Hybrid carbon fiber-textile compliant force sensors for high-load sensing in soft exosuits

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***Abstract*—Wearable robotic systems which aid or enhance human performance are the subject of substantial ongoing research efforts. Soft exosuits to assist with walking represent one class of system that leverage textiles and apparel to provide a lightweight and nonrestrictive means to interface to the lower extremity and apply assistive joint torques via a cable that applies a force across a biological joint. Current embodiments of the soft exosuit use off-the-shelf load cells attached to the distal end of a Bowden cable to measure and control the delivered force. As these systems evolve, we envision replacing all rigid components with compliant, textile-based components. Here we present a new force sensing concept suitable for exosuit applications. The approach is based on micro-machined carbon fiber composite structures encapsulated in elastomer materials as the transducer element, and high-strength, stiff textiles as the load bearing element. The transduction mechanism uses the Poisson effect in the encapsulating elastomer to create electrical contact between the carbon fiber structures. This method allows the sensor to be sensitive in tension while remaining insensitive to bending deformation. We fabricate a prototype sensor capable of detected forces up to 300 N, yet weighing just 2.15 g. The compliant nature of the materials used in fabrication allow the sensor to be flexible. The sensor output is qualitatively very repeatable, yet exhibits moderate drift at peak load. However this drift begins to stabilize over the test duration. These preliminary results demonstrate the promising potential of this sensor technology for soft exosuit systems.**

***Index Terms*—Force and Tactile Sensing; Wearable Robots; Soft Material Robotics.**

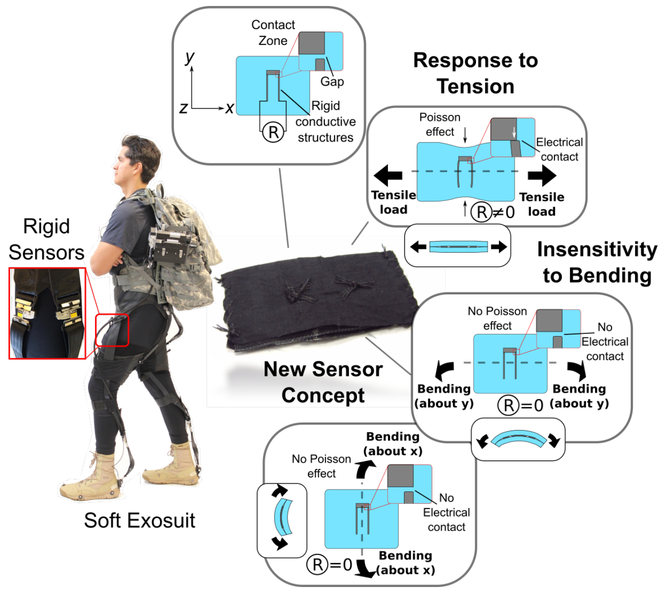


Fig. 1. Photograph of a soft exosuit system being developed at the Biodesign laboratory at Harvard University [1] (left) (inset image showing force sensors used in the exosuit), and the new force sensor presented in this work (right). The concept involves a rigid conductor encapsulated in an elastomer material, and uses the Poisson effect to bring about changes in contact resistance between the rigid structures. The approach is insensitive to bending deformations as they do not generate a substantial Poisson effect.

I. Introduction

The development of lower-limb assistive robotic devices to aid locomotion has gained significant research attention in recent years. These systems have been used to improve load carrying capabilities [2], [3], or to help restore regular walking patterns in individuals with a walking impairment [4]. Traditionally these systems are composed primarily of rigid structures, which present various practical challenges in terms of system mass, alignment to the body and user comfort.

Recently, alternatives to rigid exoskeletons have emerged in the form of soft robotic exosuits, such as the system developed by the Biodesign laboratory at Harvard University [1], [5] (see Figure 1). These systems couple to the body in a compliant manner using textiles designed to effectively and comfortably apply torques to the joints of the body. Moreover, the use of textiles enables the suit to be lightweight, allowing much of suit mass to placed proximally, rather than distally, relative to the user's center of mass. This approach can help to minimize metabolic expenditure [6].

Current embodiments of the soft exosuit have used off-the-shelf load cells attached to the distal end of the Bowden cable and the apparel body anchor to measure and control the delivered force (up to 300 N) (Figure 1-*left*). The current load cells do not sustain bending or torsion loading, and thus need to be carefully mounted and integrated to ensure accurate readings and robust operation. The load cell itself, and related mounting components are rigid and our long term goal is to have all of these replaced with fully soft and flexible components; having clear benefits for system integration, cost and potentially user comfort.

In the literature, several flexible and stretchable sensor designs exist for the detection of mechanical stimuli, including; those based on dielectric elastomers [7], [8], [9], functionalized textiles [10] and polymers loaded or coated with conductive materials [11], [12], [13]. However, to create an effective force sensor the sensor stiffness should ideally be very high in order to efficiently transmit the high loads imposed by the exosuit actuators. The sensors mentioned could be combined with stiff materials placed mechanically in parallel in order to achieve this, but many of the aforementioned sensors are optimized for high strains (> 20 %) and would suffer from poor resolution at lower strains. Moreover, many of these sensor designs are sensitive to off-axis loading, such as bending or normal pressure, making them more susceptible to mechanically induced noise.

Here we present a compliant, force sensor concept for integration into soft exosuits. The sensor is a hybrid of two main elements; a transducing element, composed of micromachined carbon fiber composite structures encapsulated in elastomeric films, and a load bearing element, made of stiff, high-strength textiles. In our sensor design, changes in electrical resistance between the carbon fiber composite structures are generated by tensile loads in the encapsulating material. By taking advantage of the mechanical properties of the encapsulating material, namely material incompressibility, the transducing element can be made sensitive to tensile loading, while being insensitive to bending. This is in contrast to other compliant sensor concepts [9], [8], which remain sensitive to deformations in multiple axes. The use of carbon fiber, elastomer and textiles enables the sensor technology to be extremely lightweight, which is important for wearable robotic systems. The use of stiff textiles allows for the detection of high loads with minimal sensor deformation (less than 5% in the work presented here), while allowing the sensor to remain flexible and compliant. This helps to maintain a high exosuit stiffness and reduce the demand on the exosuit actuators.

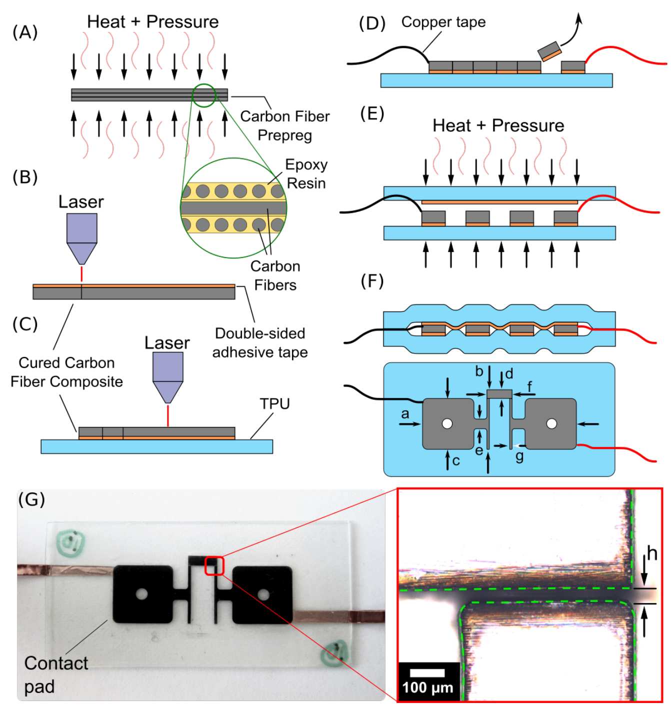
The structure of this paper is as follows: the transducer operating principle is described in detail in Section II. Section III describes the fabrication and characterization of the transducer element and a prototype hybrid sensor. The results are discussed in section IV and the conclusions provided in section V.

II. Transduction Mechanism

The transduction mechanism for our sensor concept is based on the change in contact electrical resistance of stiff yet flexible conducting structures in the shape of an upside down letter "U", with the two parallel spar sections separated from the longitudinal section by a small gap (see Figure 1-*right* and Figure 2(G)). The rigid materials are sandwiched between two elastomer films to fix their positions relative to each other. The application of tensile loads along the length axis (that is, the x-axis in Figure 1-*right*) cause contraction of the encapsulating material in the orthogonal in-plane direction, due to the Poisson effect. The orthogonal contraction is heightened due to the constraint imposed by the rigid conductor and the use of elastomeric (i.e. incompressible) materials. The in-plane contraction reduces the gap between the three carbon fiber sections until they eventually come into electrical contact. This change in electrical resistance can be detected by measuring the electrical resistance across the two parallel sections of the "U".

This transduction mechanism makes the sensor inherently insensitive to bending deformations as bending about the in-plane axes generates a net zero in-plane strain in the x-direction, and therefore zero in-plane contraction in the y-direction (Figure 1-*right*).

Compressive loads on the surface of the sensor (i.e. along the z-axis) have a mostly negligible effect on the sensor resistance, as the carbon composite structure constrains deformation of the sensor, resulting in bulging deformation in the encapsulating material rather than in-plane strain.



(H)

Dimension label	Value
a	30 mm
b	12 mm
c	10 mm
d	2 mm
e	2 mm
f	5 mm
g	500 µm
h	40 µm

Fig. 2. Schematic representation of the transducer fabrication process. (A) Carbon fiber composite lay-up fabrication. (B) Placing of double-sided adhesive and laser machining in the shape of a rectangle. (C) Adhering of carbon fiber to a TPU layer and machining of transducer geometry. (D) Removal of excess carbon fiber and placing of electrical connections using copper tape. (E) Placing of top TPU layer and application heat and pressure to bond. (F) Finished sensor, dimensions labeled. (G) Photograph of fabricated sensor, inset shows separation gap. (H) Table summarizing the dimensions of the carbon structure, as labeled in (F).

III. Experimental Characterization

A. Transducer fabrication

Carbon fiber composites are an excellent engineering material due to their high-strength, and low-mass. Moreover, when fabricated in a thin form factors, they can be made extremely flexible. Though carbon fiber composites are utilized extensively for structural design, they are seldom investigated for transduction (though other forms of carbon are used often in sensor designs). Carbon fiber composites are also relatively elastic, being less susceptible to plastic deformation than other conductors, such as metals. Here we use carbon fiber composites as the stiff conducting element.

We use thermoplastic polyurethane (TPU) (by American Polyfilm Inc.) as the encapsulating material due its expediency in fabrication, requiring only a few seconds to form an encapsulation. The use of a thermoplastic elastomer also ensures that the gap between the carbon fiber elements is not blocked, which could be a concern if elastomers which are liquid in the pre-cured state are used. The double-sided adhesive layer is used because of the inherently low adhesion between the carbon fiber composite and the TPU.

The carbon fiber composite is made by laying-up three layers of carbon fibers pre-impregnated with an epoxy resin (Toho Tenax, by Teijin). The three layers are laid perpendicular to each other, as depicted in Figure 2(A). This perpendicular stacking helps to maintain the flatness of the composite by minimizing thermally induced buckling. The carbon fiber composite lay-up is subsequently placed in a heat press and is cured using the manufacture's recommended pressure and heat profiles. The cured carbon fiber is machined and encapsulated using the following procedure:

1) The carbon fiber composite is backed with a 5 µm thin double-sided adhesive (82600, by 3M) and rectangular sections of the carbon fiber are cut to dimensions slightly larger than the bounding dimensions of the transducer.
2) The rectangular carbon fiber section is bonded to the TPU film substrate using the thin adhesive (Figure 2(B)).
3) The transducer geometry is micro-machined into the carbon fiber using a diode-pumped solid-state laser (by Oxford Lasers), and the excess material peeled away (Figure 2(C)).
4) Electrical contacts are made to the sensor using conductive copper tape (Figure 2(C)), and a second TPU layer is placed on top of carbon fiber structures using a second double-sided adhesive layer.
5) The two elastomer layers are bonded together using a heat and temperature controlled press for 15 seconds at 150 °C and 345 kPa (50 psi) (Figure 2(E)), fixing the sensor geometry in place (Figure 2(F)).

The resulting transducer is shown in Figure 2(G) and its dimensions are summarized in the table shown in Figure 2(H). The carbon fiber structure geometry is chosen as the result of a pre-characterization study where the gap spacing, parallel spar width and length were varied. The design and dimensions presented were found to be the most favorable in terms of repeatability of manufacture, repeatability of response and compactness. Square contact pads are incorporated into the spars of the carbon fiber structures to facilitate electrical connection and mechanical fixing. The thickness of the cured carbon fiber was measured to be 90 µm and the electrical sheet resistance measured to be approximately 8 $\Omega/\square$ (electrical resistivity $7.4 \times 10^{-4}\Omega$m). The Young's modulus of the carbon fiber was measured to be 32 GPA.

B. Transducer characterization

The transducer design is characterized in an Instron mechanical tester (model 5544A). Pneumatic grips clamp the transducer at the holes of the rectangular contact pads, as schematically depicted in Figure 3(A). The transducer is cycled between a load of 0.5 N and 5 N, at a rate of 0.05 mm/s for 50 test cycles. A logarithmic current amplifier circuit (EVAL LOG114, Analogue Devices) is used to measure the transducer resistance. The logarithmic amplifier measures the current I passing through the sensor (detection range 50 mA - 100 nA) for a fixed input voltage V_{in}, and outputs a voltage V_{out} proportional to the log of the current. The resistance value is derived from the current using Ohm's law i.e. $R = V_{in}/I$. Due to electrical noise in the circuit, resistance values are capped at $10^7\ \Omega$ (i.e. values $\geq 10^7\ \Omega$ are made equal to $10^7\ \Omega$). The transducer output is synchronized with the Instron displacement and force measurement via a National Instruments DAQ (model BNC-2111).

Figure 3(C) show that, qualitatively, the sensor response is highly repeatable over the 50 test cycles. The sensor reading also transitions from being insulating to conducting with resistance values < 100 Ω for relative of strains < 3% (relative to the initial spacing of the Instron grips = 20 mm). The small deflections exhibited by the transducer are further highlighted by the microscope images in Figure 3(B). The baseline strain increases over the course of the test due to hysteresis in the TPU encapsulation. However, this does not significantly affect the transducer output, we therefore conclude that the transduction mechanism is predominately governed by the stresses experienced in the transducer rather than the applied strain.

A close-up of the last 3 test cycles is shown in Figure 3(C) and shows three distinct transduction phases: Phase 1 - no electrical contact due to the initial separation gap, Phase 2 - the carbon structures initially come into contact with each other, characterized by a steep decrease in electrical resistance, and Phase 3 - contact pressure mediated electrical conduction, where the in-plane lateral compressive stress in the transducer (resulting from the Poisson effect) determines the degree of conductivity, and is characterized by a less steep gradient. Phase 3 of the transduction curve is considered the usable working range of the transducer due to its relative size and approximately linear characteristic. The position and size of Phase 3 for any given therefore transducer determines the sensor range and the offset.

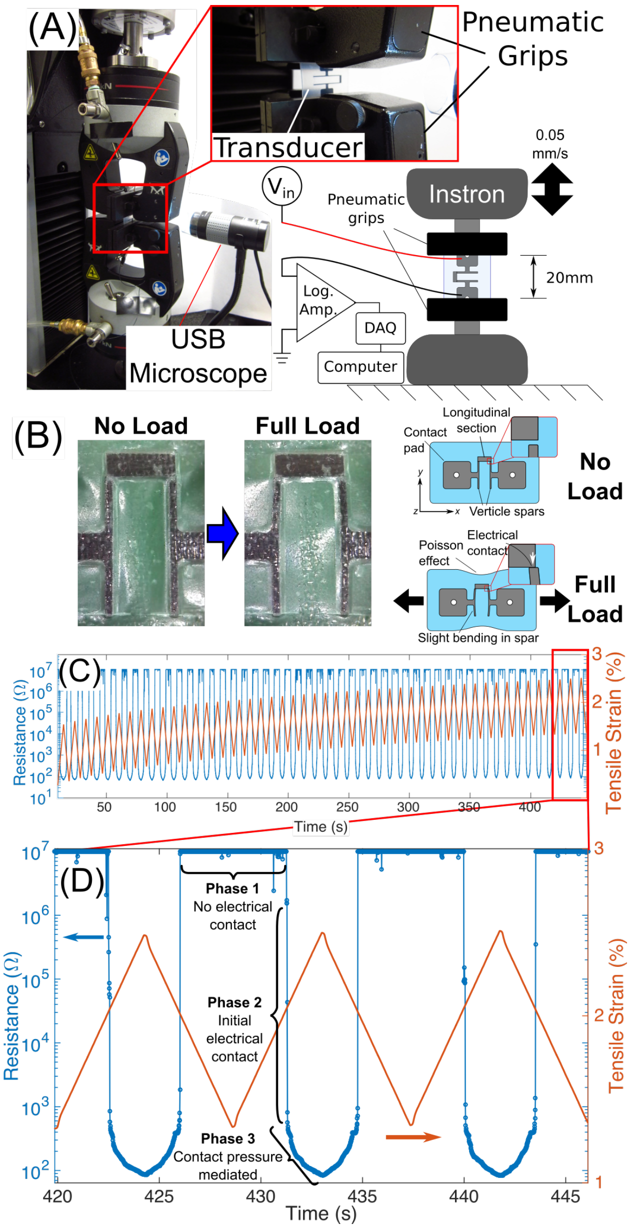


Fig. 3. (A) Experimental set-up used for transducer characterization. (B) Microscope images of a transducer in the no-load and loaded case. Schematic representation shown to the right highlights important features. (C) Resistance and tensile strain vs. time for a 50 cycle tensile extension test. (D) Close-up of the last 3 cycles of the tensile test, three distinct phases in the transduction curve can be seen: Phase 1 - no electrical conduction, Phase 2 - Initial contact of the carbon fiber structures leading to steep decrease in electrical resistance, Phase 3 - further decrease in electrical resistance mediated by contact pressure.

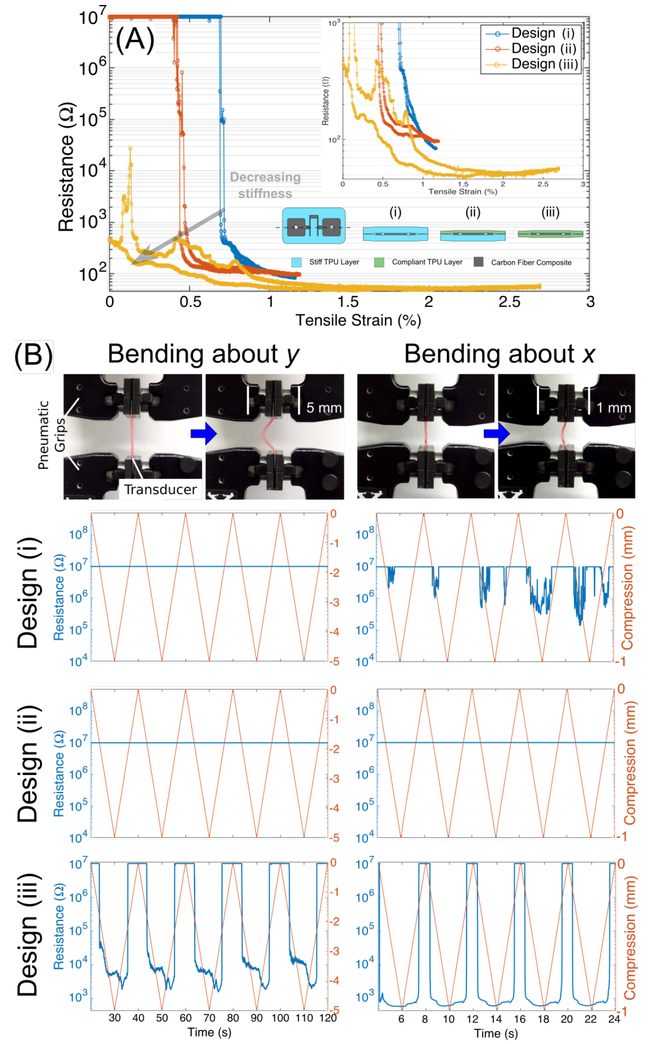


Fig. 4. Characterization of transducer resistance as a function of encapsulation stiffness. (A) Transducer resistance vs. strain for various encapsulation stiffnesses; Design (i) using two stiff TPU layers on both sides, Design (ii) using one stiff TPU layer and one layer four times more compliant, Design (iii) using two less stiff TPU layers on both sides. Inset figure depicts schematically the different transducer designs). (B) Response of the transducers to bending about y- (left) and x- (right) axes. Photographs of bending deformation shown at the top of the subfigure (transducers highlighted in red).

The response of the transducer to the stiffness of the encapsulation material is investigated and the results shown in Figure 4. TPU materials with two different stiffnesses are used as the encapsulation materials, Design (i) uses two TPU layers having a stiffness of approximately 2 kN/m, Design (ii) uses one TPU layer with a stiffness of 2 kN/m and one which is approximately four times less stiff (540 N/m), and Design (iii) uses two layers of the less stiff TPU (depicted schematically in the inset of Figure 4(A)). Figure 4(A) plots the transducers output against strain for the last test cycle and shows a decrease in the gradient of Phase 3 of transduction curve for decreasing encapsulation stiffness, resulting in a decreased sensor offset. The length of Phase 1 also decreases with decreasing encapsulation stiffness, and in device (iii) (the least stiff) it disappears altogether. This is due thermal shrinkage being greater in the TPU material with lower stiffness, therefore bringing into contact the carbon fiber structures during the heat press process.

The response of the transducers to bending deformation is also investigated. Bending is induced in the transducers by subjecting them to a compressive displacement using the Instron mechanical tester (5 mm compression for bending about the y-axis, and 1 mm for bending about the x-axis) (Figure 4(B)). This causes them to bend out-of-plane due to their low profile shape. The transducers are clamped approximately 15 mm from the center of the transducer for bending about the y-axis, and approximately 10 mm from the center of the transducer for bending about the x-axis. In both cases, the transducer is clamped at a region without carbon fiber, enabling it bend relatively freely.

Figure 4(B) also shows the results of the bending test. Designs (i) and (ii) show little or no response to bending about the x- or y- axis, with the exception of Design (i), which shows some response to bending about the x axis. This may be the result of inconsistencies in the transducer fabrication. Design (iii), on the other hand, shows significant response to bending about both the x- and y-axis. This is the result of the low-stiffness encapsulation, which buckles rather than bends under the compressive load, thereby allowing the carbon fiber structures to come into contact. Hence, for resilience to bending deformations, transducers using stiffer encapsulations are preferable.

C. Textile integration and prototype characterization

A prototype hybrid force sensor is fabricated by combining high-strength textiles with a transducer element. The textile chosen is a fiber-reinforced, sail cloth (model R/I-306800, by Dimension-Polyant Inc.). This material is extremely strong and stiff, possessing a stiffness of 500 N/mm, and yet lightweight and having low hysteresis properties, as seen in the material stress-strain profile (Figure 5(B)).

The transducer is integrated into the textile using the following procedure: TPU coated woven textiles are first bonded to the transducer element, leaving the central transducer region (the region where electrical contact is made) un-bonded. A 30 mm by 55 mm section of sail cloth is sewn onto the transducer and TPU coated textile using high-strength thread. The resulting sensor weighs 2.15 g including the electrical connections, and demonstrates a high degree of flexibility (Figure 5(A)).

The hybrid force sensor is characterized in the Instron mechanical tester, using the procedure and equipment outlined in section III-B. The Instron was cycled between 3 N - 300N, which is approximately the range of forces applied by the soft exosuit presented in [1]. A transducer using the stiffest encapsulation design (i.e. Design (i) from section III-B - having two of the stiffer TPU layers). Figure 5(C) - (E) show the results of the characterization. Figure 5(B) shows the sensor response of the last three test cycles (of a total of 50), once again showing qualitatively a very repeatable response. In particular, the characteristic three phase transduction behavior described in section III-B is retained, despite the integration of the textile layer. The sensor offset, i.e. where Phase 3 begins, is approximately 50 N. The Figure also shows that the load is approximately linear with the log of the sensor

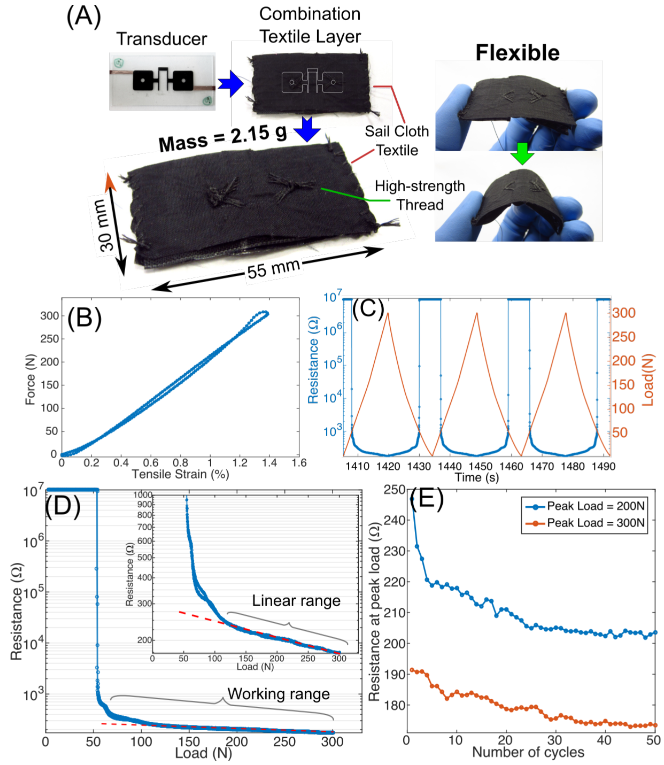


Fig. 5. Hybrid force sensor prototype. (A) Integration of textile layer on to a transducer to create the hybrid sensor. The resulting sensor is compact and lightweight, weighing only 2.15 g (B) Stress-strain characteristic of the sail cloth textile used to make the sensor. (C) Last 3 cycles of a 50 cycle tensile test showing sensor resistance and sensor strain vs. time. (D) Sensor resistance vs. load for the last cycle of the 50 cycle test (inset figure shows close-up of the region between 0 - 1 kΩ). A linear regime can be seen in the region between 150 N - 300 N, as highlighted by the red dashed line. (E) The sensor resistance at peak load for all 50 cycles for a 200 N and 300 N peak force cyclic test.

resistance in the region from 150 N - 300 N (as indicated by the red dashed line in Figure 5(D).

IV. Discussion

The prototype hybrid sensor constructed is shown to be able to detect loads up to 300 N, though the sensor itself weighs just over 2 g. Also, the transducer design means inherent stability of the baseline sensor signal as initially there is no electrical connection between the carbon fiber elements. This is, however, at the cost of a reduced sensor working range. To improve this, the separation gap can be reduced, however the fabrication procedure would need to be sufficiently optimized in order to control repeatability of gap separation and maintain bending insensitivity.

The resistance value of the hybrid sensor at peak load is plotted in Figure 5(E) as a function of the cycle number, and is used as a quantitative indicator of the sensor signal drift. The sensor resistance at a peak load of 200 N (an experiment which was conducted prior to the 300 N peak load experiment) is also plotted for comparison. The Figure shows that though there is some drift in the resistance at peak load, the sensor signal begins to stabilize over the test duration.

Moreover, the drift appears to be related to the peak force the sensor has previously seen, as indicated in Figure 5(E). That is, when the sensor was tested with a peak load of 200 N, the sensor began to stabilize by 50 cycles, but when the peak load was increased, the sensor once again drifted and began to stabilize after 50 cycles. This behavior is most likely due to the hierarchical structure of the load bearing textile. Though having a high stiffness, it is susceptible to small permanent deformations due to its woven structure. This indicates that cycling the sensor at loads higher than those expected in application prior to use will improve signal stability. Another method for improving signal stability would be to use a stiffer textile layer, either by adding additional layers, or by increasing the layer width. This would limit the maximum strain the textile layer sees in operation, thereby minimizing the permanent deformation. It is important to note, however, that this approach may come at the cost of sensor resolution.

In future work the sensing range could be increased by adding a small amount of slack into the sail cloth textile prior to integration with the transducer, shifting the position along the transducer curve at which the load begins to be borne by the textile. This may also help to improve the linearity of the sensor over a wider load range. Though the sensing resolution in the Phase 3 region of the sensor is very reasonable (49 Ohms change over 150 N), the resolution in future sensing designs could be further improved by altering the geometry at the interface of the carbon fiber structures. For example by slanting the edges of the vertical spars so that they are no longer parallel to the longitudinal section, thereby causing a change in the contact area simultaneously with the change in contact pressure. Furthermore, the development of analytical or numerical models which capture the electromechanics of the contact process could facilitate the design of transducers with a wide variety of transduction behaviors, in order to more easily adapt to the requirements of any application.

V. Conclusions

Achieving sensing of high loads in a compliant, mechanically resilient manner is a challenge for the burgeoning field of soft exosuits. Here, we present a novel force sensor solution to meet this need. The force sensor is a hybrid of micromachined carbon fiber composite structures encapsulated in elastomeric materials (the transducing element), and high-strength, high-stiffness textiles (the load bearing element). When the transducing elements are loaded in tension, the Poisson's effect in the elastomer cause in-plane contraction in the orthogonal dimension, bringing the carbon fiber structures into electrical contact. The resistance of the sensor is mediated by the contact pressure. This mechanism insures that the transducer element remains insensitive to bending. A prototype hybrid force sensor is fabricated by combining the transducer element with the high-strength textile, and is capable of detecting loads of up to 300 N, while weighing just 2.15 g. The sensor is compliant and can be conveniently integrated into textile-based soft exosuits. The sensor signal shows an initial drift, which is assumed to be due to the hierarchical structure of the textile, but begins to stabilize over the test duration. The developed prototype shows the promising potential of our sensing approach for use in soft exosuits.

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