors are housed.

II. SENSOR DEVELOPMENT

Fig. 1 shows the Polipo, a network of 12 pressure sensors distributed over the arm to dynamically measure the pressure on the human body caused by movement in extreme environments. The design and performance of the sensors is described below.

A. Sensor Design

The Polipo’s soft hyper-elastic sensors are designed to measure low-pressures applied to the body under the soft goods. The primary function and fabrication details are based on previous work [17] but is summarized here. The sensors are cast from a silicone rubber (EcoFlex00-30, Smooth-On, Inc., Easton, PA), making them hyper-elastic (modulus: 69 kPa, Shore hardness: 00-30) and easily conformal to the body. Two plastic molds, shown in Fig. 2, are 3D printed (out of VeroBlue on an Objet Connex 500, Stratasys Inc, Edina, MN) with one mold printed with a microfluidic channel in positive relief. A custom-fabricated flex circuit is sandwiched between the two sensor halves, completing the circuit between the liquid metal and wire soldered to the flex circuit. The empty microfluidic channel is then injected with a highly conductive (with resistivity $\rho = 29.4 \times 10^8$ m [52]) liquid metal, galinstan (Gallium-Indium Tin eutectic, 14364, Alfa Aesar, Ward Hill, MA). The injection process and a final sensor are shown in Fig. 2.

The cross section of the microfluidic channel is 250 $\mu$m width by 150 $\mu$m height cross section. As normal pressure is applied to the completed sensor, the channel collapses, causing an increase in resistance of the conductive path. The response profile is calibrated to correspond to the pressure value. The spiral design adopted for measuring normal pressure, rather than strain [18], were designed with a 2 cm diameter, with a total sensor diameter of 2.5 cm.
B. Sensor Performance

Sensors were calibrated using a commercially purchased apparatus (Novel, GMbH, Munich, Germany) consisting of two rigid plates and an inflatable bladder that delivers pressure to the sensors in the targeted range of 5-60 kPa. Our soft sensors exhibited an exponential response. Some sensors exhibited linear responses, likely due to variation in manufacturing resulting in variations in channel cross section shapes and thus the pressure response [53]. The sensitivity, S, is not constant but governed by the equation:

\[ S = \alpha \ln \left( \frac{x + 1}{x} \right) \]  

(1)

where \( \alpha \) is the coefficient fit to the exponential function and \( x \) is the bit output response of the sensor. Table I shows the sensitivity for each exponential sensor at the high and low end of targeted pressure regime, 5-60 kPa. Most sensors do not achieve 1 kPa sensitivity at 5 kPa of pressure, whereas all sensors have better than 1 kPa at 60 kPa. Equation (1) was rearranged to solve for the pressure at which the sensitivity \( S \) is 1 kPa, also shown in Table I. This varies for each sensor since it is a function of the calibration coefficients.

<table>
<thead>
<tr>
<th>Sensitivity over pressure range</th>
<th>Pressure for ( S = 1 ) kPa</th>
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<tbody>
<tr>
<td>Sensor kPa</td>
<td>Sensor Pressure kPa</td>
</tr>
<tr>
<td>1</td>
<td>1.8 0.27</td>
</tr>
<tr>
<td>2</td>
<td>3.3 0.97</td>
</tr>
<tr>
<td>3</td>
<td>2.5 0.5</td>
</tr>
<tr>
<td>4</td>
<td>1.4 0.19</td>
</tr>
<tr>
<td>5</td>
<td>2.8 0.7</td>
</tr>
<tr>
<td>6</td>
<td>0.79 0.02</td>
</tr>
<tr>
<td>7</td>
<td>1.2 0.06</td>
</tr>
<tr>
<td>8</td>
<td>3.2 0.57</td>
</tr>
<tr>
<td>9</td>
<td>1.4 0.1</td>
</tr>
</tbody>
</table>

The sensors did not achieve 1 kPa sensitivity at the lower end of the sensing region, but all achieved the desired 1 kPa at the higher end of pressure sensing at 60 kPa. To determine the cross-over pressure at which the targeted sensitivity was achieved, Equation (1) was rearranged to solve for the pressure at which the sensitivity \( S \) is 1 kPa, also shown in Table I. This varies for each sensor since it is a function of the calibration coefficients.

Under static loading, the sensors exhibit drift and hysteresis, the effects of which are magnified with increasing pressure. Hysteresis is present in any physical system, but the effect is worsened as the energy is allowed to dissipate more freely through the stretching of the polymer chains. The elastomer’s creep was measured by loading the sensors to a known compression. A materials testing machine (5544A, Instron Corporation, Norwood, MA) was used to measure vertical compression distance, resulting load, and voltage output from the sensor. This test setup is shown in Fig. 3. The sensor was loaded to 6.9 N for 60 seconds, corresponding to 30 kPa, before being offloaded for another 60 seconds. Although the vertical distance of the plate did not change, the pressure on the sensor did as the sensor is expanding laterally as the material relaxes, and therefore reduces the load read from the force transducer. As a result, the voltage slowly increases over time by 11%. As the sensor material relaxes, the microfluidic channels expand, increasing resistance and increasing the output voltage.

Although the effects of creep cause erroneous results when loaded statically, the Polipo was designed for dynamic movement to test the interaction between the person and the space suit during EVA movement. A constant loading rate was used to apply a pressure to the sensor area up to 30 kPa over 30 seconds. Fig. 4 shows the pressure applied to the sensor and the resulting pressure measured by the sensor system. The response consistently follows the applied pressure on the loading portion of the profile and is highly repeatable. However, the effects of creep can be seen even when loaded dynamically, but to a much smaller degree than when loaded statically. The greatest deviation from the actual pressure occurs during offloading. The large pressure spikes at the transition from unloaded to loaded, and again at the turn-around transition at 30 kPa, are due response of the Instron machine’s feedback loop to maintain a constant load rate. The sensor’s accuracy was measured by the root mean square error (RMSE) of the deviation between the actual and measured pressures with \( \text{RMSE} = 2.97 \) kPa. To evaluate the sensor’s response over a broader range of dynamic conditions, the load time to 30 kPa was halved to 15 seconds and maintained an RMSE of 3.04 kPa. When increased to 60 seconds, the RMSE increased to 3.76 kPa. The erroneous readings caused by creep are minimized during dynamic loading because over short time scales the polymers do not dissipate as much additional energy as over long timescales. In our space suit application, subjects performed movements over 10-30 seconds [54], the time period over which the sensors performed best.

Due to confounding effects of creep, the response time of the sensors was evaluated when transitioning from loaded to unloaded by step function. The time constant \( \tau = 0.1 \) seconds, giving near real time measurement of changes in pressure. The response time corresponds to a bandwidth of \( 1/(2\pi \tau) = 1.59 \) Hz. Movement within the space suit is slower than un-suited movement due to the rigidity of the suit and effort required to move. The fastest anticipated motion, an overhead hammering task, is performed in approximately 3 seconds, or 0.3 Hz. Therefore, the sensors are able to capture the anticipated suited movements.

Finally, the effect of increased temperature was tested while performing practice EVA motions inside a space suit arm pressurized using a vacuum chamber with the rest of the body exposed to ambient air conditions. The Polipo was worn for more than 30 minutes, and no deviations in baseline readings beyond normal fluctuation were measured, indicating body temperature alone did not affect measurement.

III. GARMENT DEVELOPMENT

The sensors measure pressure between 5 and 60 kPa under dynamic loading conditions. They were integrated into a wearable garment, the design and performance of which is described below.
Fig. 3. Sensor creep demonstrated. The sensor was tested using the set up shown. The top plate was moved to a vertical offset to compress the sensor. The ideal pressure loading profile and the actual pressure applied to the sensor are plotted against the corresponding sensor voltage. The pressure is relieved over time due to sensor creep. As a result, the voltage, and therefore pressure, is artificially increased.

Fig. 4. Dynamic response of the sensor to known loading. The system was designed for dynamic movement. When measured at loading speed corresponding to human movement, the sensors track the known pressure profile to a root mean square error of 3 kPa.

A. Human Accommodation

The target design population of the Polipo was a 50th percentile female to a 95th percentile male. This population range accommodates users who might work inside the Mark III space suit. Upper body dimensions from the U.S. Army Anthropometric Survey (ANSUR) [55] database were used to size the wires accordingly, shown in Table II. The percent increase in length between male and female data points is 19% for each dimension. This increase in length was taken as the minimum elasticity or accommodation length needed for the wiring.

The electronics architecture (described below), uses the Arduino Micro, limiting the maximum number of sensors to 12. The anticipated “hot spots” of contact astronauts were likely to encounter while working in the space suit determined the initial placement of the first eight sensors. The locations were identified through conversation with subject matter experts. Hot spot locations are: the inner wrist, back of the elbow, front of the elbow near the crease (one above and one below), the triceps muscle near the armpit, outside of the biceps muscle near the upper arm bearing of the space suit, and on the top of the shoulder. The remaining four sensors were place to achieve uniform spatial distribution over the rest of the arm. A schematic of the designed sensor location is seen in Table II.

The Polipo pressure sensing system is integrated to a base layer using small strips of Velcro®. The base layer, seen in Fig. 5, is sewn from a bi-directional elastic fabric (Veluntino Bielastico - Polyester lycra blend, Acc. Asolana, Asolo, Italy) that is highly sensitive to the link side of Velcro®. The base layer has numbered “targets” on the sleeve for each sensor to ensure proper placement. To prevent shifting with movement, silicone backing is placed on the skin-side of each target, anchoring it to the arm. A final cover shirt (Piave – 9300PA Anti-catch weave, Sitip S.p.a., Albino, Italy) is worn over the base layer and pressure sensing system to reduce friction and shear forces against the inside bladder layer of the space suit.

B. Wiring and Sensor Housing

Selecting the correct wiring design is a trade-off between mobility (i.e., flexibility), electrical resistance

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>BODY DIMENSIONS AND WIRING PATTERN</th>
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<tbody>
<tr>
<td>Dimension</td>
<td>50% Female</td>
</tr>
<tr>
<td>Acromion-Radiale</td>
<td>300</td>
</tr>
<tr>
<td>Shoulder-Elbow</td>
<td>335</td>
</tr>
<tr>
<td>Elbow-Wrist</td>
<td>274</td>
</tr>
<tr>
<td>Wrist-Wall</td>
<td>619</td>
</tr>
</tbody>
</table>

Dimensions from ANSUR Database.
Fig. 5. Components of the pressure sensing system. A) The base layer garment with sensor target spots. The opposite shoulder has a pocket built to house a high-pressure sensor mat. B) The Polipo sensor system attached to the base layer. C) The cover shirt over the Polipo sensor system to prevent catching of the wires or movement of the sensors.

Fig. 6. Wiring, implementation, and wear. A) Wires are combination of seven strands of copper wrapped polyester. B) Flexible wires sewn in pairs in a zig-zag pattern to allow additional stretch. C) Over time, friction causes the strands to break, causing slow, steady deterioration.

(i.e., wire diameter), and durability (i.e., material properties). For the Polipo, a wire with seven strands of copper wrapped polyester (Tecnospir, 24066 Pedrengo, Italy) was used, shown in Fig. 6. The copper gives the wire a low resistance of 0.6 ohms/meter, while the polyester core allows it to be very flexible. The wire was tacked into a zig-zag pattern on an elastic material (Tess Carezza Soft Garzato - Nylon lycra blend, Sitip S.p.a., Albino, Italy), with a water-soluble backing to provide stiffness, which was later dissolved away. Each of the two wires of the circuit were attached using an industrial machine that tacked, rather than sewed, the wires to the fabric with a 0.5 cm zig-zag pattern and 0.2 cm spacing, giving a total 1.5 cm width for each sensor. This spacing was found by iteration to give the best elasticity and ease of construction. An additional layer of elastic fabric with a glue backing (Tess 0917 Charmeus + Web 35, Sitip S.p.a., Albino, Italy) was heat pressed to the top to prevent short circuits. Excess fabric was removed and strain relief slits were cut.

The zig-zag method allowed the wires to stretch by 20%, achieving the previously calculated strain of 19% for population accommodation. However, additional length was needed to accommodate dynamic motion. Three subjects were measured in a resting posture, arm fully abducted, and arm fully extended in front of the body. Subjects needed between 10-15% additional wire length to accommodate movement. The additional length was added to the wires, giving the Polipo near shirt-sleeve mobility. Nine subjects within the target population validated full range of motion was achieved. The wire patterning is shown in Table II.

The sensors were enclosed in a fabric attached to the ends of the wires, shown in Fig. 7. The sensor rests in the bed, but it not directly attached to it, preventing any strain or shear on the fabric to be transferred to the sensor, which would cause erroneous voltage readings. The top of the sensor bed has the sensor number heat pressed onto it.

The wiring limited the durability of the Polipo. Over time, as the wires flexed, stretched, and folded, the top fabric layer became delaminated. With each movement, friction on the wire’s surface degraded the copper strands. This effect can be seen in Fig. 6. Although low in resistance, copper fractures under repeated bending. The system was used under a variety of conditions of different durations and intensities, such as outside the space suit in fit trials and sensor testing or inside a space suit for long duration (more than 2 hours each) experiments. The earliest wire failure began after approximately 30 uses, while some remain intact after over 50 uses. The wiring was substantially deteriorated after the space suit experiments due to the length of the tests and large number of movements performed by the subjects [56].

C. Electronics Architecture

The custom electronics board, housing, and wiring input into the electronics are shown in Fig. 8. Each sensor consumes 2.5 mW, and with the microprocessor and data logging, the entire system consumes 500 mW. Changes in resistance of the sensor are measured as changes relative to the reference voltage. The amplified analog voltage is read by an Arduino Miro microprocessor (Turin, Italy), which collects up to 12 analog signals simultaneously. Data can be viewed either while tethered over USB or stored to a micro SD card. The system is powered with an alkaline 9 Volt battery, chosen for its safety and small profile for human applications, with an upper limit of 4.4 hours of untethered testing. The low profile box has an elastic belt that clips in the front of the subject’s waist to hold it securely in place.
and respiration, increase concern for electrical shock. Before along with additional moisture accumulation through sweat uses water to maintain body temperature. Potential leaks, emergency situation. The space suit’s liquid cooling garment confined to the space suit and cannot be removed easily in an emergency. The harsh nature of the environment inside the space suit posed additional concerns. The space suit is a pressurized, confined environment, with potential for temperature rise and increased risk of off-gassing and flammability. The electronic architecture must be designed to provide stable, reliable performance under these conditions.

D. Environmental Factors

Maintaining subject safety is the most important requirement for wearable electronic systems. The harsh nature of the environment inside the space suit posed additional concerns. The space suit is a pressurized, confined environment, potentially using a mixed gas atmosphere. This poses problems for materials off-gassing and flammability. Also, the subject is confined to the space suit and cannot be removed easily in an emergency situation. The space suit’s liquid cooling garment uses water to maintain body temperature. Potential leaks, along with additional moisture accumulation through sweat and respiration, increase concern for electrical shock. Before the human subject experiment, a full review was conducted in conjunction with engineers and managers at NASA Johnson Space Center. A hazard analysis and list of materials used in the sensor system was compiled. The hazards analyzed were: 1. Subject overheating, 2. General personnel injury, 3. Electrical shock, 4. Battery failure, 5. Subject-borne bulk, 6. Performing a Hammering Task, and 7. Loss of habitable environment. Each material, including the sensor elastomer and foam inserts used in the electronics box, was analyzed for potential off-gassing and stability. All potential hazards were mitigated to a NASA defined risk assessment code of 4 or higher, where each risk is considered “Acceptable with controls”.

IV. Discussion

The Polipo fulfills the need for a low-pressure sensing system with high mobility and less encumbrance from hardware and wires [14]–[16]. Previoulsy, in-suit sensing concepts have focused on traditional physiologic measures [41]–[43], [57], [58] or display and control information [44]–[47]. The sensors used in the Polipo build upon previous research [17], [18] to measure pressures normal to the body dynamically within the 5-60 kPa range. The sensor responds in real time and is highly repeatable, unlike other available technologies [20]–[25]. A discrete sensor architecture was chosen over a sensor mat configuration for simplicity and the ability to optimize sensor placement, another limitation seen in other commercially available systems [12], [15], [16]. Sensor sensitivity varies by sensor as measured in calibration. All sensors achieved pressure sensitivity of 1 kPa within, but not throughout, the targeted pressure sensing range.

The sensors are accurate when used under intended dynamic conditions, but are limited in their utility under static loading. As shown, this is due to creep as energy dissipates. As a result, the sensors exhibit hysteresis as well as drift at higher pressures, but is not as pronounced at lower pressures. When the sensors are loaded dynamically, their performance is greatly improved since the initial compression of the elastomer causes the first order signal response, and second order changes due to creep are only exhibited over time. Over the time scales of movements we evaluated experimentally (between 10-30 seconds [54]), the Polipo is has a RMSE of 3 kPa of the targeted response profile. The response of the elastomer can be thought of as a dashpot in a mechanical system model. With rapid fluctuation the response is dampened by the elastomer. However, with constant load, the elastomer will slowly reach a steady state response of minimum energy. Previous work on the sensors has modeled straight single-channel designs under rapid loading where the creep was minimized [17], [18]. An analytical model of the current channel design may not be possible, but future work includes developing finite element modeling of the sensor’s response to pressure that incorporates the effect of creep to improve channel designs and improve performance under static loading.

The primary limitation of the Polipo is the durability of the system’s wires. With the materials available, the wiring chosen was the best achievable design. Over time, however, the integrity of the wires deteriorates. Durability would have likely improved if the wires had been re-heat pressed after each use to prevent the material from delaminating. In future versions, the wires could be implemented in a different manner by using another material with less friction to isolate the wires, such as an elastomer. A better wiring solution with the same flexibility and low resistance but without the fracture characteristics of copper may be sought. The current system’s durability is acceptable for a baseline from which to iterate the design, but it is desirable to improve performance on this metric. An alternative design may include embedding wires into sensor channels for a more secure connection.

Future work also includes expanding the flexibility of the system for additional applications. Sensor size could be changed to characterize pressures over different areas of the body or to increase sensor density. The electronics architecture was sufficient for the purpose of this work, however if future iterations use more than 12 sensors, additional electronics must be added to consolidate and store the data from multiple sources. After using the sensors for a human subject experiment, it became clear that multiple versions of the Polipo would be useful to characterize pressures over different areas of the body or to increase sensor density over a particularly targeted region, potentially utilizing work done on distributed computing and data collection in a space suit environment to allow for sensor coverage over the entire body [48]–[50].
As with this version, future development should be mindful of the operational environment and remain a standalone system with limited electrical, material, and battery hazards. The contributions from this work have the potential to be used in other extreme working environments, such as for high altitude pilots wearing gas-pressurized suits with similar rigidity. Additionally, designs of soldier packs and armor would benefit from a similar analysis of encumbrance and pressure/force distribution over the body to optimize comfort and prevent injury [59], [60]. The capability may also be used in biomedical applications. Hip protection devices have obvious advantage in preventing lateral impact from falls for the elderly [61]. Unfortunately, effectiveness is contingent upon patient compliance to wear the device, which is typically low [61], [62]. Evaluating the comfort and wearability of protective devices with the Polipo may improve compliance, decreasing mortality and morbidity rates of hip injuries.

V. CONCLUSION

The wearable Polipo pressure sensing system directly quantifies interaction between the person and the space suit, revealing interface pressures underneath the soft goods of gas pressurized space suits for the first time. This allows us to move beyond external visual measures, such as motion capture and cinematography. It is used for dynamic upper-body motions to measure pressures in the 5-60 kPa range in the confined environment of the space suit, which imposes extreme conditions for implementing wearable electronics. The system has a sensitivity of less than 1 kPa within the designed pressure range, and it is accurate to within 3 kPa root mean square error when dynamically loaded. It is conformal on the body and can be transferred to different subjects easily as a stand-alone system. The Polipo may be worn by subjects in the 50th percentile female to 95th percentile male population for upper body dimensions from the ANSUR database. It was designed for applications requiring high mobility and safety. Its use could be further extended to any field where humans wear protective hardware, such as evaluating the design of hip protectors for the elderly or personal protection for soldiers.

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