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(54) **Title:** SOFT SENSOR FIBER AND METHOD OF MAKING A SOFT SENSOR FIBER

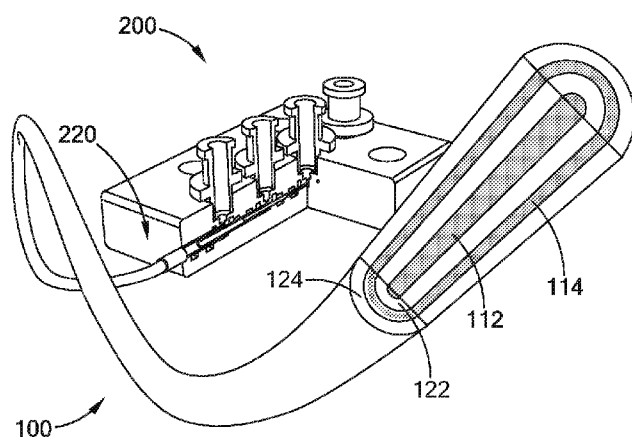


FIGURE 1A

(57) **Abstract:** A soft sensor fiber includes a core conductor surrounded by a dielectric layer, an outer conductor layer and an encapsulation layer. The two conductive layers can be separated by the dielectric layer forming a cylindrical capacitor with resistive electrodes capable sensing strain as function of capacitance, resistance and decay time. The dielectric layer and encapsulation layer can include an elastomer material capable of enduring strains of 250% or more. The core conductor and the outer conductor layer can include a viscoelastic liquid that can include a solvent, an ion source and a thixotropic agent. The soft sensor fiber can be formed by extruding all four layers together to form a four layer fiber having two conductive layers and two insulating or dielectric layers. The soft sensor fiber can be fabricated by a 3D printing process that includes extruding the fiber onto a moving stage.

SOFT SENSOR FIBER AND METHOD OF MAKING A SOFT SENSOR FIBER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present patent document claims priority under 35 U.S.C §119(e) to U.S. Provisional Patent Application No. 62/031,496, filed July 31, 2014, and which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with government support under grant no. DMR-1305284 awarded by the National Science Foundation. The government has certain rights in the invention.

TECHNICAL FIELD OF THE INVENTION

[0003] The present invention is directed to soft, highly elastic sensors that may be useful for soft robotic devices and wearable devices. More specifically, the present invention is directed to a capacitive and resistive sensor that can be embodied in a fiber capable measuring strains of 250% or more.

BACKGROUND

[0004] Soft sensing devices and wearable robotics provide tremendous potential for interfacing directly with humans and enabling human-like operation in various local and remote environments. Applications for interfacing with humans include the areas of prosthetics and rehabilitation devices. Applications that require human like manipulation of objects without human presence include space missions, factory automation and dangerous or hazardous environments. Furthermore, many industries, such as the food industry, still rely on a significant amount of human handling and could benefit from systems that provide human-like manipulation, such as for example, a system that could pick and place delicate objects like eggs or fruit. It is desirable for a system designed for these applications to have proprioceptive and tactile feedback like humans have. Sensors that can detect strains, pressure and/or shear forces can enable a system to perceive human like proprioceptive and

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tactile information. The mechanical properties of these sensors in terms of stretchability and Young's modulus can match or exceed that of human skin, a stretchability of 100% or more, if joint angles are to be measured.

SUMMARY

[0005] Described herein are a soft sensor fiber, a device adapted for producing a soft sensor fiber, and a method of making a soft sensor fiber.

[0006] The soft sensor fiber comprises a core conductor surrounded by a dielectric layer, an outer conductor layer and an encapsulation layer. The dielectric layer and encapsulation layers include an elastomeric material and the core conductor and the outer conductor layer include a conductive liquid material.

[0007] The device adapted for producing a soft sensor fiber comprises an extrusion head having a manifold adapted to: direct the flow of a first viscoelastic conductor material to a first extrusion tube, whereby the first viscoelastic material flows through the first extrusion tube; direct the flow of a first uncured dielectric material to a second extrusion tube, whereby the first uncured dielectric material flows through the second extrusion tube; direct the flow of a second viscoelastic conductor material to a third extrusion tube, whereby the second viscoelastic material flows through the third extrusion tube; and direct the flow of a second uncured dielectric material to a fourth extrusion tube, whereby the second uncured dielectric material flows through the fourth extrusion tube. The fourth extrusion tube is aligned with and overlies the third extrusion tube, the third extrusion tube is aligned with and overlies the second extrusion tube, and the second extrusion tube is aligned with and overlies the first extrusion tube, whereby the first uncured dielectric material flows around and encloses the first viscoelastic conductor material, the second viscoelastic conductor material flows around and encloses the first uncured dielectric material and the second uncured dielectric material flows around and encloses the second viscoelastic conductor material.

[0008] The method of making a soft sensor fiber comprises flowing a first viscoelastic conductor material through a first extrusion tube; flowing a first uncured dielectric material through a second extrusion tube overlying the first extrusion tube,

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the first uncured dielectric material flowing around and enclosing the first viscoelastic conductor material; flowing a second viscoelastic conductor material through a third extrusion tube overlying the second extrusion tube, the second viscoelastic conductor material flowing around and enclosing the first uncured dielectric material; and flowing a second uncured dielectric material through a fourth extrusion tube overlying the third extrusion tube, the second uncured dielectric material flowing around and enclosing the second viscoelastic conductor material. A soft sensor fiber comprising a core conductor surrounded by a dielectric layer, an outer conductor layer and an encapsulation layer is thereby formed.

[0009] The present disclosure is directed to a soft sensor fiber that can measure axial or elongational strains of 250% or more. The soft sensor fiber can take the form of a flexible microfiber and function as a cylindrical capacitor and a resistor. The sensor can include an inner conducting core surrounded by a dielectric layer, an outer conductor layer, and an encapsulation layer forming a cylindrical capacitor. The soft sensors can be fabricated in a highly compact form that can be used in small spaces (for example, in places where sheet based sensor cannot function such as, micro robotics, small manipulators and fingers). The small form enables the sensor fibers to be more easily protected. The soft sensor fibers can be fabricated with virtually any cross-sectional shape enabling the fibers to be used in a broader range of applications. In addition, the cross-section of the fiber can increase and/or decrease over the length of the fiber. Individual sensor fibers can be arranged into groups and arrays that enable multiple modes of sensing (e.g., strain in combination with pressure and position).

[0010] The microfiber can be woven into or bonded to fabrics and integrated into articles worn on the body to measure motion, such as joint movement. The microfibers can also be applied to mechanical devices and systems, for example, to sense the motion of robotic manipulator joints. The sensor fibers can co-molded, embedded 3D printed or otherwise embedded into other elastic or flexible materials. The sensor fibers can be bonded to other elastic or flexible structures. In addition, the flexible fibers can be used to sense strains and pressure in complex structural configurations (e.g., around or through multiple joints of a finger).

[0011] The dielectric layer and the encapsulation layer can include a silicone elastomer. A thixotropic agent can be added to the uncured silicone elastomer to achieve the desired rheological properties needed for fabrication (e.g., printing of form-stable filaments) and various modes of operation (e.g., compensate for environmental impacts).

[0012] The inner conductor core and the outer conductor layer can include a conductive (either electronic or ionic) fluid having predefined rheological properties. The conductive fluid can include a non-volatile solvent (e.g., glycerol), a conductive ionic species (e.g., sodium chloride) and a rheology modifier (e.g., polyethylene glycol). The conductor material can include a very stretchable and tough hydrogel soaked with glycerol in order to decrease the cross sensitivity to pressure. The ionic conductor can include a simulated body fluid (e.g., having similar physiological properties as human blood plasma) for use in medical applications.

[0013] The soft sensor fiber can be fabricated by extruding all four layers at the same time through an extrusion head (or print-head). The print-head can include a multi-core/shell nozzle through which each material can be co-flowed simultaneously at a controlled flow rate. In some configurations, the print-head can be attached to one or more axis manipulator that moves the print-head on one or more dimensions to apply the extruded soft sensor filament to a surface enabling fibers of various lengths and linear configurations to be produced. In some configurations, the print head can also be held stationary while the extruded soft sensor filament is applied to a moving belt, stage (e.g., a 1, 2, or 3 axis motion controlled stage), or surface (e.g. cylindrical, spherical or flat). In some configurations, the print-head can be part of a 3D printer.

[0014] The print-head can include portions fabricated using a pop up MEMS process. This process can be used to fabricate support elements to define and/or support one or more of the tubes/shells that make up the multi-core/shell nozzle. Using this process, a print-head for extruding a very small diameter filament can be constructed. The process can also be used to fabricate portions of the manifold that can be used to feed uncured elastomer material and viscoelastic conductor material into the nozzle.

[0015] The uncured elastomer layer materials and the conductor layer materials can be modified to enable them to be extruded to form a four layer fiber or filament that can be subsequently cured to form a soft sensor fiber according to the invention. In accordance with some embodiments, the uncured elastomer layer materials and the conductor layer materials can be shear thinning materials or modified to be shear thinning materials.

[0016] The ends of the soft sensor fiber can be further processed to connect wires to the conductor layers and structurally reinforce the ends to enable them to be secured in place without the connecting wires becoming disengaged. The ends of the soft sensor fiber can be extruded at a slower speed or higher flow rate such that the elastomer walls are thicker and the ends can be reinforced with a stiffer elastomer to reduce the elastic properties of the fiber at the ends to enable better electrical connection to the connecting wires. In accordance with some embodiments, end caps formed of a stiffer elastomer and/or having a tapered shape that can be molded onto the ends of the soft sensor fiber to provide better mechanical and electrical attachment.

[0017] The soft sensor fiber can be formed by flowing each of the elastomer layer materials and the conductor layer materials into an extrusion head that includes a concentric arrangement of cylindrical features (e.g., tubes or extrusion openings) that form the core conductor layer surrounded by the dielectric layer, an outer conductor layer, and an encapsulation layer in a continuous process.

[0018] The thickness of the elastomer layers can be controlled by controlling the speed of the print-head relative to the print surface or flow rate of the elastomer material through the nozzle. Reducing the speed of the x-y stage or increasing the elastomer flow rate can increase the thickness of the elastomer layers. Increasing the speed of the x-y stage or decreasing the elastomer flow rate can decrease the thickness of the elastomer layers.

[0019] The extruded fiber can be allowed to cure at room temperature for a length of time or the extruded fiber can be actively cured through the application of heat or light energy.

[0020] The resulting soft sensor fiber can be used in many different sensing modalities to reduce the impact of environmental effects such as temperature over a very large range of strains or to increase the sensitivity and the signal to noise ratio. The soft sensor fiber according to the various embodiments of the invention can be used to sense strain as a function of capacitance and/or resistance and/or sensor decay time.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIGS. 1A, 1E and 1F show diagrammatic views of an extruded soft sensor fiber according to some embodiments of the invention.

[0022] FIGS. 1B, 1C and 1D show diagrammatic views of an extrusion system and extrusion head for producing a soft sensor fiber according to some embodiments of the invention.

[0023] FIGS. 2A – 2G show diagrammatic views of assembly of an extrusion head according to some embodiments of the invention.

[0024] FIGS. 3A – 3J show diagrammatic views of a process for connecting wires and end caps to ends of a soft sensor fiber according to some embodiments of the invention.

[0025] FIGS 4A – 4D show graphs of some of the mechanical properties of a soft sensor fiber according to some embodiments of the invention and method of testing the mechanical properties.

[0026] FIGS. 5A – 5D show a diagram for modeling a soft sensor fiber as a cylindrical capacitor with resistive electrodes and graphs showing the time decay, resistance, and capacitance of the soft sensor fiber as a function of strain for step response and capacitance for low frequency repetitive strain.

[0027] FIG. 6 shows a plot of a sensitivity analysis of soft sensor fibers of length 4.0 cm, 6.0 cm, 8.0 cm and 10.0 cm according to some embodiments of the invention.

[0028] FIGS. 7A – 7D show an example of an application in which the soft sensor fiber is used to measure walking on a treadmill at various speeds.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0029] The present disclosure is directed to a capacitive soft sensor that can endure elongational or axial strains of 250% or more. The sensor can be produced in the form of a microfiber that enables the sensor to be used in a wide range of applications including fabrics, artificial skin and other soft and elastic materials that are exposed to pressure, large strains and many pressure and/or strain cycles, for example, wearable robotics and biomedical devices. Multiple soft sensor fibers can be arranged in parallel or overlapping (or more complex) configurations that can be used to measure pressure and strain magnitude and location. In addition, the sensor can function as both a resistor and a capacitor enabling more robust sensing modalities.

[0030] The present disclosure is also directed to a method and device for fabricating a capacitive sensor having an inner conductive core surrounded by a dielectric layer, an outer conductive layer and an outer insulating or encapsulation layer. The method can include extruding all four layers at the same time wherein the conductive core and outer conductive layers comprise conductive (e.g., electron based or ionic) liquids or fluids (e.g., viscoelastic or Newtonian) and the dielectric and encapsulation layers comprise an uncured elastomeric material. The method can further include providing an interface for electrically connecting the conductive layers to external systems to measure resistance, capacitance and/or decay time.

[0031] Figure 1A shows a diagrammatic view of an extruded soft sensor fiber 100 according to some embodiments of the invention. The extruded soft sensor fiber 100 can include a conductor core 112 surrounded by a dielectric layer 122, an outer conductor layer 114 and an encapsulation layer 124. The outer conductor layer 114 surrounds the dielectric layer 122, and the encapsulation layer 124 surrounds the outer conductor layer 114. The conductor core 112 and the outer conductor layer 114 may comprise an electronically or ionically conductive material, and the dielectric and encapsulation layers 122, 124 may comprise an elastomeric material, such as a silicone elastomer. Thus, the dielectric and encapsulation layers 122, 124 may in some embodiments be referred to as elastomeric layers 122, 124. The

electronically or ionically conductive material and/or the elastomeric material may be viscoelastic.

[0032] The soft sensor fiber 100 may be flexible and may have an axial length from about 1 mm to about 1000 mm. In some cases the axial length may be in the range of about 10 mm to about 200 mm. Each of the layers 114,122,124 and the core conductor 112 may have a thickness of from about 50 microns to about 500 microns. The thicknesses may be uniform or non-uniform along the axial length of the soft sensor fiber 100. For example, for the purpose of stiffening the ends of the soft sensor fiber 100, it may be advantageous for the thickness of one or more of the layers 114,122,124 or the core conductor 112 to increase at the ends, as discussed further below.

[0033] The soft sensor fiber 100 may function as a capacitive soft sensor having a sensor response in which capacitance is linearly proportional to axial strain. The soft sensor fiber 100 may have an axial strain capacity of at least about 250% while outputting the capacitance, and the capacitance may change by 100% over a 100% strain. In one example, a soft sensor fiber 100 may exhibit a sensitivity of about 0.1 pF to about 10 pF per 100% axial strain for an axial length of 60 mm.

[0034] The dielectric layer 122 and the encapsulation layer 124 may include any elastomeric material that is compatible with the operating environment of the sensor 100 and the conductive layer materials. Where the soft sensor fiber 100 is to be fabricated by extrusion, the uncured elastomeric material should be compatible with the extrusion process. In accordance with some embodiments, the dielectric layer 122 and the encapsulation layer 124 can include an elastomeric material that, in its uncured state, has a viscosity in the range from approximately 5 to 220 Pascal-seconds and is shear thinning and form stable, enabling the material to be extruded. In its cured state, the elastomeric material may have a high toughness, a high extensibility and a low Young's modulus. Suitable elastomeric materials may include silicone elastomers. For example, the (uncured) elastomeric material include Ecoflex 30 or DragonSkin 10 (Smooth-On, Inc., Easton, PA). In one exemplary embodiment, the uncured elastomeric material can include DragonSkin 10 slow cure material along with a thixotropic agent (e.g., approximately 0 - 5 wt.%, Thivex,

Smooth-On, Inc., Easton, PA) and a cure retarding agent (e.g., approximately 0 - 5 wt.%, SlowJo, Smooth-On, Inc., Easton, PA).

[0035] The conductive layers (e.g., the conductive core 112 and the conductive outer layer 114) can be formed from any electronically or ionically conductive material or fluid that is compatible with the application and the elastomeric material. The electronically or ionically conductive material or fluid may be referred to as a conductive ink. In accordance with some embodiments of the present invention, the conductive ink may be viscoelastic (e.g., shear-thinning) with a viscosity in the range from approximately 5 to 220 Pascal-seconds, enabling the ink to be extruded. In accordance with some embodiments of the invention, the conductive ink can also be non-volatile (e.g., vapor pressure below 1 Pa), may exhibit no hysteresis in sensing and may be non-irritating to the body. Examples of suitable conductive inks include conductive liquid metals, such as for example, mercury and eutectic gallium-indium (eGaIn). These materials are generally suitable because they have similar conductivities to metal and can adapt to the form of their container. Other conductive inks suitable for specific applications may include a dispersion of conductive particles. For example, the conductive particles may comprise a metal such as gold or silver, or another conductive material such as carbon, and may be dispersed in a base material such as an elastomer, grease or oil. Where the soft sensor 100 is to be fabricated by extrusion, the conductive ink should be compatible with the extrusion process. The conductive ink may be ionically conductive, and, in one example, may include a solvent (e.g., glycerol or water), a conductive ion source or salt (e.g., imidazole (which may also function as a solvent), sodium chloride or magnesium chloride) and/or a thixotropic agent (e.g., polyethylene glycol (such as PEG 1500 available from Sigma-Aldrich Corp., St. Louis, MO), clay, microgel or colloidal silica). In accordance with some embodiments of the invention, the soft sensor can be rendered biocompatible by including a simulated body fluid (e.g., a fluid with an ion concentration close to that of human blood plasma and optionally, other similar physiological properties to human blood plasma) in or as a substitute for the conductive ink. The rheological properties of the simulated body fluid can be

modified (e.g., by adding a thixotropic agent) to render the simulated body fluid compatible with the printing process.

[0036] Figures 1B, 1C, and 1D show diagrammatic views of a system for fabricating the soft sensor 100 shown in Fig. 1A according to some embodiments of the invention. As shown in Figs. 1B and 1C, the system can include an extrusion head 200 and connectors 212, 214, 216, 218 for material feed tubes for each of the conductor materials 112, 114 and the dielectric materials 122, 124. The extrusion head 200 forms the multi-layer soft sensor fiber 100 by extruding the conductive core layer 112 inside the dielectric layer 122 and the conductive layer 114, forming the inner layers. The inner layers 112, 114, 122 are extruded inside of the insulating encapsulating layer 124. Figure 1E shows a cross-section of a soft sensor fiber produced according to some embodiments of the invention. Figures 1F and 3H shows a completed soft sensor with end caps 142, 144 and electrical interfaces 132, 134 attached.

[0037] As shown in Figs. 1C, 1D and 2G, the extrusion head can include a set of tube connectors 212, 214, 216, 218 that mate with tubing that supplies the conductive viscoelastic fluid 112, 114 and uncured elastomer 122, 124 to the extrusion head 200. The extrusion head 200 can also include a first half 202 and a second half 204 that can be secured together to form a manifold 206 that directs the conductive fluid 112, 114 and the uncured elastomer 122, 124 to a multi-core/shell nozzle 220. The nozzle 220 can include a set of concentric tubes 222, 224, 226, 228 that can function as individual nozzles that extrude the individual concentric layers that form the cylindrical soft sensor structure during the extrusion process. The extrusion head 200 can be fabricated by securing each of the tubes 222, 224, 226, 228 in place, for example, using an adhesive (e.g., epoxy), press-fitting, or heat or ultra-sonic welding. As shown in Figs. 1C, 1D, 2B and 2D, the tubes 222, 224, 226, 228 can be arranged in a linear configuration with each tube extending into the next adjacent nozzle by predefined amount to enable the next outer layer to be formed. During print-head 200 fabrication, removable tubing can be used to support the overlapping tubes 222, 224, 226, 228 and provide concentric alignment, see Fig. 2B. Alternative alignment methods can be used, such as those common to pop-up

manufacturing. Each of the tubes 222, 224, 226, 228 can be constructed from a substantially rigid material that is compatible with the filament components and compatible with the extrusion process such as plastics, glasses and metals (e.g., nylon, pulled glass, stainless steel and aluminum). In accordance with some embodiments of the invention, the manifold 206 can be formed in the mating surfaces of two blocks 202, 204 of a plastic or metal material that forms the extrusion head 200. The blocks can be 3D printed or fabricated using molding or machining processes.

[0038] The print-head 200 can include portions fabricated using a pop-up MEMS fabrication process such as that described in commonly owned U.S. Patent Application no. 13/961,510, now U.S. Patent 8,834,666, which is hereby incorporated by reference. This process can be used to fabricate support elements to define and/or support one or more of the tubes 222, 224, 226, 228 that make up the multi-core/shell nozzle 220. The support elements can be constructed having four or more walls extending substantially perpendicular to a substrate having a hole that can define an extrusion orifice or accept an extrusion tube. The support elements can be fabricated as a two-dimensional structure and then walls can be popped up to extend substantially perpendicular to the substrate. Using this process, a print-head 200 for extruding a very small diameter filament can be constructed. The process can also be used to fabricate portions of the manifold 206 that can be used to feed uncured elastomeric material and viscoelastic conductor material into the nozzle 220.

[0039] In accordance with some embodiments of the invention, a single soft sensor filament or fiber 100 can be produced by moving the extrusion head 200 relative to a surface (e.g., a horizontal, inclined or curved surface) while extruding the four layers at the same time, as shown in Fig. 1B. In accordance with some embodiments of the invention, a single soft sensor filament or fiber 100 can be produced by moving a surface (e.g., a horizontal, inclined or curved surface) relative to the extrusion head 200 while extruding the four layers at the same time. An additional amount of the outer encapsulation layer material can be extruded to seal the ends of the filament 100 to contain the conductive viscoelastic fluid (conductive

ink) layers. The elastomeric layers 122, 124 can be cured by any known process, including for example, passive curing at room temperature or active curing by exposing the filament to an energy source, such as thermal curing (e.g. heating the filament) or light (e.g. exposing the filament to ultraviolet light). The extrusion head 200 can be configured whereby the extruded filament 100 is exposed to an active curing environment (e.g., heat or UV light) upon exiting the nozzle 220 and prior to contacting the surface. In addition, the length of the filament 100 can be determined by the length of travel of the print-head 200 or the surface on which it is printed.

[0040] In accordance with some embodiments of the invention, the extrusion head 200 can include a core tube 222 for extruding the core conductive layer 112, a dielectric tube 224 for extruding the dielectric layer 122 around the core conductor 112, an outer conductor tube 226 for extruding the outer conductor layer 114 around the dielectric layer 122, and an encapsulation tube 228 for extruding the encapsulation layer 124 around the outer conductor layer 114. In one example, the core tube 222 has an inner diameter of 0.254 mm, the dielectric tube 224 has an inner diameter of 0.686 mm, the outer conductor tube 226 has an inner diameter of 1.168 mm, and the encapsulation tube 228 has an inner diameter of 1.956 mm. Depending on the desired filament diameter and dielectric layer properties, smaller or large diameter nozzles (e.g., tubing) in the extrusion head can be used. In general, the inner diameter of the core tube 222 may be in the range of from 0.05 mm to 2 mm, the inner diameter of the dielectric tube 224 may be in the range of from 0.05 mm to 5 mm, the inner diameter of the outer conductor tube 226 may be in the range of from 0.05 mm to 10 mm, and the inner diameter of the encapsulation tube 228 may be in the range of from 0.05 mm to 15 mm. In accordance with some embodiments of the invention, the diameter of the filament can be as small as 0.25 mm or less. In accordance with some embodiments of the invention, the diameter of the filament can be as large as 10 mm or larger.

[0041] The final at-rest (e.g., unstretched) diameter of the core conductor 112 of the soft sensor 100 can be determined as a function of the core tube 222 which, along with the material flow rates and the extrusion head 200 velocity relative to the surface, determines the outer diameter of the core conductor 112 and the inner

diameter of the dielectric layer 122. The at-rest diameter of the core conductor 112 can also be influenced by the pressure or flow rate of core conductor viscoelastic fluid and the extrusion rates and material properties of the other layers (e.g., cured elastomer that forms the dielectric layer 122, the conductive viscoelastic fluid that forms the outer conductor layer 114 and the cured elastomer that forms the encapsulation layer 124). Depending on the materials, these layers can shrink or expand during or after extrusion and/or curing. The thickness of the dielectric layer 122 can be determined as a function of the space between the core tube 222 and dielectric tube 224. The thickness of the outer conductor layer 114 can be determined as a function of the space between the dielectric tube 224 and the outer conductor tube 226. The thickness of the encapsulation layer 124 can be determined as a function of the space between the outer conductor tube 226 and the encapsulation tube 228. The extrusion temperature, pressure, extrusion flow rates, and extrusion nozzle speed can also impact the layer thicknesses. In accordance with some embodiments of the invention, the diameter of the filament 100 and the thickness of the core conductor 112 or any of the layers 114, 122, 124 can be reduced by increasing the speed of the extrusion nozzle 220 relative to the surface and increased by reducing the speed of the extrusion nozzle 220 relative to the surface. In accordance with some embodiments of the invention, the diameter of the filament 100 and the thickness of core conductor 112 or any of the layers 114, 122, 124 can be reduced by decreasing the flow rate of the material through the extrusion nozzle 220 and increased by increasing the flow rate of the material through the extrusion nozzle 220.

[0042] To summarize, a method of making a soft sensor fiber includes flowing a first viscoelastic conductor material through a first extrusion tube; flowing a first uncured dielectric material through a second extrusion tube overlying the first extrusion tube, the first uncured dielectric material flowing around and enclosing the first viscoelastic conductor material; flowing a second viscoelastic conductor material through a third extrusion tube overlying the second extrusion tube, the second viscoelastic conductor material flowing around and enclosing the first uncured dielectric material; and flowing a second uncured dielectric material through a fourth

extrusion tube overlying the third extrusion tube, the second uncured dielectric material flowing around and enclosing the second viscoelastic conductor material. The term “enclosing” may be understood to mean fully enclosing or partially enclosing (e.g., radially covering). A soft sensor fiber comprising a core conductor surrounded by a dielectric layer, an outer conductor layer and an encapsulation layer is thus formed.

[0043] The method may further include providing an extrusion head (or printhead) including the first, second third and fourth extrusion tubes arranged in a concentric configuration, and moving the extrusion head relative to a surface during the flowing of the materials, such that the soft sensor fiber is deposited on the surface in a predetermined configuration or pattern. Such a process may be referred to as 3D printing or direct-write printing. Additional details about 3D printing may be found in International Patent Application Serial No. PCT/US2014/043860, filed on June 24, 2014, and International Patent Application Serial No. PCT/US2014/065899, filed on November 17, 2014, both of which are hereby incorporated by reference in their entirety.

[0044] The flowing of the first viscoelastic conductor material may occur at a first flow rate f_1 , the flowing of the first uncured dielectric material may occur at a second flow rate f_2 , the flowing of the second viscoelastic conductor material may occur at a third flow rate f_3 , and the flowing of the second uncured dielectric material may occur at a fourth flow rate f_4 , where $f_4 > f_3 > f_2 > f_1$. Typically, each of the flow rates f_1 , f_2 , f_3 and f_4 is from about 0.1 $\mu\text{L/s}$ to about 10 $\mu\text{L/s}$, although flow rates of up to tens of mL/s or hundreds of mL/s are possible depending on the nozzle size and print speed.

[0045] The printhead or extrusion head may move relative to the surface at a print speed of from about 1 mm/s to about 100 mm/s, and more typically from about 1 mm/s to about 10 mm/s. In some cases, the printhead may move relative to the surface at a first print speed and at a second print speed different from the first speed during printing. The first print speed may be lower than the second print speed and may be employed to form ends of the soft sensor fiber having increased layer thicknesses.

[0046] Each of the first and second viscoelastic conductor materials may comprise an electronically or ionically conductive material, as described elsewhere in this disclosure. And each of the first and second uncured dielectric materials may comprise an uncured silicone elastomer, also as discussed elsewhere in this disclosure.

[0047] As illustrated in Figures 3A-3F and discussed further below, the method may further include, after forming the soft sensor fiber, attaching a first wire to the first viscoelastic conductor material and a second wire to the second viscoelastic conductor material at at least one end of the soft sensor fiber, thereby establishing electrical connections to the soft sensor fiber. In some embodiments, before attaching the second wire to the second viscoelastic conductor material, a third uncured dielectric material may be used to electrically isolate the first and second viscoelastic conductor materials. Thus, attaching the second wire may comprise inserting the second wire through the third uncured dielectric material. It may be advantageous for the third uncured dielectric material to have a higher stiffness than that of the first or second uncured dielectric materials. In some embodiments, an end cap may be secured to the at least one end of the soft sensor fiber.

[0048] The method may further include curing the uncured first, second and/or third viscoelastic materials by, for example, thermal curing, UV radiation curing and/or chemical curing.

[0049] While the embodiments of Figs. 1A – 1F and 2A – 2G show a soft sensor 100 that takes the shape of a fiber or filament having a round or oval cross-section, the sensor can also be fabricated to include a polygonal (e.g., square or rectangular) cross-section, and individual layers can be provided with either rounded or polygonal (e.g., square or rectangular) shaped cross-sections by using tubes 222, 224, 226, 228 that have the desired cross-sectional shape. More complex cross-sectional shapes can also be provided. In accordance with some embodiments of the invention, the soft sensor can include more than one conductive core surrounded by a dielectric layer and one or more outer conductor layers within a common encapsulation layer.

[0050] After the soft sensor fiber 100 is fabricated, additional processes can be used to provide mechanical and electrical connection points for the soft sensor 100. Figures 3A – 3J show a process for terminating each end of a soft sensor 100 fiber according to some embodiments of the invention. Generally, the process can include two steps. The first step can include electrically connecting the ends of the conductive layers to wires to enable electrical connection of the sensor. The second step can include attaching an end cap to the end of the fiber that serves as a physical attachment point for the soft sensor and can serve to limit the strain at the end of the sensor fiber to support the electrical connection.

[0051] Figures 3A – 3F show a diagrammatic view of a process for electrically connecting the conductive layers 112, 114 of a soft sensor fiber to wires 132, 134 for connection to a sensing system. In accordance with some embodiments of the invention, the extruding process can produce a soft sensor fiber 100 that has sealed ends by extruding uncured elastomeric material without the conductor material at the ends of the fiber. In order to attach wires to the conductive layers, the sealed end can be cut off with a sharp edge exposing the conducting layers 112, 114 as shown in Fig. 3B. In order to provide a space to seal the end of the fiber, the dielectric layer 122 can be trimmed inside the encapsulation layer 124 as shown in Fig. 3C. In accordance with some embodiments, this can be accomplished by pulling (e.g., stretching) the dielectric layer 122 beyond the end of the encapsulation layer 124 and cutting off a length of the dielectric layer 122. When the dielectric layer 122 is released, it will retract as shown in Fig. 3C. Next, a connecting wire 132 (e.g., a 127 micron silver wire) can be inserted into the core conductor material 112 and an uncured elastomeric material 136 can be injected (e.g. using a syringe) into the space created at the end of the encapsulation layer 124 making sure to seal the core conductor 112 from the outer conductor layer 114, as shown in Figs. 3D and 3E. In the final step, a second wire 134 (e.g., a 127 micron silver wire) can be inserted through the elastomeric material 136 into the outer conductor layer material 114. In accordance with some embodiments of the invention, the uncured elastomeric material 136 that is inserted into the end of the encapsulation layer 124 can include a stiffer formulation (e.g., DragonSkin 30, Smooth-On, Inc., Easton, PA) to strengthen

the ends for subsequent attachment to the end caps 142, 144. In accordance with some embodiments of the invention, the wall thickness of the dielectric layer 122 and the encapsulation layer 124 can be increased at one or both ends of the fiber 100 by slowing the speed of the extrusion head or increasing the elastomeric flow rate at the ends of the fiber 100. This can serve to make the ends of fiber less elastic and reduce the possibility that the wires 132, 134 will move relative to the conductor core or the outer conductor layer and produce unacceptable signals.

[0052] Figures 3G – 3J show a diagrammatic view of a process for attaching end caps 142, 144 to the ends of the soft sensor fibers 100 to enable mechanical connection to the ends of the soft sensor fibers 100. One of challenges of using a soft elastic material as a sensor includes providing stable electrical connections to the conductor core and outer conductor layer. The electrical connections can be created by inserting wires into the conductor core and the outer conductor layer; however, when the sensor is exposed to strains, the conductor core and outer conductor layer can move relative to the wire, leading to signal errors. In accordance with some embodiments of the invention, the ends of the soft sensor can be modified to include a stiffer elastomeric material that limits the strain in the area of the fiber where the wires come in contact with the conductor layers. Stiffening can be accomplished by thickening the dielectric layer and encapsulation layer near the ends of the fiber. Stiffening can also be accomplished by injecting a stiffer material 136 into the end of the encapsulation layer to seal the end of the fiber and secure the wires 132, 134 in place.

[0053] After the injected uncured elastomer has cured, the end caps can be attached by molding. The molds enable the end caps to take any desired shape and molds can be fabricated using a 3D printer (e.g., an Object 30 3D printer). The end caps can be fabricated from a stiffer formulation (e.g., DragonSkin 30, Smooth-On, Inc., Easton, PA) of the elastomer that produces a soft sensor design that increases in stiffness towards the end to provide a more robust design and facilitates attachment to harder substrates. The connection wires 132, 134 can be looped within or around a portion of the end cap 142 as shown in Figs. 3I and 3J to provide a strain relief and avoid the wire being pulled out of the sensor. As shown in Figs.

3G – 3J, the end caps 142, 144 can be tapered and increase in thickness and/or stiffness toward the ends to provide a stable attachment point for mechanical and electrical connection.

[0054] Figures 4A – 4D show some of the mechanical properties of a soft sensor fiber according to some embodiments of the invention. To facilitate printing of continuous soft sensor filaments or microfibers, the conductor material (conductive ink) can be shear thinning and have a yield stress and the elastomeric (dielectric) material can be modified to have similar rheological properties. For example, a thixotropic agent may be added to the uncured elastomeric material such that both the conductor material and the uncured elastomeric material have similar rheological properties, as shown in Fig. 4A.

[0055] Fig 4A shows the storage (G') and loss moduli (G'') for an exemplary dielectric material (e.g., Dragonskin/PDMS) and an exemplary viscoelastic conductor material (or conductive ink) (e.g., Glycerol/PEG). This diagram provides information about the ability of the dielectric and conductor materials to be printed (e.g., extruded) and retain their shape. When the moduli are constant with applied shear stress and $G' > G''$, the material (e.g., the dielectric or conductor materials) is said to be in the “linear viscoelastic regime” and it is unyielded. In other words, substantially all of the strain is recoverable and the inherent structure to the material has not been irreversibly disturbed), and the material will not flow. When the curves start to “bend over” and $G' < G''$, the material has yielded and will begin to flow. Any structure inherent to the material is being disrupted, and there will be a time scale associated with the recovery (if any) of the structure of the fluid. This type of behavior is embodied by the Glycerol/PEG ($t=0d$) and Dragonskin/PDMS curves.

[0056] The Glycerol/PEG ($t=30d$) curves are different from the Glycerol/PEG ($t=0d$) and Dragonskin/PDMS curves. The Glycerol/PEG ($t=30d$) curve is derived from a material identical in composition to the Glycerol/PEG ($t=0d$) curve, with the exception that the material composing the former curve has been exposed to atmospheric conditions for 30 days – allowing it to spontaneously absorb water. In this example, $G'' > G'$ for all shear stresses and is constant with shear stress. As a

result of water absorption, the structure of the viscoelastic material has changed to that of a viscous Newtonian fluid. Such a fluid will flow for all applied shear stresses.

[0057] These diagrams provide insight into a material's ability to print and retain its shape. When printed, a yield stress material flows through the nozzle tube via plug flow and a thin slip layer of yielded material occurs near the tube wall, while an unyielded plug moves through the tube via rigid body movement. Once deposited, the plug like filament retains its shape because outside the nozzle, the filament is in a zero stress condition. Because $G' > G''$ for the zero stress condition, the material will not flow and the filament will take the shape of whatever cross-section it was printed from and ideally remain in the location where it was printed. This type of behavior would apply to the Glycerol/PEG ($t=0d$) and Dragonskin/PDMS curves, which are the materials that can be used to make the soft sensor fibers according to the invention. The behavior of a Newtonian fluid is distinctly different. When a Newtonian fluid moves through a nozzle, all of the material in the nozzle is flowing. The Newtonian material continues to flow once it exits the nozzle and has no ability to retain shape. Figure 4A shows that the printed materials according to the present disclosure can be extruded because the above-described yield stress property enables the printed filament to retain its shape.

[0058] Figs. 4B – 4D show a mechanical analysis (e.g., elongation to failure) of a sample set of soft sensor fibers according to embodiments of the invention. As shown in Fig. 4B, the soft sensor failed at approximately 770% strain and a peak force of 3 N.

[0059] In accordance with some embodiments of the invention, the soft sensor fiber 100 can be modeled as cylindrical capacitor with resistive electrodes. The conductive core 112 with a finite resistivity is surrounded by a dielectric 122 of known thickness, which in turn has another conductive layer 114 around it. This whole structure is then encapsulated by an outer stretchable layer 124, as shown in Fig. 5A. The sensor behavior can be modeled via equations for a cylindrical capacitor and a resistor with a known cross-section. Specifically, a lumped element model is applied to a unit cross-section of the sensor, as shown for example in Fig. 5A. The sensor can be analyzed in terms of three components – a cylindrical resistor (R_i), a

cylindrical capacitor (C_s), and a cylindrical ring resistor (R_o) – arranged in series. When an axial strain (ϵ) is applied to the geometry, the sensor capacitance (C_s), resistance (R_s), and decay time (τ_s) vary linearly, quadratically, and cubically, respectively, with elongation, as indicated in FIG. 5A. Fig. 5B shows the decay time of three sensors of various lengths as a function of strain and demonstrates that the sensor response (decay time) follows a cubic relationship with strain.

[0060] Fig. 5C shows the resistance and capacitance of the soft sensor fiber as a function of axial strain. As shown in Fig. 5C, resistance follows a quadratic relationship with strain and capacitance follows a linear relationship with strain. While both models deviate at low strains, this deviation can be overcome by pre-straining the sensor. Fig. 5D shows output (e.g., capacitance) for strain applied at different frequencies.

[0061] Fig. 6 shows a plot of a sensitivity analysis of soft sensor fibers of length 4.0 cm, 6.0 cm, 8.0 cm and 10.0 cm. The sensitivity of the soft sensor fibers can be determined as a function of the geometry of the sensor (e.g., the original length and the ratio of the original radii, and of the dielectric constant of the elastomer between the two conductors. For a silicone elastomer-based dielectric material, the dielectric constant is approximately 2.3-2.8. This value was used to plot the sensitivity as a function of the ratio of the two radii for different lengths shown in Fig. 6. As shown in Fig. 6, for a radii ratio in the range from 1.05 to 1.50, where r_{10} refers to and r_{20} refers to the outer radii of the conductive core 112 and the dielectric layer 122, respectively, the sensitivity ΔC_s of a set of soft sensor fibers according to some embodiments of the invention were in the range of 25 – 250 pF per 100% strain.

[0062] Figs. 7A – 7D show an example of an application in which a soft sensor fiber according to some embodiments of the invention can be used to measure kinematic motion of a test subject. In this example, a soft sensor fiber according to some embodiments of the invention can be clothing worn by a subject, specifically the soft sensor fiber can be attached (as shown in Figs. 7A and 7B) to a body suit or a flexible sleeve worn by the subject, such that when the knee is flexed, the soft sensor is strained. Fig. 7D shows the change in RC-decay time of the sensor as the subject walks at various speeds on a treadmill to track the kinematics of the knee

joint in real time (e.g. for physical therapy applications). Similarly, the soft sensor fiber can be attached to a sleeve worn on wrist or hand to monitor the kinematics of one or more aspects of the wrist or hand.

[0063] In accordance with other embodiments of the invention, two or more soft sensor fibers can be arranged in parallel or overlapping configurations that can provide additional sensing modalities. For example, the soft sensor fibers can be overlaid or woven into a fabric that includes overlapping fibers in a transverse configuration (e.g., sensor fibers extending in both x and y directions). In this configuration, the strain or pressure indicated by signals (e.g., resistive, capacitive or decay time) can be used to identify the location as well as the magnitude of the strain or pressure based on the location of sensor fibers producing the largest signal or change in signal. In other configurations, two or more sensor fibers can be arranged in a star (e.g. each fiber intersecting each other fiber) to detect strain direction as well as magnitude. In other configurations, sensor fibers can be wrapped around three dimensional objects (e.g., pressure vessels and enclosed structures) to monitor stresses and stress hot spots or failure points in these objects.

[0064] In accordance with some embodiments of the invention, two or more sensor fibers can be used in parallel or overlapping configurations where at least one sensor fiber has a different diameter or layer wall thickness than other sensor fibers. In some configurations, the some or all the sensor fibers can have different diameters, layer wall thicknesses and sensitivities relative to other sensor fibers.

[0065] In accordance with some embodiments of the invention, the sensor fibers can be fabricated having small or compact outer diameters enabling individual sensor fibers to fit in small spaces or to enable many more sensor fibers to be used in a common location.

[0066] In accordance with some embodiments of the invention, one or more sensor fibers can be used secured to the outside of moveable joint (e.g., a finger, a knee or a hip) such that flexion causes one or more of the sensor fiber to be strained. One or more of the sensor fibers can be positioned on the surface of the joint to record contact (e.g., pressure) as well as location of the contact point.

[0067] Examples

[0068] *Materials System:* An exemplary ionic conductive ink is prepared by dissolving as-received sodium chloride until saturation (MACRON) in glycerol (99.5%, Aldrich) under continuous stirring at 100 °C overnight. The glycerol solution is mixed with polyethylene glycol (PEG) (PEG 1500, Aldrich) in a ratio of 10:1 by weight and heated to 100 °C under continuous stirring until all PEG is dissolved. The solution is degassed for 5 min under vacuum and subsequently poured into a plastic 10 mL Becton Dickinson syringe and cooled down to room temperature. The dielectric and encapsulation layer is fabricated from Dragonskin 10 Slow Cure Part A (60 g) and B (60 g), Thi-Vex Silicone Thickener (0.12 g) and Slo-Jo Platinum Silicone Cure Retarder (0.6 g) all obtained from Smooth-On, Inc. Thi-vex modified the rheological properties and the silicone cure retarder increased pot life. Before homogenizing, the solution is degassed under vacuum for 2 min. Homogenizing and additional degassing are performed for 30 s each using a planetary mixer (ARE-310, Thinky Mixer USA) at 2000 and 2200 rpm, respectively. To transfer the final ink into a 5 mL syringe without introducing air, the hole at the tip of a 60 mL syringe is increased to ≈ 1 cm by using a rotary cutting tool. The ink is then drawn up into the modified syringe and injected into a 5 mL syringe for dispensing with the syringe pumps.

[0069] *Rheological Characterization:* The rheological properties of the conductive ink and the dielectric/encapsulant are characterized under ambient conditions using a controlled stress rheometer (Discovery HR-3 Rheometer, TA Instruments). The rheology of the conductive ink is assessed one day after ink fabrication, while the dielectric/encapsulant is measured immediately after homogenization. The properties of the conductive ink and the dielectric/encapsulant are measured using a 40 mm tapered cone (2.005° taper, 56 μm truncation gap). The conductive ink is also evaluated after aging for 30 days at ambient conditions. For these measurements, a 60 mm cone and plate geometry is utilized (2.000° taper, 55 μm truncation gap). All oscillatory measurements are performed at 21°C with an angular frequency of 6.28 rad s^{-1} within the strain range of $10^{-4}\%$ – $10^3\%$.

[0070] *Ink Conductivity:* Ink conductivity is measured using a bench top conductivity meter (Sper Scientific). Ten ml of ink is allowed to equilibrate for 24 h before a measurement is taken. To evaluate the effect of water absorption on conductivity and rheology, 25 petri dishes of size 5.5 mm × 1.2 mm each with 10 g of conductive ink are exposed to ambient conditions. Conductivity (1 sample per measurement) and weight (10 samples per measurement) are measured every 2–4 days for 30 days while oscillatory strain experiments were performed one day and 30 days after ink synthesis. For water absorption of the filaments, six CS3 fibers are weighed after printing and their weight gain is monitored over four days.

[0071] *Printhead Fabrication:* The mount for the printhead is fabricated using a Connex500 3D printer with VeroBlue RGD840 as the feed material. Tubes used to create the nozzle are obtained from McMaster-Carr (Precision Miniature 304 Stainless Steel Tubing) and cut to the corresponding length with a rotary cutting tool. The tube sizes and lengths are as follows: (Gauge, Inner diameter [mm], Outer diameter [mm], Length [mm]): Core (27, 0.254, 0.406, 16), Intermediate layer 1 (IL1) (23, 0.431, 0.635, 42), Shell 1 (20.5, 0.685, 0.863, 16), IL2 (19, 0.889, 1.066, 30), Shell 3 (17.5, 1.168, 1.4224, 16) IL3 (15, 1.524, 1.8288, 18), and Shell 4 (13, 1.956, 2.413, 16). The tubes are fixed in place with epoxy (Loctite 5 min Epoxy).

[0072] *Multicore–Shell Printing:* Four syringe pumps (two PHD Ultra (Harvard Apparatus – 703007) and two PHD 22/2000 (Harvard Apparatus – 702001)) are used in order to pump the inks through the printhead. The flow rates for each layer are as follows [$\mu\text{L s}^{-1}$]: Core (0.251), Shell 1 (0.754), Shell 2 (1.257), and Shell 3 (4.021), which can yield the following layer diameters [μm]: 364, 610, 879, and 1433. The printhead is attached to a custom built 3D printer (ABG 10000, Aerotech Inc.), which translates the printhead in the prescribed pattern. All print paths are generated using G-code commands. The print height of the nozzle is approximately 1 cm above the substrate. Filament thicknesses are assessed for five samples from top-down optical micrographs (VHX 2000, Keyence). Refractive index differences between layers and filament curvature leads to discrepancies between the actual filament dimensions and the imaged dimensions. As such, the reported thickness of the outer

conductor and encapsulant are calculated based on the relative flow rates of the material rather than image measurements.

[0073] *Electrical Connections:* For insulating the two conductive layers at the sensor ends, Dragonskin 30 (1 Part A and 1 Part B) are mixed with 0.1 Part Silicone Thinner (Smooth-on, Inc) using a planetary mixer with the same settings as prescribed for Dragonskin 10. After mixing, Dragonskin 30 is injected with a syringe into the filament. The end caps are fabricated by casting Dragonskin 30 (same recipe as above but without any thinner) into 3D printed molds (Connex500, VeroBlue RGD840).

[0074] *Signal Processing and Readout Electronics:* The voltage across a 1 M Ω resistor in series with the sensor is monitored after applying step voltage to the system. From the voltage decay profile, the decay time is calculated. The decay time is then used to obtain both the capacitance and the resistance of the sensor. Data analysis is performed on an ATMEGA328P chip (Arduino Pro Mini, Sparkfun). The step response was 5 V in magnitude and applied at a frequency of 50–200 Hz. The decay voltage is sampled by an internal analog-to-digital converter with a sampling frequency of 75 kHz and 8 bit resolution. Signal segmentation, linearization and sensor quantities are calculated on the device and transmitted via a serial port to a computer. Data acquisition and visualization are performed in Python.

[0075] *Mechanical Testing:* The elongation at break is determined by straining the sensors at a crosshead speed of 5 mm s⁻¹ until failure (Instron 5544A, Instron).

[0076] *Static Sensor Testing:* A custom-designed testing jig with fixtures that allowed the sensors to be strained to predefined values is employed. The sensors are stretched to the prescribed strain level, attached to the jig, and the relevant outputs are measured. Data are acquired with an ATMEGA328P microcontroller (Sparkfun, Inc.) and transmitted via serial to a computer. For every data point 100 sensor property samples are acquired and averaged. Every sensor is elongated and retracted three times. The gauge factor is calculated from the static characterization of six sensors.

[0077] *Dynamic Sensor Testing:* The same sensor for which the static characterization is shown is also used for the dynamic testing. The sensor has an

original length of 60 mm and for every experiment it is prestrained by 20 mm (33.3% strain) at a velocity of 10 mm s^{-1} and then cycled 20 times at a speed of 20 mm s^{-1} from 80 mm elongation to 100 mm elongation, and then again retracted from 80 to 60 mm at a speed of 10 mm s^{-1} . Different amplitudes (20, 40, and 80 mm) were explored and, for the biggest amplitude, different speeds also (10 and 20 mm s^{-1}). This resulted in four different actuation frequencies ($1/2$, $1/4$, $1/6$, and $1/8 \text{ Hz}$) and maximum strains of 66.6%, 100%, and 166.66%. Limitations on the maximum crosshead velocity of the load frame (Instron 5544A, Instron) prevented exploration of more rapid frequencies for the given strain levels. Elongation data are acquired by the Instron, while an ATMEGA328P microcontroller (Sparkfun, Inc.) monitored sensor output.

[0078] *Walking Tests:* The sensor is sewn onto the knee region of spandex athletic tights. The wearer of the athletic tights walked at four different speeds on a treadmill (1, 2, 3, and 4 mph) while data were recorded with an average sampling frequency of 65 Hz. The data were processed on an ATMEGA328P microcontroller (Sparkfun, Inc.) and transmitted via serial to a computer, where the data were filtered with a low pass filter with a cutoff frequency of 1.6 Hz.

[0079] Although the present invention has been described in considerable detail with reference to certain embodiments thereof, other embodiments are possible without departing from the present invention. The spirit and scope of the appended claims should not be limited, therefore, to the description of the preferred embodiments contained herein. All embodiments that come within the meaning of the claims, either literally or by equivalence, are intended to be embraced therein.

[0080] Furthermore, the advantages described above are not necessarily the only advantages of the invention, and it is not necessarily expected that all of the described advantages will be achieved with every embodiment of the invention.

CLAIMS

1. A soft sensor fiber comprising:
a core conductor surrounded by a dielectric layer, an outer conductor layer
and an encapsulation layer,
wherein the dielectric layer and encapsulation layers include an elastomeric
material and the core conductor and the outer conductor layer include a conductive
liquid material.
2. The soft sensor fiber of claim 1, wherein the outer conductor layer
surrounds the dielectric layer, and wherein the encapsulation layer surrounds the
outer conductor layer.
3. The soft sensor fiber according to claim 1 or 2 comprising a first end
and a second end, and wherein at least one of the first end and the second end
includes a first wire extending from the core conductor establishing an electrical
connection to the core conductor.
4. The soft sensor fiber according to claim 3, wherein at least one of the
first end and the second end includes a second wire extending from the outer
conductor layer establishing an electrical connection to the outer conductor layer.
5. The soft sensor fiber according to any one of claims 1-4 having a first
end and a second end, and wherein the dielectric layer has a thickness, and wherein
the thickness of the dielectric layer increases near at least one of the first end and
the second end.
6. The soft sensor fiber according to any one of claims 1-5 having a first
end and a second end, and wherein the encapsulation layer has a thickness and the
thickness of the encapsulation layer increases near at least one of the first end and
the second end.

7. The soft sensor fiber according to any one of claims 1-6 having a first end and a second end, and wherein the dielectric layer has a first stiffness, and wherein at least one of the first end and the second end comprises an additional elastomeric material having a stiffness greater than the first stiffness.

8. The soft sensor fiber according to any one of claims 1-7 having a first end and a second end and at least one end cap secured to at least one of the first end and the second end.

9. The soft sensor fiber according to claim 8, wherein the dielectric layer has a first stiffness and the at least one end cap has a stiffness greater than the first stiffness.

10. The soft sensor fiber of any one of claims 1-9, wherein each of the layers and the core conductor have a thickness of from about 50 microns to about 500 microns.

11. The soft sensor fiber of any one of claims 1-10 having an axial length of from about 1 mm to about 1000 mm.

12. The soft sensor fiber according to any one of claims 1-11, wherein the conductive liquid material is a conductive viscoelastic material comprising an ionically or electronically conductive material.

13. The soft sensor fiber according to claim 12, wherein the conductive viscoelastic material includes a solvent, an ion source and a thixotropic agent.

14. The soft sensor fiber according to claim 13, wherein the solvent includes glycerol, water or imidazole.

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15. The soft sensor fiber according to claim 13 or 14, wherein the ion source includes sodium chloride, magnesium chloride or imidazole.
16. The soft sensor fiber according to any one of claims 13-15, wherein the thixotropic agent includes polyethylene glycol, clay, microgel or colloidal silica.
17. The soft sensor fiber according to claim 12, wherein the conductive viscoelastic material is selected from the group consisting of a liquid metal and a dispersion of conductive particles.
18. The soft sensor fiber according to any one of claims 1-17, wherein the elastomeric material comprises a silicone elastomer.
19. The soft sensor fiber according to any one of claims 1-17, wherein the elastomeric material includes a thixotropic agent.
20. The soft sensor fiber according to any one of claims 1-19 having a sensor response where capacitance is linearly proportional to axial strain.
21. The soft sensor fiber according to claim 20 comprising an axial strain capacity of at least about 250% while outputting the capacitance.
22. The soft sensor fiber according to any one of claims 1-21 comprising a sensitivity of 0.1 pF to 10 pF per 100% axial strain for an axial length of 60 mm.
23. A capacitive sensing device comprising one or more of the soft sensor fibers according to any one of claims 1-22.
24. The capacitive sensing device of claim 23, wherein the one or more of the soft sensor fibers are attached to a textile.

25. The capacitive sensing device of claim 23 or 24, comprising a plurality of the soft sensor fibers in a woven configuration.

26. A device adapted for producing a soft sensor fiber, the device comprising:

an extrusion head having a manifold adapted to
direct the flow of a first viscoelastic conductor material to a first extrusion tube whereby the first viscoelastic material flows through the first extrusion tube;

direct the flow of a first uncured dielectric material to a second extrusion tube whereby the first uncured dielectric material flows through the second extrusion tube;

direct the flow of a second viscoelastic conductor material to a third extrusion tube whereby the second viscoelastic material flows through the third extrusion tube;

direct the flow of a second uncured dielectric material to a fourth extrusion tube whereby the second uncured dielectric material flows through the fourth extrusion tube;

wherein the fourth extrusion tube is aligned with and overlies the third extrusion tube, the third extrusion tube is aligned with and overlies the second extrusion tube and the second extrusion tube is aligned with and overlies the first extrusion tube;

whereby the first uncured dielectric material flows around and encloses the first viscoelastic conductor material, the second viscoelastic conductor material flows around and encloses the first uncured dielectric material and the second uncured dielectric material flows around and encloses the second viscoelastic conductor material.

27. The device according to claim 26 wherein the first extrusion tube is concentric with the second extrusion tube, the second extrusion tube is concentric

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with the third extrusion tube and the third extrusion tube is concentric with the fourth extrusion tube.

28. A method of making a soft sensor fiber, the method comprising:
flowing a first viscoelastic conductor material through a first extrusion tube;
flowing a first uncured dielectric material through a second extrusion tube overlying the first extrusion tube, the first uncured dielectric material flowing around and enclosing the first viscoelastic conductor material;
flowing a second viscoelastic conductor material through a third extrusion tube overlying the second extrusion tube, the second viscoelastic conductor material flowing around and enclosing the first uncured dielectric material; and
flowing a second uncured dielectric material through a fourth extrusion tube overlying the third extrusion tube, the second uncured dielectric material flowing around and enclosing the second viscoelastic conductor material,
thereby forming a soft sensor fiber comprising a core conductor surrounded by a dielectric layer, an outer conductor layer and an encapsulation layer.

29. The method of claim 28, further comprising providing an extrusion head including the first, second, third and fourth extrusion tubes arranged in a concentric configuration,
wherein the extrusion head is moved relative to a surface during the flowing of the materials, the soft sensor fiber being deposited on the surface in a predetermined configuration.

30. The method of claim 28 or 29, wherein each of the first and second viscoelastic conductor materials comprises an electronically conductive material.

31. The method of claim 30, wherein the electronically conductive material is selected from the group consisting of a liquid metal and a dispersion of conductive particles.

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32. The method of claim 28 or 29, wherein each of the first and second viscoelastic conductor materials comprises an ionically conductive material.

33. The method of claim 32, wherein the ionically conductive material comprises an ion source, a solvent and a thixotropic agent.

34. The method of claim 33, wherein the ion source is selected from the group consisting of: NaCl, MgCl₂ and imidazole.

35. The method of claim 33 or 34, wherein the solvent is selected from the group consisting of: glycerol, water and imidazole.

36. The method of any one of claims 33-35, wherein the thixotropic agent is selected from the group consisting of: polyethylene glycol, clay, microgel and colloidal silica.

37. The method of any one of claims 28-36, wherein each of the first and second uncured dielectric materials comprises an uncured silicone elastomer.

38. The method of any one of claims 28-37, wherein the flowing of the first viscoelastic conductor material occurs at a first flow rate f_1 , the flowing of the first uncured dielectric material occurs at a second flow rate f_2 , the flowing of the second viscoelastic conductor material occurs at a third flow rate f_3 , the flowing of the second uncured dielectric material occurs at a fourth flow rate f_4 , and wherein $f_4 > f_3 > f_2 > f_1$.

39. The method of claim 38, wherein each of the flow rates f_1 , f_2 , f_3 and f_4 is from about 0.1 $\mu\text{L/s}$ to about 10 $\mu\text{L/s}$.

40. The method of any one of claims 29-39, wherein the extrusion head moves relative to the surface at a print speed of from about 1 mm/s to about 10 mm/s.

41. The method of any one of claims 29-40, wherein the extrusion head moves relative to the surface at a first print speed and at a second print speed, the first print speed being lower than the second print speed and being employed to form ends of the soft sensor fiber having increased layer thicknesses.

42. The method of any one of claims 28-41, further comprising curing the first and second uncured viscoelastic materials.

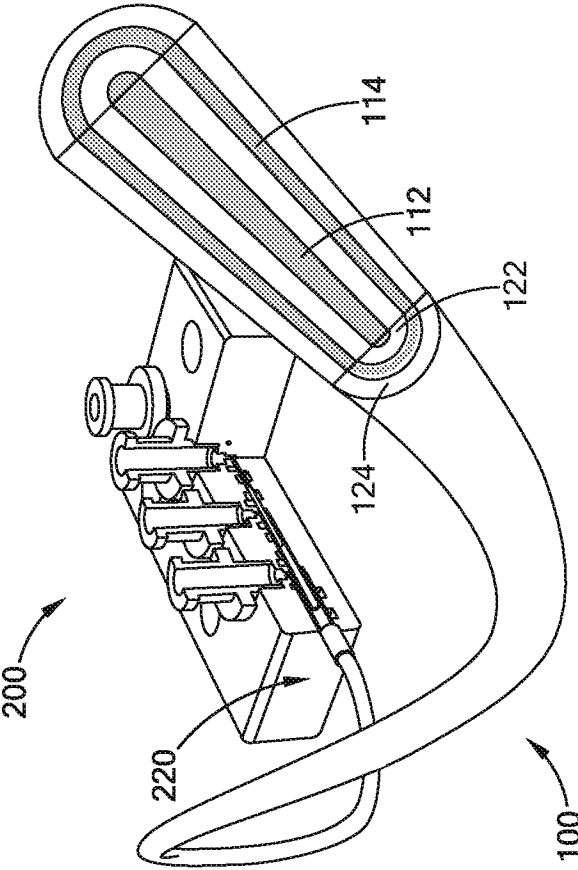
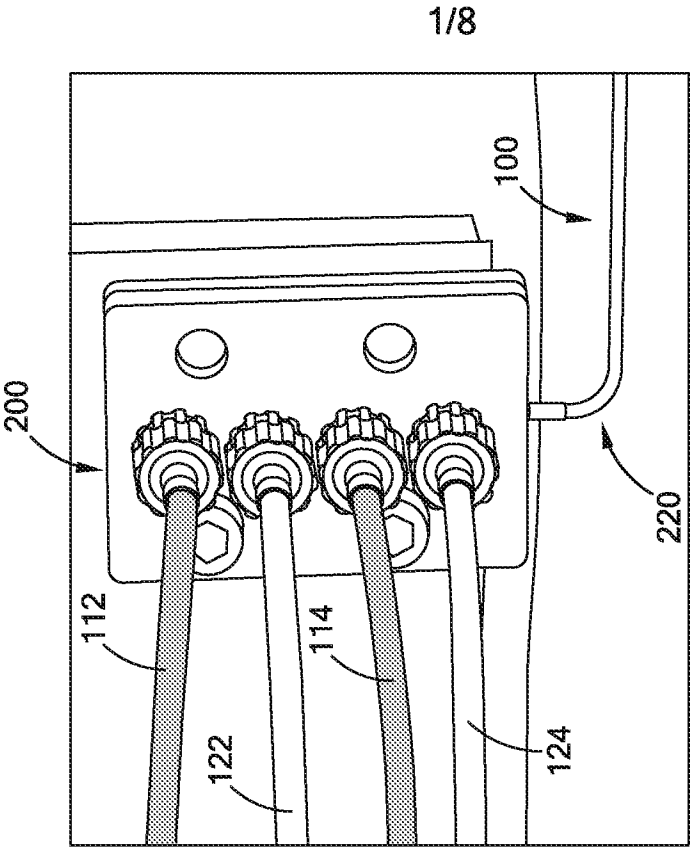
43. The method of claim 42, wherein the curing entails thermal curing, UV radiation curing and/or chemical curing.

44. The method of any one of claims 28-43 further comprising, after forming the soft sensor fiber, attaching, at at least one end of the soft sensor fiber, a first wire to the first viscoelastic conductor material and a second wire to the second viscoelastic conductor material, thereby establishing electrical connections to the soft sensor fiber.

45. The method of claim 44, further comprising, before attaching the second wire to the second viscoelastic conductor material, using a third uncured dielectric material to electrically isolate the first and second viscoelastic conductor materials, wherein attaching the second wire comprises inserting the second wire through the third uncured dielectric material.

46. The method of claim 45, wherein the third uncured dielectric material comprises a higher stiffness than that of the first or second uncured dielectric materials.

47. The method of any one of claims 44-46, further comprising securing an end cap to the at least one end of the soft sensor fiber.



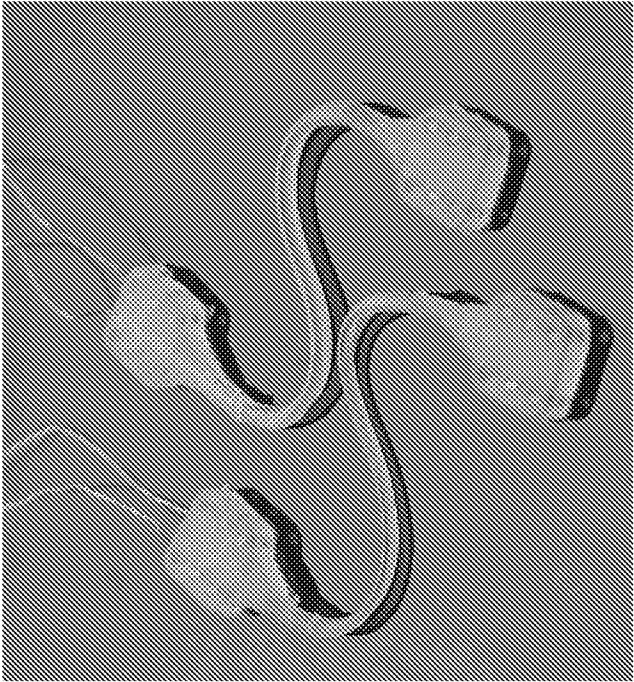


FIGURE 1F

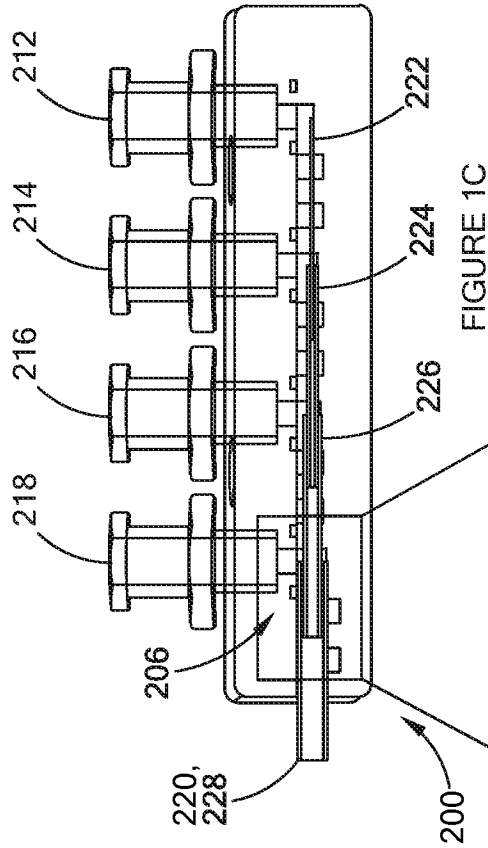


FIGURE 1C

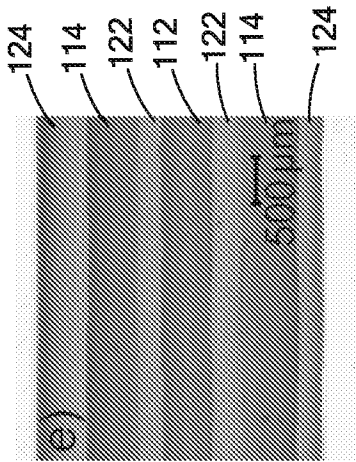


FIGURE 1E

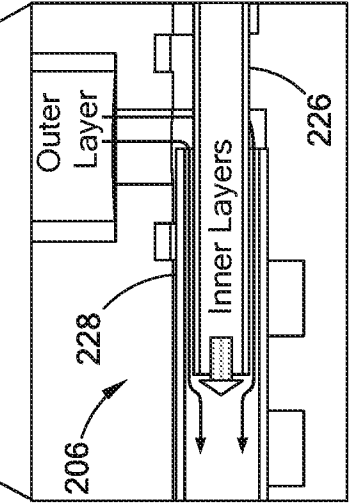
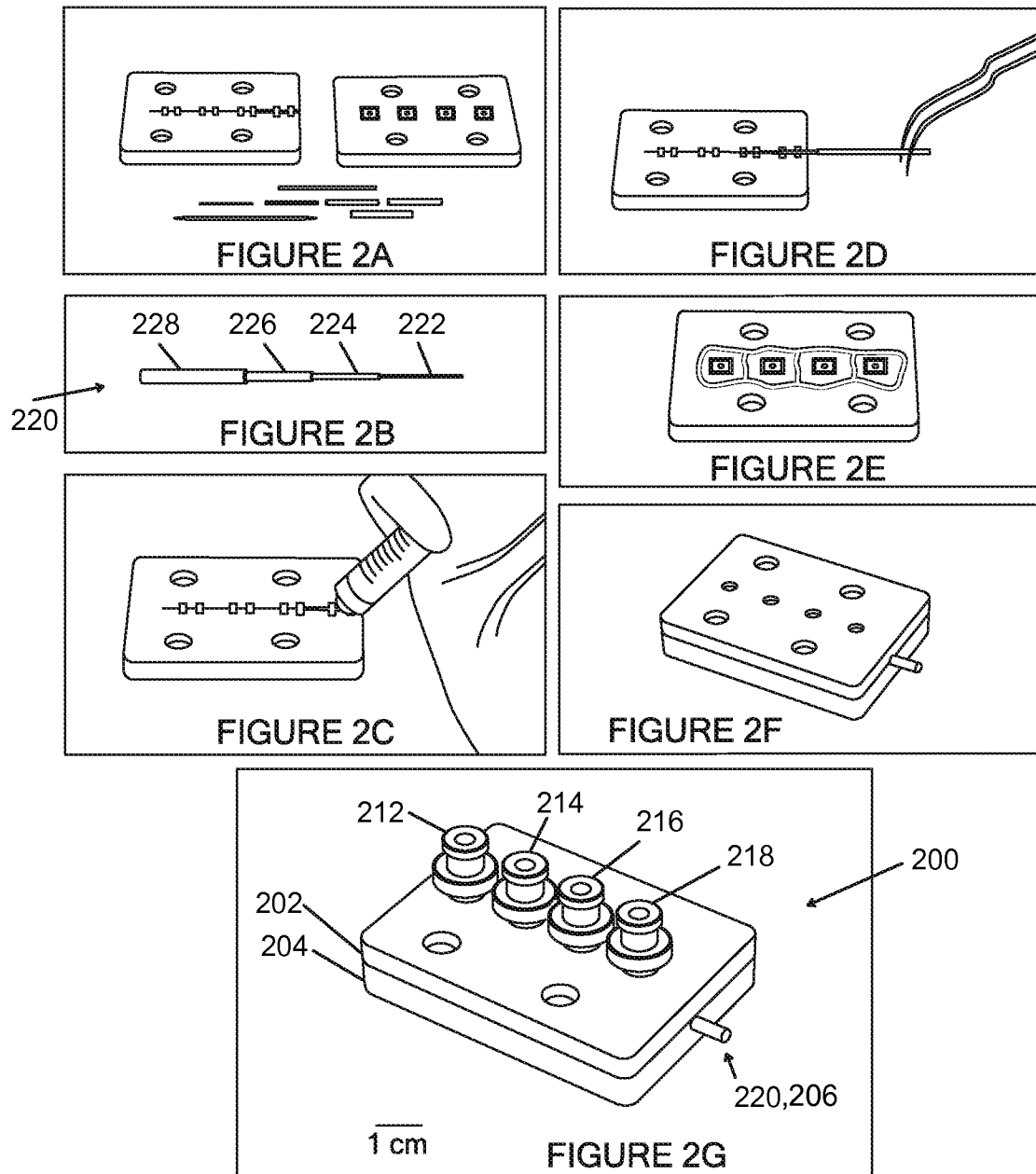
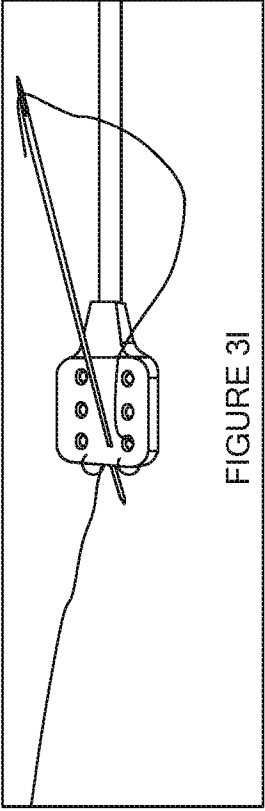
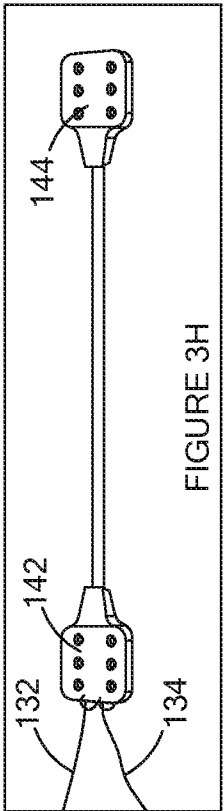
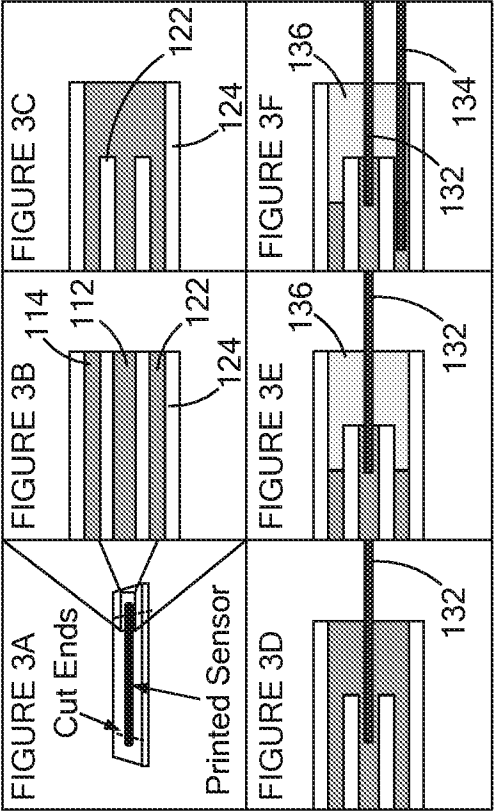
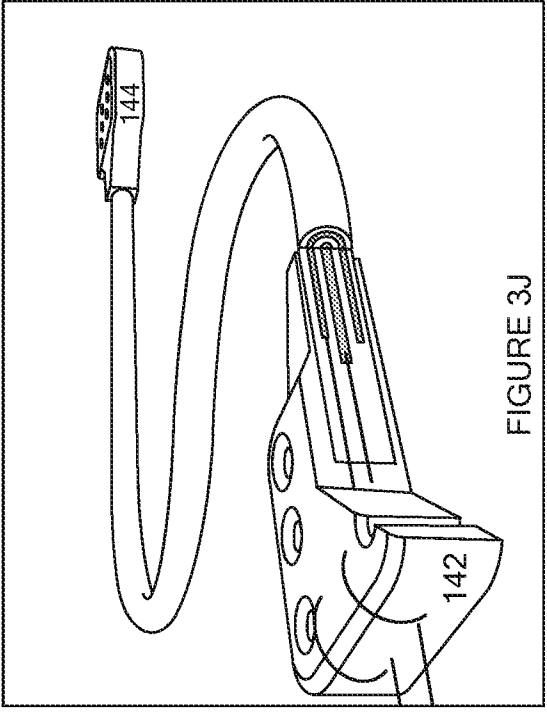
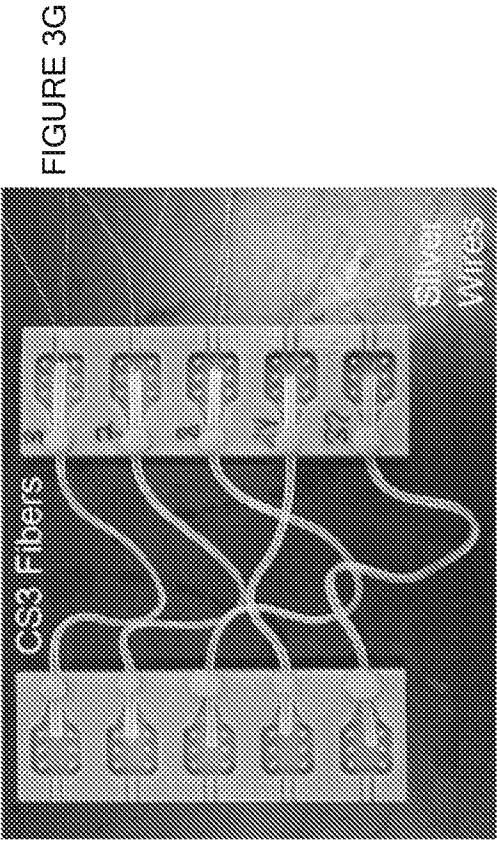


FIGURE 1D





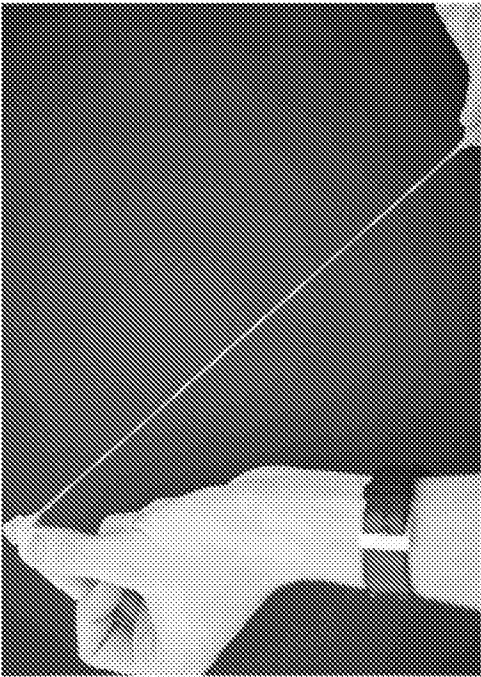
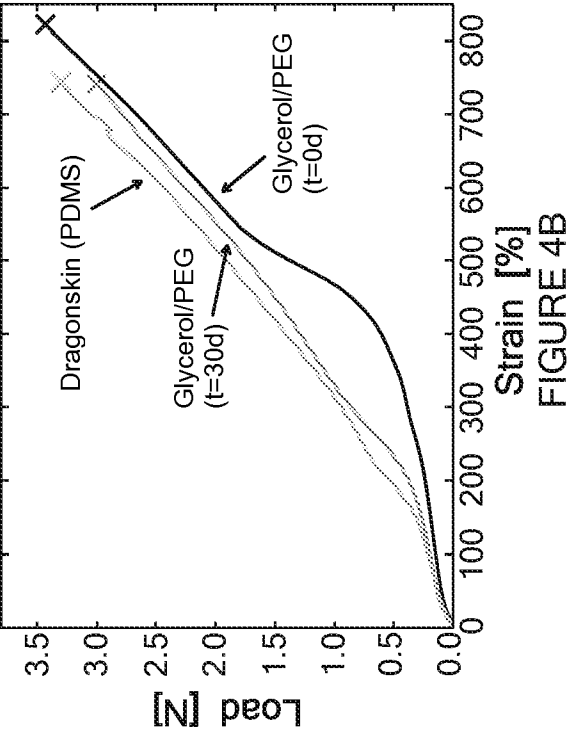


FIGURE 4D

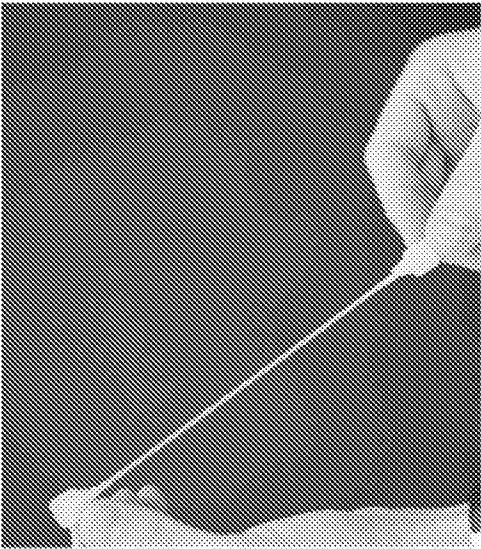
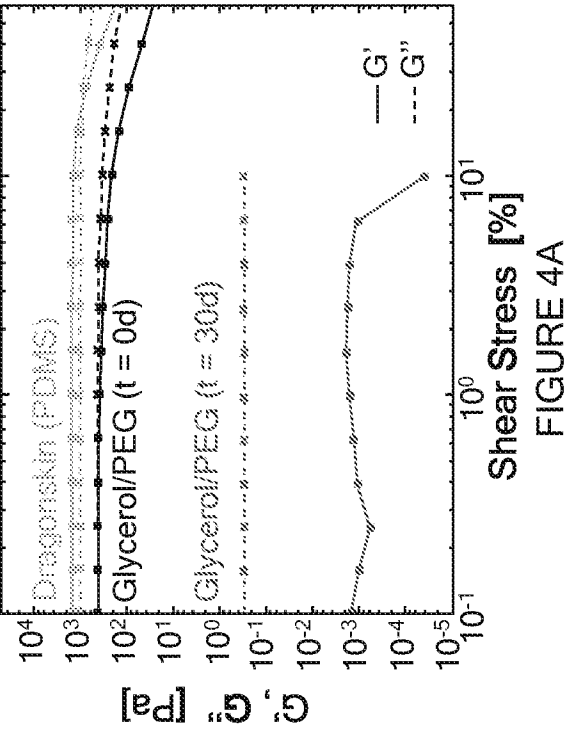


FIGURE 4C

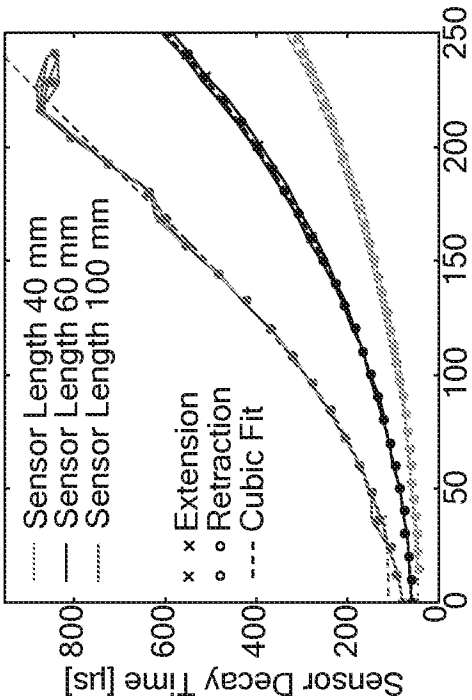


FIGURE 5B

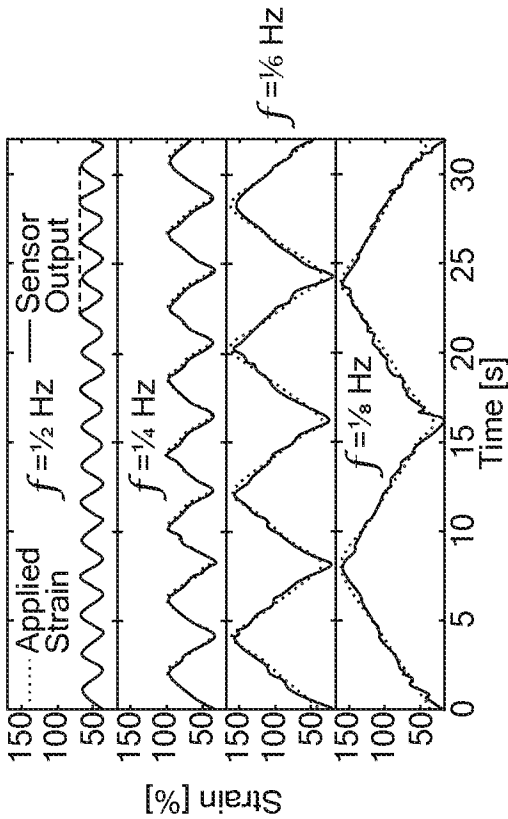


FIGURE 5D

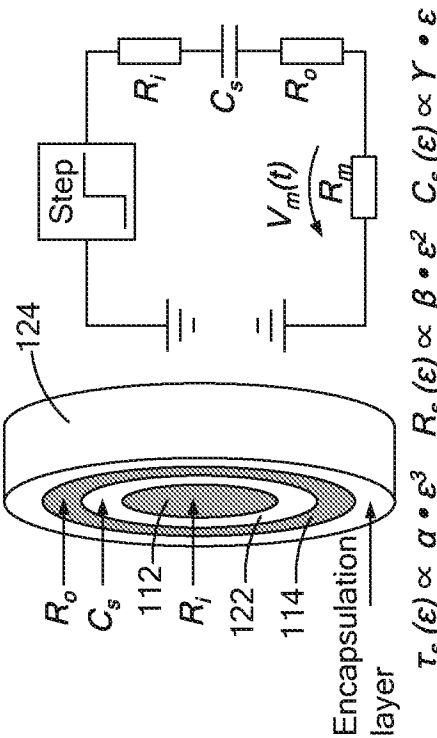


FIGURE 5A

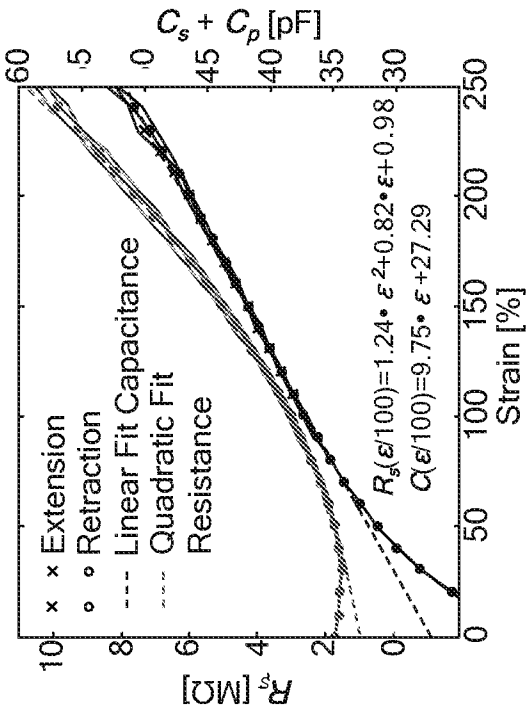


FIGURE 5C

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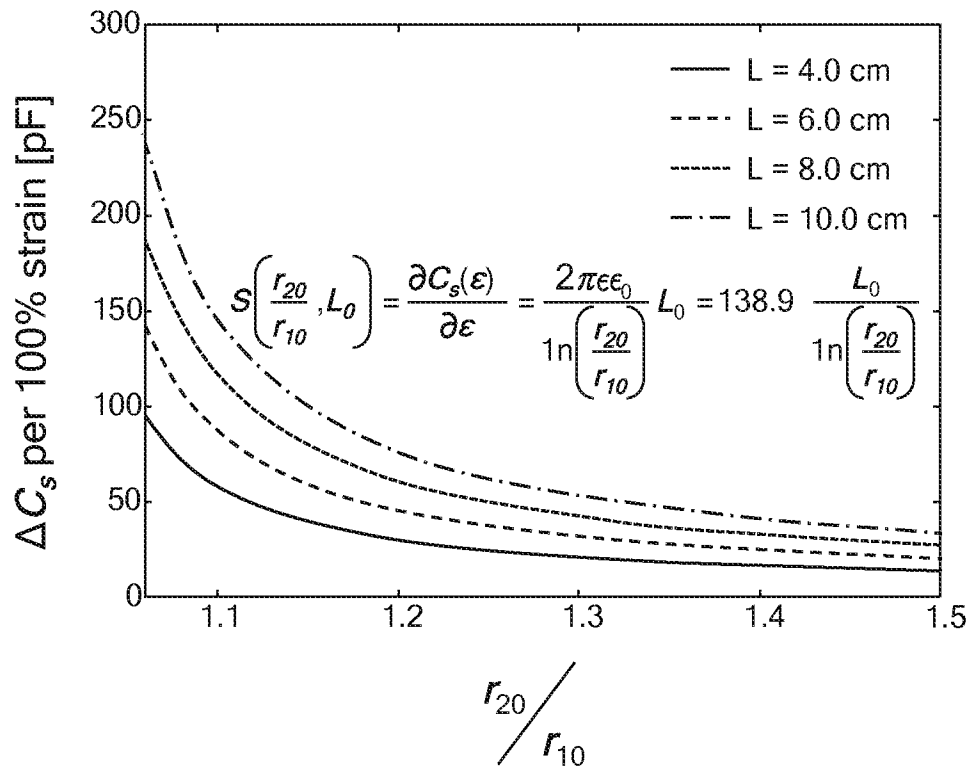


FIGURE 6

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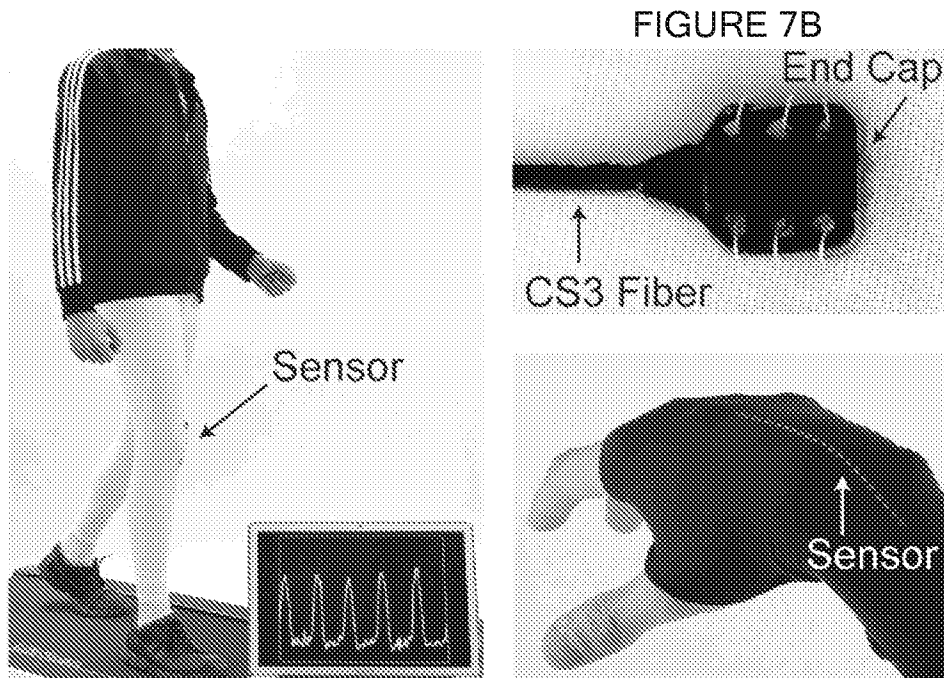


FIGURE 7A

FIGURE 7C

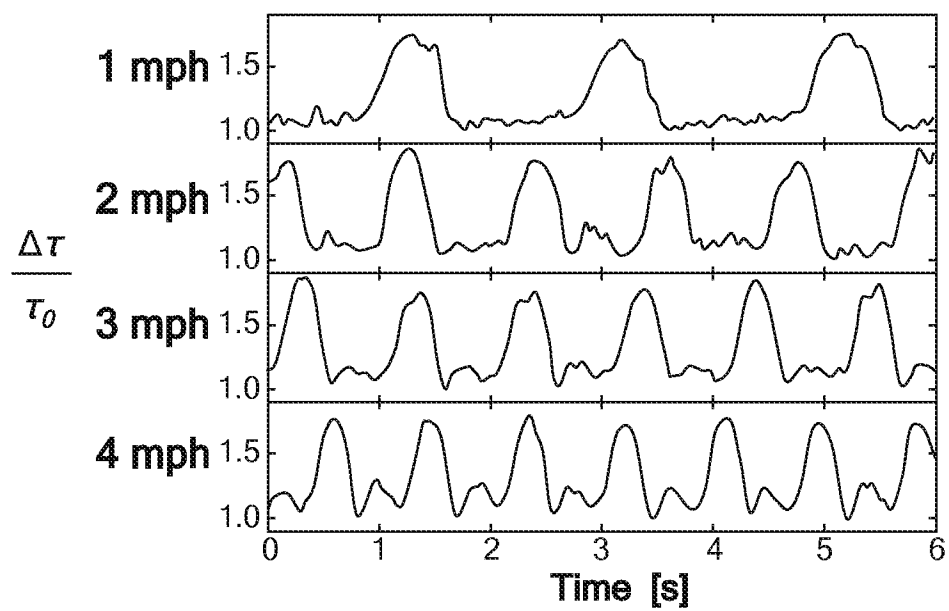


FIGURE 7D

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/42784

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01L 41/087, 41/23, 41/333 (2015.01)

CPC - H01L 41/087, 41/23, 41/333

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): H01L 41/08, 41/087, 41/22, 41/23, 41/33, 41/333 (2015.01)

CPC: H01L 41/08, 41/0836, 41/087, 41/22, 41/23, 41/33, 41/333

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google; Google Scholar; ProQuest; KEYWORDS: soft sensor fiber core conductor dielectric layer elastomeric material outer conductor conductive liquid encapsulation layer extrusion head

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — A	US 2009/0085444 A1 (RIVERA, R. et al.) April 02, 2009; abstract; figures 1E-1F, 2H, 4O-4P; paragraphs [0009, 0068-0069, 0088, 0116, 0142, 0198-0199]	1-4 — 26, 28
A	US 2014/0072703 A1 (POZZATI, G. et al.) March 13, 2014; paragraphs [0004, 0056, 0061, 0066, 0073-0074]	26, 28
A	US 2014/0212100 A1 (OPTISENSE NETWORK, LLC) July 31, 2014; abstract; paragraphs [0056, 0069]	28
P, Y	FRUTIGER, A. et al. Capacitive Soft Strain Sensors via Multicore-Shell Fiber Printing, March 9, 2015, Advanced Materials, Vol. 27, No. 15 (2015) [online], [retrieved on 2015-10-06]. Retrieved from the Internet <URL: http://scholar.harvard.edu/files/lewisgroup/files/capacitive_soft_strain_sensors_via_multicore-shell_fiber_printing.pdf >	1-4, 26-34

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

07 October 2015 (07.10.2015)

Date of mailing of the international search report

04 NOV 2015

Name and mailing address of the ISA/

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Shane Thomas

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/42784

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 5-25, 35-47
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.