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# Stretchable bifilar coils for soft adhesion and sensing

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## HIGHLIGHTS

- A new manufacturing solution to multi-functional, scalable, stretchable, planar bifilar composite coils is presented.
- A liquid-metal-elastomer based, morphologically adaptive electroadhesive is demonstrated.
- A multimodal, soft sensor capable of resistive, capacitive, and inductive sensing is demonstrated.

## GRAPHICAL ABSTRACT
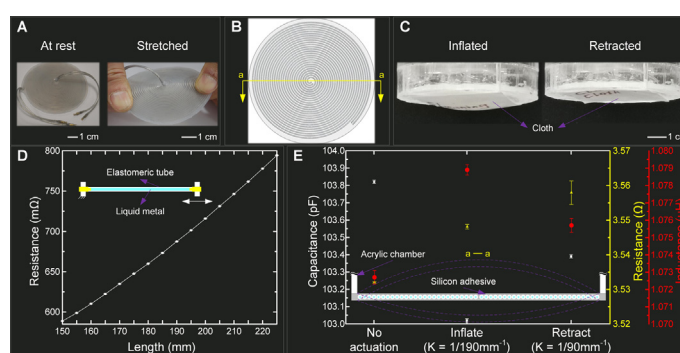
## ABSTRACT

It is desirable to equip soft-smart materials and structures with actuation, sensing, and adhesion functionalities. A multifunctional stretchable bifilar coil capable of soft adhesion and sensing is presented in this work. The fully-soft flat bifilar coil, based on the Tesla coil design, can be fabricated by encapsulating a cost-effective, easy-to-implement, and scalable liquid-metal-elastomer-tube in a soft planar composite. By combining pneumatic actuation of the soft coil with application of a high voltage across the two electrodes, a morphologically adaptive and soft electroadhesive is demonstrated and can be used to lift lightweight and flexible textiles from curved surfaces. At the same time, capacitive, resistive, and inductive sensing functionalities can be achieved by interrogating the bifilar coil. This stretchable bifilar coil has the potential to enable soft multimodal adhesives such as entirely-soft electro-magneto adhesives with incorporated soft resistive, capacitive, and inductive sensing for soft robotics and implantable devices.

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Soft machines, made of soft-smart materials and structures, have been supplementing, extending, augmenting, and replacing conventional hard counterparts [1]. This is because soft devices have intrinsic compliance-matching and biocompatibility capabilities [2] that could enable them to have safer interactions with human beings and natural

environments, and better resilience and adaptability to changing conditions [3]. Integrating soft-smart materials and structures with multimodal sensing, morphologically adaptive actuation, and versatile gripping functionalities has the potential to endow soft-smart end effectors, an important application of soft robotics and machines, with the capability to intelligently and safely lift difficult-to-handle and delicate materials. Prior examples include an ionic polymer metal composite microgripper [4], a dielectric elastomer minimum energy structure

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gripper [5], and a pneumatically actuated visio-tactile sensory end-effector [6], but these all suffer from fabrication complexity or limited capabilities.

In this paper, the first multifunctional, stretchable, planar bifilar coil, a new soft-smart composite gripper, capable of soft adhesion and sensing is reported (see Fig. 1A). Fabrication of this all-soft flat bifilar coil, inspired by the Tesla bifilar coil design, includes four major steps. Firstly, two silicon tubes, with inner diameter 0.4 mm, wall thickness of 0.3 mm, and length 1300 mm (Hilltop Products Ltd., UK), were cleaned with acetone (Sigma-Aldrich, USA). Secondly, Galinstan liquid metal (composed of 68.5% Gallium, 21.5% Indium, and 10.0% Tin) was injected into the two tubes. This eutectic liquid alloy has low melting point ($-19$ °C), low viscosity ($2.4 \times 10^{-3}$ Pa·s), high deformability, low toxicity, and high electrical conductivity ($3.5 \times 10^6$ S·m$^{-1}$) [7,8]. Four gold-plated metal pins were inserted into the tube ends for electrical connections. A one-component silicon rubber adhesive (curing time of 12 min, Sil-Poxy™, Smooth-On Inc., USA) was used to seal the metal pins to the tubes. Thirdly, two acrylic plates were laser cut to aid the winding of the concentric coil (see Fig. 1B). One was coated with double-sided tapes so that the two Galinstan-silicone tubes can be adhered onto the plate. The two Galinstan-silicone composite tubes were then wound in parallel and concentrically outwards from the center into a planar bifilar coil shape. The silicon adhesive was then cast evenly on top of the wound coil and a second acrylic plate was pressed onto the coil to produce a smooth coating surface. After curing, the coil was peeled from the double-sided tape. The silicon adhesive coating process was repeated on the second side of the coil. The silicone rubber adhesive can optionally be thinned with silicone oils to produce a softer coil composite. Finally, after the coil was fully cured, any silicone excess was trimmed, yielding a bifilar coil with an outside diameter of 30 mm. The perimeter of the planar composite coil was then bonded to an acrylic chamber (see Fig. 1C). For more compact and softer coils, one can also use custom-made elastomeric tubes [9]. Using off-the-shelf silicone tubing, this work provides a new, cost-effective, easy-to-implement, scalable, and planar liquid-metal-elastomer-tube composite for integrated soft actuation, sensing, and gripping [10] applications.

Soft adhesion is defined as integrating conventional adhesion technologies with soft materials and structures. Making adhesion technologies in a soft state is desirable for them to seamlessly merge into soft

robotics applications. These include stretchable electroadhesion which has been used for various soft gripping and active adhesion applications [6]. A voltage of 5 kV was applied, using a high voltage amplifier (E60, EMCO High Voltage Corporation, USA), across the two electrodes of the bifilar composite coil, inducing electroadhesive forces to adhere to and lift soft materials such as a cleaning cloth (see Fig. 1C). The surface of the coil can be dynamically adapted to match concave and convex surfaces by increasing or decreasing the internal pressure of the chamber. Pneumatically actuating the soft coil, with simultaneous application of a high voltage across the two electrodes, offers a morphologically adaptive and soft electroadhesive that can be used to lift a range of light-weight and flexible textiles from a wide variety of surfaces.

Soft sensing capabilities such as soft resistive, capacitive, and inductive functionalities can be integrated into soft actuators and soft adhesion systems to provide sensory feedback for autonomy and closed-loop control. These include liquid-metal-elastomer based sensors that can be used to enable multimodal soft sensing capabilities. The resistance change of a single liquid-metal-elastomer tube via an LCR meter (E4980AL, Keysight Technologies, USA) was firstly characterized when stretching it from an original length of 150 mm to 225 mm (beyond which plastic deformations occurs) using a linear rail (X-LSQ150B-E01, Zaber Technologies Inc., USA). An approximately linear relationship was obtained, with a relative resistance increase of 34.94% when the tube was stretched by 50% (see Fig. 1D). The capacitance (under 1 V and 1 kHz), resistance, and inductance (under 1 V and 10 kHz) change in the soft bifilar coil composite were then measured via the LCR meter when the coil was flat, and pneumatically inflated and retracted to a curvature (K) of 1/190 mm$^{-1}$ and 1/90 mm$^{-1}$ respectively, as measured by a laser displacement sensor (LK-G3001, Keyence, Japan). All tests were conducted in air and at room temperature. The resistance and inductance of the coil were measured when the two electrodes were connected in series, the same with the Tesla's bifilar coil configuration, whereas the capacitance was measured when the two electrodes were disconnected. The capacitance of the composite decreased when deforming the coil, whereas the resistance and inductance increased, indicating that the coil can be used as soft proprioceptive sensors for soft fluidic actuators (see Fig. 1E).

In this work, a new, low-cost, easy-to-implement, scalable, stretchable, and planar bifilar coil composite has been presented. In addition,
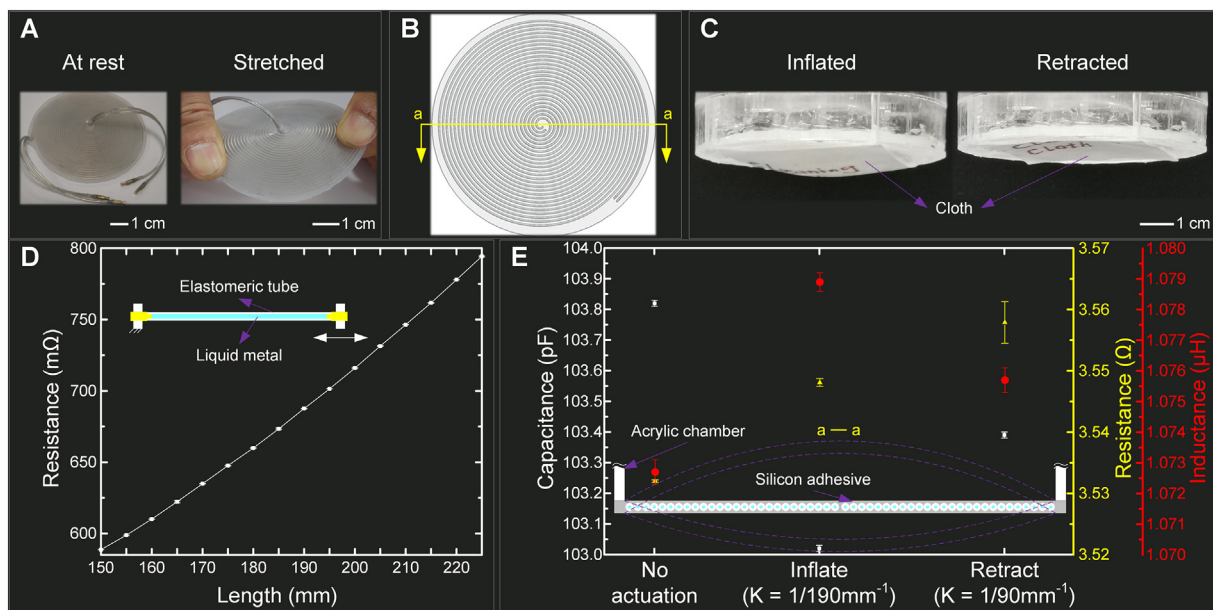


**Fig. 1.** (A) A stretchable Tesla bifilar coil composite at rest and under stretch by hand. (B) Device schematic design. (C) A shape-changing bifilar coil composite electroadhesive gripper under pneumatic inflation and retraction. (D) Relationship between resistance and stretching length of a liquid-metal-elastomer-tube composite. (E) Capacitive, resistive, and inductive sensing demonstrations of the coil under pneumatic actuations.

the multi-functionality (i.e., soft adhesion and sensing) of the composite coil has been demonstrated. Stretchable bifilar coils have the potential to deliver soft, multimodal, and active adhesives including all-soft electro-magneto grippers and fully-soft, multimodal (resistive, capacitive, and inductive) sensors for soft robotics applications. Furthermore, soft planar bifilar coils are promising candidates for low-profile actuators and implantable sensors for medical devices.

## CRediT authorship contribution statement

**Jianglong Guo:** Conceptualization, Data curation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Jonathan Rossiter:** Funding acquisition, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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