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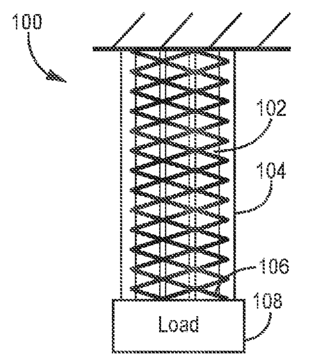


FIG. 1A

(57) **Abstract:** A selectively actuated textile includes one or more pieces of fabric having one or more circumferentially constrained channels and one or more hollow elastic tubes located within the circumferentially constrained channels and configured to receive a working fluid. Selectively providing or removing working fluid from the hollow elastic tubes provides for selective actuation of the textile.

WO 2020/056271 A1

SOFT ACTUATOR AND METHOD OF MAKING THE SAME

GOVERNMENT LICENSE RIGHTS

[0001] This invention was made with government support under contracts 1623459 and 1628831 awarded by the National Science Foundation. The government has certain rights in the invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application claims the benefit ofU.S. Provisional Application No. 62/731,583, filed September 14, 2018, titled “SOFT ACTUATOR AND METHOD OF MAKING THE SAME”. The provisional application is incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0003] The present invention is related to actuators, and in particular to soft actuators.

BACKGROUND

[0004] An array of soft actuator technologies has emerged in recent years, offering the promise to enable safe and powerful actuation in a growing number of common environments and applications, and facilitating new designs for soft robotic systems. Among these actuators are artificial muscles, which emulate the ability of biological muscles to perform mechanical work via contractile motions. Many approaches to the design of such actuators have been proposed, for applications in industry, wearable devices, or medical systems.

[0005] Typical actuators utilized in robotic applications - such as electromagnetic motors, hydraulic pistons, and piezoelectric actuators, are inappropriate due to the rigidity associated with these systems. A variety of ‘soft’ actuators have been proposed, including shape memory alloys (SMA), shape memory polymers (SMP), electroactive polymers (EAPs), and pneumatic artificial muscles (PAM) such as the McKibben muscle, which can be selectively actuated to provide a force and embedded within garments and textiles. However, each of the proposed soft actuators has drawbacks. For example, SMA provides high force density, but poor total strain (i.e., displacement or movement) as well as poor efficiency. In addition, SMAs require heat to actuate, which makes it a poor choice for embedding in textiles/fabrics. SMPs exhibit very high strains, but only limited force production. EAPs provide large strains but require high voltages for operation. Pneumatic artificial muscles provide a high force density, but relatively poor total strain.

[0006] It would therefore be beneficial to develop a soft actuator that overcomes these def ciencies, providing high force density in combination with high strain.

SUMMARY OF THE INVENTION

[0007] According to one aspect, a method of fabricating a soft actuator includes forming one or more channels within one or more pieces of fabric, wherein the channels provide constraint in a circumferential direction. One or more hollow elastic tubes are placed within the one or more channels. At least one end of each of the one or more hollow elastic tubes is connected to a delivery system capable of providing a working fluid to the one or more hollow elastic tubes.

[0008] According to another aspect, a selectively actuated textile is provided that includes one or more pieces of fabric having one or more circumferentially constrained channels formed within the one or more pieces of fabric. In addition, the selectively actuated textile includes one or more hollow elastic tubes positioned within the one or more channels and configured to receive a working fluid, wherein working fluid is selectively provided to or removed from the one or more hollow elastic tubes to actuate the selectively actuated textile.

[0009] According to another aspect, a haptic feedback garment is provided that includes one or more soft actuators, one or more tubes, and one or more pumps. The one or more soft actuators are embedded within the haptic feedback garment, wherein each actuator includes a hollow elastic tube configured to receive a working fluid. Each of the one or more tubes is connected on a first end to an input associated with each of the soft actuators. Each of the one or more pumps is configured to provide a working fluid to one of the one or more soft actuators via one of the one or more tubes, wherein application of the working fluid to the soft actuator provides a haptic response to a user wearing the haptic feedback garment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figures 1A and 1B are side and cross-sectional schematics of a soft actuator in a first, pressurized state according to some embodiments.

[0011] Figures 1C and 1D are side and cross-sectional schematics of a soft actuator in a second, non-pressurized or relaxed state according to some embodiments.

[0012] Figures 2A and 2B are cross-sectional views of a soft actuator that illustrates the forces applied within the textile according to some embodiments.

[0013] Figure 3 is a schematic illustrating the fabrication of a soft actuator according to some embodiments.

[0014] Figures 4A-4B are schematic views of a soft actuator operating in a force mode according to some embodiments.

[0015] Figures 4C-4E are views illustrating a plurality of applications utilizing soft actuators operating in a force mode according to some embodiments.

[0016] Figures 5A-5B are schematic views of a soft actuator operating in a displacement mode according to some embodiments.

[0017] Figures 5C-5D are views illustrating a soft actuator operating in a displacement mode according to some embodiments.

[0018] Figures 6A-6D are graphs illustrating the relationship between force and displacement, length and volume, force and displacement, and external force and displacement according to some embodiments.

[0019] Figures 7A-7C are graphs illustrating the relationship between force and displacement according to some embodiments.

[0020] Figures 7D-7F are graphs illustrating the results of tests according to some embodiments.

[0021] Figures 8A and 8B are schematic views of a soft actuator that incorporates one or more soft sensors according to some embodiments.

[0022] Figures 9A and 9B are photographs of soft actuator that incorporates one or more soft sensors according to some embodiments.

[0023] Fig. 10 is a picture of a glove that utilizes soft actuators and soft sensors according to some embodiments.

[0024] Figs. lla and llb are side views of a multi-actuated Fluidic Fabric Muscle Sheet (FFMS) according to some embodiments.

[0025] Figs. l2a-l2c are views of a Fluidic Fabric Muscle Sheet (FFMS) combined with a second, passive layer to provide out-of-plane bending according to some embodiments.

[0026] Figs. l3a-l3e are views of a Fluidic Fabric Muscle Sheet (FFMS) that provides biaxial bending according to some embodiments.

DETAILED DESCRIPTION

[0027] The present disclosure is directed generally to a soft actuator that is actuated in response to a change in volume and/or pressure of a working fluid. In general, the soft actuator includes one or more hollow elastic fibers located within a textile fabric, wherein the hollow elastic fibers are constrained circumferentially. Actuation of the device includes selectively providing a working fluid into the one or more hollow elastic fibers to operate the actuator in either a pressurized state or a relaxed state. In a pressurized state, the circumferential constraints placed around the hollow elastic fibers prevent the hollow elastic fibers from expanding in a circumferential direction, resulting in the actuator lengthening in a direction transverse to the circumferential direction (i.e., along the axis of the hollow elastic fibers). When lengthened, elastic energy is stored in the elastic fibers of the soft actuator. When operated in a relaxed state by removing the working fluid the stored elastic energy causes the soft actuator to contract.

[0028] Figures 1A and **IB** are side and cross-sectional schematics, respectively, of a soft actuator 100 in a first, pressurized state according to some embodiments, and Figures 1C and **ID** are side and cross-sectional schematics, respectively, of a soft actuator 100 in a second, non-pressurized state according to some embodiments.

[0029] In the embodiment shown in Figures 1A-1D, a soft actuator 100 includes one or more hollow elastic fibers 102, fabric 104, and circumferential constraint 106. In the cross-sectional view shown in Figure 1B, a plurality of hollow elastic fibers 102 extend parallel to one another along the length of elastic fabric 104. In some embodiments, the plurality of hollow elastic fibers 102 may include a single elastic fiber 102 that is wound back and forth to provide the plurality of hollow elastic fibers 102 visible in Figures 1A-1D. The one or more hollow elastic fibers 102 are configured for coupling to a hydraulic or pneumatic motor that supplies a working fluid (either hydraulic or pneumatic) to the one or more hollow elastic fibers 102.

[0030] In the embodiment shown in Figures 1A-1D, the plurality of hollow elastic fibers 102 are restrained circumferentially by circumferential constraint 106. In some embodiments, circumferential constraint 106 is comprised of inextensible stitching that extends along the outer circumference of the hollow elastic fiber. That is, in some embodiments the stitching defines a channel in which the hollow elastic fibers are housed. In some embodiments, the stitching is directed linearly along the respective sides of the channel in what is known as a side-stitch pattern. In other embodiments, the stitching is arranged in a different pattern, such as cross-stitched back and forth over the channel such that the inextensible stitching extends in a direction approximately transverse to the direction of actuation of the hollow elastic fiber 102 as shown in Figures 1A-1D. The cross-sectional view shown in Figure 1B illustrates how the stitching 106 surrounds and constrains circumferentially each hollow elastic fiber 102. Although the embodiment shown in Figures 1A-1D utilizes inextensible stitching 106 to restrain hollow elastic fibers 102, in other embodiments other means may be utilized to provide circumferential restraint of each of the one or more hollow elastic fibers 102. For example, in some embodiments the one or more fabric layers 104 are glued to form the circumferential constraint 106. In other embodiments heat sealing and/or ultrasonic welding to form the circumferential constraint 106.

[0031] As described above, hollow elastic fibers 104 are configured to be coupled at a first end (e.g., top end) to a hydraulic or pneumatic pump that provides a working fluid to the one or more hollow elastic fibers 104. In some embodiments, the working fluid is nearly incompressible (e.g., liquid or hydraulic working fluid) and in other embodiments may be compressible (e.g., gaseous or pneumatic working fluid). In some embodiments, a pump is utilized to provide the working fluid to the one or more hollow elastic fibers 102. The working fluid may be gaseous or liquid, and therefore the pump utilized may be pneumatic or hydraulic. For example, in some embodiments a syringe and linear motor is utilized to provide the working fluid (e.g., liquid) to the one or more hollow elastic fibers 102, resulting in the length of the soft actuator 100 to increase.

[0032] In the embodiment shown in Figures 1A and 1B, the selectively-actuated textile 100 is in a first, pressurized state in which a pressurized working fluid is provided to each of the hollow elastic fibers 102. Because the one or more hollow elastic fibers 102 are constrained in the circumferential direction (i.e., the A-dircction) by circumferential constraint 106, the only direction in which the one or more hollow elastic fiber 102 is allowed to extend in response to the pressurized working fluid is in the longitudinal direction (i.e., the y-dircction). More particularly, the provision of pressurized working fluid causes the volume of hollow elastic fiber 102 to increase. Because of the circumferential constraint, the one or more hollow elastic fibers 102 lengthens to accommodate the increase in volume. As the hollow elastic fiber 102 lengthens, the entire textile (e.g., fabric 104) lengthens. Lengthening of the fabric 104 and hollow elastic fibers 102 stores potential energy in the elastic components of the selectively-actuated textile 100. When the pressure associated with the working fluid is removed, the one or more hollow elastic fibers 102 experience a decrease in volume, which causes both the hollow elastic fibers 102 and the elastic fabric 104 to release stored elastic energy, allowing the textile to apply a contracting force to load 108 as shown in Figures 1C and ID.

[0033] A variety of different materials may be utilized to fabricate the selectively actuated textile 100. The selection of materials may depend on the application, specifically on the elongation and/or force requirements. In some embodiments, the hollow elastic fibers 102 must be elastic. The fabric 104 may be elastic or inelastic, but the dynamic forces delivered by the actuator depend, in part, on the tension remaining in the hollow elastic fibers 102 and/or the elastic fabric (if present) 104 after the addition of the hydraulic fluid. In some embodiments, the fabric is selected to provide negligible stiffness in the axial direction of the tube. In some embodiments, non-stretchable fabrics such as cotton weaves are utilized in combination with a wrinkling process to allow lengthening in the axial direction. In some embodiments, stretchable fabrics may be utilized in combination with across-tube stitching to provide radial constrain of the hollow elastic fibers 102. Stretchable fabrics may include uniaxially elastic (two-way stretch) or biaxially elastic (four-way stretch). In some embodiments, this may include elastic fibers such as Spandex, spun into stretchable yam, and integrated along weft, warp, or both directions of the weave, yielding one or two-way stretch fabric, respectively. In other embodiments, either elastic or non-elastic fibers may be used to create a knit, wherein stretchability depends on the design of the looping structure. In some embodiments, the stiffness of the elastic fabric 104 and the hollow elastic fibers 102 is approximately equal. In other embodiments, the fabric 104 is inelastic but is bunched in a manner that makes it less stiff than the hollow elastic fibers 102. The stitching 106 circumferentially constrains the hollow elastic fibers 102 but allows for lengthening of the overall textile 100. In some embodiments, stitching 106 is provided transverse to the direction of actuation (i.e., lengthening direction), in a cross-stitch configuration. In some embodiments, stitching 106 defines the width of channels utilized to accept hollow elastic fibers 102, and the fabric is used to provide the circumferential constraint. In some embodiments, the width of the channel defined by the stitching 106 and the diameter of the hollow elastic fibers 102 are selected such that the increase in fluid volume in the hollow elastic fiber 102 elicits the greatest increase in the rest length of the rest length of the hollow elastic fiber 102. In some embodiments, the width of the channel defined by the stitches 106 are equal to approximately one-half of the outer circumference of the hollow elastic fiber 102. In some embodiments, the type of thread utilized for the stitches may include inextensible high-strength nylon thread

[0034] In addition to selection of materials for hollow elastic fibers 102, elastic fabric 104 and circumferential constraint 106, various fluids may be utilized with respect to hollow elastic fibers 102. In some embodiments, the working fluid is an incompressible working fluid (e.g., liquid). One benefit of incompressible fluids is that the lengthening of the textile is directly related to the volume of incompressible fluid provided, which provides quasi-static response. In other embodiments, the working fluid may be a compressible fluid (e.g., gas). Benefits of compressible fluids include a reduction in mass of the actuator (as compared with embodiments that utilized incompressible fluids). However, the volume-pressure relationship are not static, and therefore complicate methods of controlling the length of the textile in response to a measured attribute (e.g., pressure).

[0035] Figures 2A and 2B are side schematic views of a selectively actuated textile 100 that illustrates the forces acting on a single hollow elastic fiber 102 according to some embodiments. In the embodiment shown in Figures 2A and 2B, hollow elastic fiber 102 is constrained circumferentially by inelastic stitches 106.

[0036] In the circumferential direction, the tension T_w in the stitches 106 wrapped around the hollow elastic fiber 102 balances the force of pressure P exerted by the working fluid within the hollow elastic fiber 102, which can be expressed as, $T_W N = 2PLr$, where N is the number of wraps or stitches, L is the current length of the hollow elastic fiber 102, and r is the radius of the hollow elastic fiber 102. In the radial direction, the stress in the hollow elastic fiber 102 is relatively small (equal to P on the inner surface), but between fibers, the tubing can bulge as shown in Figure 2B. The deflection of the center of the bulge away from the neutral position is approximated for large stretch as $\delta = atan\left(\frac{\beta}{2}\right)$ wherein $\beta = \frac{aP}{\mu h_0}$, and a is half the separation of the fibers, μ is the shear modulus, and ho is the thickness with no pressure. This model suggests that a thicker wall, lower operating pressures, and a denser stitching all aid in the prevention of ballooning. However, when the fabric is a non-stretch fabric, the fabric itself prevents any ballooning.

[0037] In the axial direction, the elastic force in the hollow elastic fiber, F_e, that causes the elastic fiber 102 to contract is balanced by the external force, F_{ext} and the force due to the pressure inside the fiber, F_p, wherein $F_{ext} = F_e - F$, where $F_e = k(L - Lf)$ and $F_p = AP$: Here, k is the stiffness of the elastic tubing, Lf is the free length of the elastic membrane, and A is the cross-sectional area of the tubing (i.e., nr^2). This model suggests a thicker wall can increase the elastic force F_e (by increasing the stiffness coefficient k), but also that this thicker wall requires a higher pressure to attain elastic force $F_e = 0$. A number of simplifications were made in describing the model: rubber stress-strain is considered linear, Poisson contraction of the wall is ignored, and angle changes of the stitching are considered small.

[0038] Figure 3 is diagram illustrating fabrication of a soft actuator 300 according to some embodiments. At step 302, two or more pieces of fabric 304 are stacked together. As described in more detail below, fabric 304 may be non-stretch, a two-way stretch fabric, or a four-way stretch fabric. At step 308, one or more channels are formed between the stacked layers of fabric 304 that form a circumferential constraint around the channels. In some embodiments, inextensible stitching 306 is utilized to form these circumferential constraints. Various types of stitches may be utilized, including side-stitching, cross-stitching, and/or a combination of side-stitching and cross-stitching.

[0039] In some embodiments, the channels formed by way of stitching include a plurality of openings for receiving a plurality of individual hollow elastic fibers 310, as shown in the top embodiment of steps 308 and 312. In other embodiments, the channels formed by way of stitching include openings for receiving a single hollow elastic fiber 310 which is wound back and forth as shown in the bottom embodiment of steps 308 and 312. Various materials may be utilized for hollow elastic fiber 310, and selection may be based on attributes such as desired lengthening, force generation, and Young's modulus. For example, in some embodiments, latex tubing generates a relatively large elastic force, has a relatively large Young's modulus, and is capable of extending up to five times its original size. In other embodiments, silicone tubing may be utilized.

[0040] At step 314, one end of the hollow elastic fibers 310 are sealed. In the embodiment in which a plurality of individual hollow elastic fibers 310 are utilized, this may include sealing each of the hollow elastic fibers 310 on one side of the fabric (i.e., left side). The other end of the hollow elastic fibers 310 remains open for connection to the pneumatic or hydraulic pump for receiving the working fluid during actuation. In embodiments in which a single hollow elastic fiber 310 is utilized, this requires that one end of the fiber 310 be sealed.

[0041] In some embodiments, at step 314 the fabric 304 may be wrinkled (if necessary) to allow the fabric to lengthen during actuation. In some embodiments, wrinkling of fabric 304 may be utilized to allow fabric 304 to lengthen, by taking up the slack afforded by the wrinkles. This may be particularly beneficial if utilizing a non-stretch or inelastic fabric. In other embodiments, wrinkling of the fabric 304 may not be required. In particular, if fabric 304 is a stretch or elastic fabric, it may not be necessary to wrinkle the fabric as shown at step 314. In the embodiment shown at step 314, wrinkles 315 are shown. In some embodiments, wrinkling of the fabric includes stretching the hollow elastic fibers 310 along the axial direction, clamping or otherwise securing the fibers 310 to maintain the fibers in an extended state, bunching/wrinkling the fabric 304, and then attaching the hollow elastic fibers 310 to the fabric 304 at the ends of the actuator 300 to ensure a pre-tensioning of the hollow elastic fibers 310. In some embodiments, because the fabric 304 is inelastic, side-stitching may be utilized to form the channels for receiving the hollow elastic fibers 310 because the inelastic nature of the fabric 304 will provide circumferential constraint.

[0042] At step 316, additional stitching may be provided as necessary following sealing of the hollow elastic fibers at step 314. For example, this may include adding cross-stitching to stitching that originally included only side-stitching, or vice versa. In the embodiment shown in the bottom, additional stitching is provided around the channels that switch back and forth.

[0043] At step 318, the one or more hollow elastic fibers 310 are connected to fittings and/or tubing 320 for delivery of the working fluid. For example, in some embodiments the one or more hollow elastic fibers 310 are connected to a rigid tube via one or more fittings that allow the working fluid to be selectively provided to the hollow elastic fibers 310.

Stitches / Combined Fabrics	Side stitch only	Cross stitch only	Both Stitches	Pros	Cons
Non-stretch				Cross stitch not needed. No alignment needed. No ballooning.	No fabric stretchability.
Two-way				Own stretchability even without wrinkle.	Difficult to align accurately.
Four-way		Limited wrinkle	Limited wrinkle	No alignment needed.	Must use cross stitch.
Pros	Easy to insert tube.	Better constrain in the direction other than actuation.	Best for preventing ballooning.		
Cons	Slight ballooning for stretch fabrics.	Difficult to insert tube. Ballooning inbetween stitches at sides.	Difficult to insert tube.		

TABLE 1

[0044] Table 1, provided above, describes a number of the various features/attributes that may be selected with respect to fabrication of the planar actuation. For example, various fabrics are described in the left column, which includes non-stretch fabric, two-way stretch fabric, and four-way stretch fabric. In addition, pros and cons of each are provided. For example, non-stretch fabric is described as not requiring cross-stitching, and because the fabric does not stretch does not exhibit the ballooning problems noted with respect to Figure 2B, above. However, non-stretch fabric is not stretchable, and therefore does not naturally allow for lengthening in the direction of actuation. In embodiments utilizing non-stretch fabric, wrinkling of the fabric is required to allow for the desired lengthening of the actuator. In comparison, two-way stretch fabric (allows stretching along one-axis) allows for lengthening of the planar actuator without wrinkling but requires alignment of the hollow elastic fibers along the direction of stretchability. Four-way stretch fabric, which allows stretching along both axes) allows lengthening of the planar actuator without wrinkling and does not require alignment of the hollow elastic tubes with the direction of stretchability but does require the use of cross-stitching (as opposed to just side-stitches) in order to prevent ballooning issues.

[0045] In addition, the top row of Table 1 describes various types of stitching that may be utilized, including side-stitches, cross-stitches, and a combination of side-stitches and cross-stitches. Pros and cons of each are provided. For example, a benefit of side-stitches is that the stitching process itself is relatively straightforward, and insertion of the hollow elastic tubes is fairly easy. However, side-stitching suffers from ballooning issues when utilizing stretchable fabrics. In contrast, cross-stitches provide better circumferential constraint of the hollow elastic fibers/tubing but is more difficult to form the channels for accepting the hollow elastic tubing. A combination of side-stitches and cross-stitches can provide improved performance with respect to reducing ballooning issues but is similarly difficult to form the channels for accepting the hollow elastic tubing.

[0046] In the embodiment shown in Figure 3, the actuator 300 is a soft planar actuator. For example, the planar actuator is approximately two-dimensional (e.g., length and width), with a relatively small depth. In some embodiments, this is particularly beneficial for use in articles of clothing such as sleeves.

[0047] Figures 4A and 4B illustration a force mode planar actuator 400 operating in a pressurized state and a relaxed state, respectively. A force mode planar actuator is utilized to selectively generate a force on a desired load, and may be utilized in a number of applications, examples of some of which are shown in Figure 4C.

[0048] In the embodiment shown in Figures 4A and 4B, planar actuator 400 includes a plurality of hollow elastic fibers 402 fabricated within a fabric 404. In this embodiment, both ends of the planar actuator 400 are fixed in space. Application of a working fluid to the hollow elastic fibers 402 opposes the elastic force F_e associated with the hollow elastic fibers 402 and/or fabric

404 and therefore reduces the force applied to the load 406 (i.e., fixed force gauge). That is, increasing the pressure of the working fluid provided to the planar actuator 400 reduces the force applied to the respective load. Conversely, reducing the pressure of the working fluid provided to the planar actuator 400 reduces the force provided by the working fluid to oppose the elastic force F_e, thereby increasing the force applied to the respective load.

[0049] The change in force provided by planar actuator 400 may be utilized in a number of applications. For example, compression applications in which the planar actuator is wrapped around a structure. Figures 4C-4E illustrates a plurality of such application, including a uniform structure 420, a tapered structure 422, or an arbitrarily shaped structure 424. The uniform structure 420 could be utilized to provide compression to a person’s arm, while the tapered structure 422 may be more appropriate for providing compression on a patient’s leg. The arbitrary structure 424 could be utilized on a variety of shapes, allowing force to be selectively applied via transition from a pressurized state to a relaxed state.

[0050] Figures 5A and 5B illustration a displacement mode planar actuator 500 operating in a pressurized state and a relaxed state, respectively. A displacement mode planar actuator 500 is utilized to selectively displace an object in a desired direction, and may be utilized in a number of applications, examples of some of which are shown in Figure 5C.

[0051] In the embodiment shown in Figures 5A and 5B, planar actuator 500 includes a plurality of hollow elastic fibers 502 fabricated within a fabric 504. In this embodiment, one end of the planar actuator 500 is fixed in space, or neither end of the planar actuator 500 is fixed in space. Application of a working fluid to the hollow elastic fibers 502 opposes the elastic force F_e associated with the hollow elastic fibers 502 and/or fabric 504 and therefore causes the planar actuator 500 to lengthen or actuate in a desired direction as shown in Figure 5A, in which planar actuator 500 is in a pressurized state. Reduction of the pressure of the working fluid causes the planar actuator 500 to contract in length in response to the elastic force F_e associated with the one or more hollow elastic fibers 502 and/or fabric 504. In the embodiment shown in Figures 5A and 5B, the total displacement of the object due to the contraction of the elastic fibers 502 is measured as a distance d. In some embodiments, such as that shown in Figure 5B, fabric 502 is wrinkled to allow for the contraction and lengthening of the fabric 502 as desired.

[0052] The change in length provided by planar actuator 500 may be utilized in a number of applications. For example, planar actuator may be utilized in applications to lift a weight, operate a hinge structure (as shown in Figure 5C) or to create surface tension (as shown in Figure 5D). For example, in the linear application example, the planar actuator 510 is connected on a first end to a first portion 512 and on a second end to a second portion 514. The first and second portion are pivotable connected to one another. When in a pressurized state, the planar actuator 510 is lengthened, which allows the second portion 514 to pivot relative to the first portion 512 like a muscle relaxing. When in a relaxed state, the planar actuator 510 contracts, which causes the second portion to pivot upward relative to the first portion like a muscle contracting. In this way, the planar actuator 510 can be utilized to provide linear actuation.

[0053] In other application, the planar actuator may be utilized to provide surface actuation. In this embodiment, two sheet actuators 520a and 520b are combined vertically when both actuators are pressurized. Thus, the combined sheet 522 is flat when the pressure is high in both actuators 520a and 520b, while it generates biaxial curvature when both are at low pressure as shown in Figure 5D.

[0054] Figures 6A-6B are graphs illustrating the volume-displacement response of the planar actuator with a prescribed force (i.e., set force condition). In Figure 6A, the elastic force generated in response to displacement in the direction of actuation is illustrated. As shown in Figure 6A, displacement describes the lengthening of the actuator in response to an increase in pressure or volume of the working fluid. In the example provided, three discrete volumes of working fluid (Vo, Vi, and V_2) are provided. As the volume of working fluid increases, the elastic force generated by the planar actuator increases monotonically as shown in Figure 6A

[0055] Figure 6B illustrates the relationship between length and volume for a plurality of set force conditions (e.g., lines 602, 604, 606 and 608 represent set force levels *Fo, Fi, F2,* and *F3).* Once again, the length of the planar actuator is observed to increase monotonically in response to increases in the volume of the working fluid (incompressible fluid). This monotonically increasing relationship remains true despite the initial force exerted on the planar actuator.

[0056] Figures 6C and 6D illustrates the relationship between force and displacement assuming a constant volume. As shown in Figure 6C, an increase in force results in an increase in displacement of the planar actuator (e.g., lengthening). For example, application of a force F_1 results in a displacement length of L_1. Assuming the volume of working fluid V_1 remains constant, an increase in force from F_1 to F_2 increases the displacement length from L_1 to L_2. Likewise, additional increases in force result in monotonical increases in displacement.

[0057] Figure 6D illustrates the relationship between external force and displacement for a plurality of set volume conditions (e.g., lines 612, 614, 616, 618, and 620 represent set volumes V_0, V_1, V_2, V_3, and V_4). Displacement or lengthening of the planar actuator increases monotonically with increases in external force. For example, as external force increases from F_1 to F_2 to F_3 the measured displacement increases from length L_1 to L_2 to L_3, assuming volume of the working fluid remains unchanged. As shown in Figure 6D, if the volume of working fluid is increased, the displacement curve is similarly increased.

[0058] Figures 7A-7C are graphs illustrating the relationship between force and displacement assuming set force, set length and set volume, respectively. For example, Figure 7A illustrates the relationship between force and displacement at various volumes of working fluid (i.e., incompressible working fluid). As the planar actuator increases in length (i.e., as displacement increases), the elastic force exerted by the planar actuator increases monotonically. That is, as the planar actuator is stretched or lengthened, the elastic force exerted by the planar actuator increases. In the graph shown in Figure 7A, increases the volume of working fluid in the working actuator increases the length the actuator, assuming the external force F_1 applied to the actuator remains constant.

[0059] Figure **7B** illustrates the relationship between force and displacement given a set length L_1. Assuming a set length, the force applied by the planar actuator is related to the volume of the working fluid (incompressible working fluid). As the volume of the working fluid increases, the force exerted on an object increases (assuming that the length L_1 of the actuator remains constant).

[0060] Figure 7C illustrates the relationship between force and displacement given a set volume V_1. In particular, assuming volume of the working fluid remains constant, increases in external force applied to the planar actuator result in an increase in displacement of the planar actuator. For example, increases in force from F_1 to F_2 to F_3, the displacement or length of the planar actuator increases from L_1 to L_2 to L_3.

[0061] Figures 7D-7F provide further evidence of the relationship between various attributes. For example, Figure 7D describes the relationship between displacement and volume in the presence of Figure 7D further illustrates the relationship between volume and displacement, wherein increases in volume of working fluid provided to the planar actuator results in a monotonic increase in displacement or lengthening of the planar actuator. Similarly, Figure 7E illustrates the relationship between volume and force, wherein the length of the planar actuator is held constant. In this example, as volume increases the force applied by the actuator decreases (assuming again, that length remains constant) as expected. Finally, Figure 7F illustrates the relationship between the force displacement relationship with volume held constant. As expected, as volume increased, the rate of change of force with displacement, reflecting the actuator stiffness increased.

[0062] Although some of the data presented in Figures 7D-7F illustrates small hystereses and/or non-linearities, the data overall is in agreement with expectations. In addition, loads of 500 kPa, with no-load tests illustrating textile strain of over 40%.

[0063] Figures 8A and 8B are schematic views of a soft actuator that incorporates one or more soft sensors according to some embodiments. In the embodiment shown in FIG. 8A, soft actuator 800 includes one or more hollow elastic fibers 802, elastic fabric 804, and circumferential constraint 806. A working fluid (e.g., hydraulic, pneumatic) is selectively applied to the one or more hollow elastic fibers 802 to selectively actuate the actuator as described above. That is, circumferential constraint 806 (e.g., stitching, side-stiches, cross-stitches) are provided in the fabric 804 to form one or more channels configured to receive the one or more hollow elastic fibers 802. Provision of a working fluid into the one or more hollow elastic fibers results in the actuation (e.g., lengthening) of soft actuator 800 in a direction parallel to the length of the one or more hollow elastic fibers 802. In the embodiment shown in Figure 8A, in addition to the components utilized to selectively actuated the soft actuator, one or more strain sensors 808 are included in the soft actuator 800. In some embodiments, the strain sensors 808 are located adjacent one or more of the hollow elastic fibers 802 and extend along the length of the soft actuator. In some embodiments, an attribute (e.g., resistance) of the strain sensor changes in response to stretching or lengthening of the strain sensor 808. For example, in some embodiments strain sensor 808 may utilize a hollow tube (e.g., elastic) that is filled with a liquid metal. The conductivity (e.g., inverse of resistance) of the strain sensor 808 changes in response to a strain applied to the strain sensor (e.g., lengthening or stretching of the sensor). In some embodiments, the hollow tube comprising liquid metal is braided to selectively modify the sensitivity of the strain sensor. One of the benefits of including a strain sensor 808 as part of the soft actuator 800 is that it allows the strain data collected from the strain sensor 808 to be utilized in feedback to control the actuator of the soft actuator (i.e., detect the lengthening/movement of the actuator).

[0064] In the embodiment shown in FIG. 8B, soft actuator 820 includes one or more hollow elastic fibers 822, elastic fabric 824, and circumferential constraints (not explicitly shown in this view). A working fluid (e.g., hydraulic, pneumatic) is selectively applied to the one or more hollow elastic fibers 822 to selectively actuate the actuator as described above. In this embodiment, the soft actuator 820 is in a non-compression state when the working fluid is pressurized and in a compression state when the working fluid is de-pressurized (e.g., low working fluid pressure). For example, soft actuator 820 may be utilized as a compression sleeve or haptic sensor selectively providing pressure as required.

[0065] In the embodiment shown in Figure 8B, in addition to the components utilized to selectively actuate the soft actuator, one or more pressure sensor 828 are included in the soft actuator 820. In some embodiments, the pressure sensors 828 are located in a grid pattern along the outer circumference of the soft actuator 820. In some embodiments, an attribute (e.g., resistance) of the strain sensor changes in response to pressure applied by the soft actuator 820 to an underlying surface (e.g., limb). As discussed above with respect to strain sensors, pressure sensor 828 work under the same principle, wherein the pressure sensors comprise one or more hollow tubes (e.g., elastic) filled with a liquid metal. The application of pressure to the pressure sensor changes the measured conductivity (e.g., resistance) associated with the pressure sensor. In some embodiments, the hollow tube comprising liquid metal is braided to selectively modify the sensitivity of the pressure sensor. One of the benefits of including a pressure sensor 828 as part of the soft actuator 800 is that it allows the pressure data collected from the pressure sensor 828 to be utilized in feedback to control the actuation of the soft actuator. For example, in embodiments in which the soft actuator 820 is utilized as a compression sleeve, the feedback can be utilized to apply a desired amount of compression (e.g., one size fits all compression sleeves).

[0066] For additional information regarding strain sensors is provided in PCT Appl. US20 16/050769, titled "TACTILE SENSORS AND METHODS OF FABRICATING TACTILE SENSORS", by Yon Visell and Bin Li, and PCT Application No. 2018/016214, titled "STRETCHABLE, CONDUCTIVE INTERCONNECT AND/OR SENSOR AND METHOD OF MAKING THE SAME" by Yon Visell and Do Thanh Nho, both of which are incorporated by reference herein.

[0067] Figures 9A and 9B are photographs of strain sensors that may be incorporated into the soft actuator according to some embodiments. In particular, Figure 9A shows an embodiment in which strain sensor 900 includes two microtubules 902a, 902b braided together with an inelastic component (e.g., sewing thread) 904 in order to increase the stiffness of the microtubules. As the strain sensor 900 is stretched, the braided portions apply force to one another, reducing the cross-sectional area of the liquid metal within the respective microtubules 902a, 902b and thereby reducing the conductivity of each (conversely, increasing the resistance of each). In addition, the result of braiding the microtubules with non-elastic thread 904 is that as the strain sensor 900 is stretched, more force is exerted at the turns of the microtubules 902a, 902b, resulting in a larger resistance change and therefore higher sensitivity.

[0068] Similarly, Figure 9B shows an embodiment in which strain sensor 920 includes two microtubules 922a, 922b are braided with two elastic cords 924a, 924b. The elasticity of the elastic cords 924a, 924b decreases the strain applied on the microtubules 922a, 922b in response to stretching of the strain sensor 920, thereby decreasing the sensitivity of the strain sensor 920. The trade-off, however, is that strain sensor 920 is more flexible and provides a greater range of motion as compared with strain sensor 900.

[0069] Fig. 10 is a perspective view of a garment 1000 (e.g., glove) that integrates a plurality of soft actuators 1002 to provide haptic feedback to a user. In some embodiments, the garment is utilized to provide haptic feedback to the hand for human-computer interaction or virtual reality. Garment 1000 includes a plurality of soft actuators 1002, a pair of tubes 1004 connected to each soft actuator, and a plurality of pumps 1006 connected to selectively provide a working fluid to each of the plurality of soft actuators 1002 via tubes 1004. In this way, one of the plurality of pumps 1006 may be utilized to selectively apply or remove a working fluid from one of the corresponding soft actuators 1002, thereby providing haptic feedback to the user. In some embodiments, the garment 1000 further includes one or more sensors (not shown) that provide feedback regarding position and/or movement of the user's fingers.

[0070] Fig. lla and llb illustrates a multi-actuated Fluidic Fabric Muscle Sheet (FFMS) 1100 operating in a first state and a second state, respectively. The FFMS 1100 is comprised of a plurality of soft actuators H04a, H04b, and H04c provided within a fabric 1102 according to some embodiments. Although not shown, each of the plurality of soft actuators H04a-ll04c is coupled via a tube to a pump (e.g., hydraulic pump, pneumatic pump, etc.) to selectively pressurize one or more of the soft actuators 1l04a-l l04c.

[0071] Figure 1l a illustrates FFMS 1100 in a state in which all three soft actuators 1l04a-ll04c are pressurized. The pressurization of each of the soft actuators H04a, H04c results in a lengthening of the FFMS 1100 in an axial direction. Figure llb illustrates the FFMS 1100 in a state in which one of the soft actuators H04a is depressurized causing differential elongation in the respective soft actuators H04a-ll04c. As a result of the depressurization the soft actuator H04a is shortened, inducing a large amplitude planar rotation of the FFMS 1100 as shown in Figure llb.

[0072] Fig. l2a-l2c illustrate a FFMS 1200 capable of providing out-of-plane bending as a result of combination of a first soft actuator layer 1202 with a relatively stiff layer 1214. In the embodiment shown in Fig. l2a, a soft actuator layer 1202 includes one or more soft actuators 1204 (i.e., hollow elastic fiber combined with circumferential constraint) located in a first plane. The soft actuator layer 1202 is adhered or stitched to the relatively stiff, passive layer 1214. In some embodiments, the relatively stiff layer is a fiberglass sheet that includes a plurality of pre-pattemed holes 1216 utilized to adhere the soft actuator layer 1202 to the stiff layer 1214. Fig. 12b is a side view of the FFMS 1200 in a first state (pressurized state). Fig 12c is a side view of the FFMS 1200 at various pressure levels Pl, P2, P3, P4, P5, and P6. In some embodiments, pressure P1 represents a maximum pressure level (e.g., approximately 724 kPa) and pressure P6 represents a minimum pressure level (e.g., 241 kPa). At a a maximum pressure (e.g., 724 kPa) the one or more soft actuators 1204 are fully extended to provide a relatively flat surface. As the pressure decreases the length of the actuators shortens, but due to the attachment of the soft actuator layer 1202 to the relatively stiff, passive layer 1214 the FFMS 1200 achieves large amplitude bending. In some embodiments, the large amplitude bending exceeds 180°.

[0073] Figs. l3a-l3e illustrate a FFMS 1300 capable of biaxial bending. In some embodiments, FFMS 1300 utilizes first and second FFMS sheet actuators 1301 and 1308, aligned perpendicular to one another. Selective pressurization of the respective FFMS sheet actuators allows the FFMS to realize biaxial bending as shown in Figures l3b-l3e.

[0074] In the embodiment shown in Fig. l3a, first FFMS sheet actuator 1301 includes one or more soft actuators 1302 (i.e., including hollow elastic fiber circumferentially constrained) located within fabric 1304 and aligned in a first direction, and second FFMS sheet actuator 1308 includes one or more soft actuators 1310 within fabric 1312 and aligned in a second direction perpendicular to the first direction. First FFMS sheet actuator 1301 includes an input port 1306 for receiving a working fluid (i.e., pneumatic, hydraulic, etc.), which would be connected to a pump (not shown) capable of selectively pressurizing the one or more soft actuators 1302. Likewise, second FFMS sheet actuator 1308 includes an input port 1314 for receiving a working fluid (i.e., pneumatic, hydraulic, etc.). In some embodiments, the first FFMS sheet actuator 1301 is stitched or otherwise adhered to the second FFMS sheet actuator 1308. In the embodiment shown in Fig. l3a the soft actuators 1302 associated with the first FFMS sheet actuator 1301 are aligned approximately perpendicular to the soft actuators 1310 associated with the second FFMS sheet actuator 1308. In other embodiments, the soft actuators associated with the first and second FFMS sheet actuators 1301, 1308 may be aligned at different angles relative to one another.

[0075] Based on the configuration shown in Fig. l3a, the FFMS 1300 may provide uniaxial bending along two different axes as well as bi-axial bending. For example, in the embodiment shown in Fig. l3b, uniaxial bending of FFMS 1300 is provided by pressurizing first FFMS sheet actuator 1301 and de-pressurizing second FFMS sheet actuator 1308. In response, FFMS 1300 bends around a single axis as indicated by arrow 1320. In the embodiment shown in Fig. l3c, bi-axial bending of FFMS 1300 is provided by de-pressurizing both first FFMS sheet actuator 1301 and second FFMS sheet actuator 1308. In response, FFMS 1300 bends around both a first axis as indicated by arrow 1322 as well as a second axis as indicated by arrow 1324. In the embodiment shown in Fig. l3d, FFMS 1300 is approximately flat as a result of pressurizing both first and second FFMS sheet actuators 1301 and 1308. In the embodiment shown in Fig. l3e, uniaxial bending of FFMS 1300 is provided by de-pressuring first FFMS sheet actuator 1301 and pressuring second FFMS sheet actuator 1308. In response, FFMS 1300 bends around a single axis as indicated by arrow 1326. However, as compared with the embodiment shown in Fig. l3b, FFMS 1300 bends around an axis perpendicular to the axis shown in Fig. l3b.

[0076] While the invention has been described with reference to an exemplary embodiment(s), it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment(s) disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.

CLAIMS:

1. A method of fabricating a soft actuator, the method comprising:
stacking two or more layers of fabric adjacent to one another;
forming one or more channels between the stacked layers of fabric, wherein the channels provide a circumferential constraint;
placing one or more hollow elastic tubes within the one or more channels; and
connecting at least a first end of each of the one or more hollow elastic tubes to a delivery system capable of providing a working fluid to the one or more hollow elastic tubes.

2. The method of claim 1, further including:
sealing a second end of each of the one or more hollow elastic tubes..

3. The method of claim 1, further including:
connecting the second end of each of the one or more hollow elastic tubes to the delivery system capable of providing a working fluid to the one or more hollow elastic tubes.

4. The method of claim 1, wherein the two or more layers of fabric are non-stretch.

5. The method of claim 1, wherein the two or more layers of fabric are two-way stretch.

6. The method of claim 1, wherein forming the one or more channels between the stacked layers of fabric includes stitching the two or more layers of fabric together using a side-stitch to form the one or more channels.

7. The method of claim 6, wherein the stitching is provided in a direction transverse to a direction of lengthening, wherein the direction of lengthening is along a length of the hollow elastic tubes.

8. The method of claim 1, wherein forming the one or more channels between the stacked layers of fabric includes stitching the two or more layers of fabric together using a cross-stitch to form the one or more channels.

9. The method of claim **1,** wherein forming the one or more channels between the stacked layers of fabric includes gluing the two or more layers of fabric together.

10. A selectively actuated textile comprising:

one or more pieces of fabric, wherein the one or more pieces of fabric include one or more channels formed within the one or more pieces of fabric and constrained in a circumferential direction; and

one or more first hollow elastic tubes positioned within the one or more channels and configured to receive a working fluid, wherein working fluid is selectively provided to or removed from the one or more first hollow elastic tubes to actuate the selectively actuated textile.

11. The selectively actuated textile of claim 10, wherein the fabric is elastic and allowed to stretch in response to the working fluid being selectively provided to the one or more first hollow elastic tubes.

12. The selectively actuated textile of claim 10, wherein the fabric is inelastic, wherein the fabric is bunched to allow the selectively actuated textile to lengthen in response to the working fluid being selectively provided to the one or more first hollow elastic tubes.

13. The selectively actuated textile of claim 10, wherein the one or more first hollow elastic tubes includes a first plurality of hollow elastic tubes positioned parallel to one another along a length of the selectively actuated textile.

14. The selectively actuated textile of claim 10, wherein the one or more channels is fabricated utilizing stitching along edges of each of the one or more channels.

15. The selectively actuated textile of claim 10, wherein the selectively actuated textile has a length, wherein the length changes in response to the working fluid being selectively provided to or removed from the one or more first hollow elastic tubes.

16. The selectively actuated textile of claim 15, wherein the length of the selectively actuated textile increases in response to working fluid being selectively provided to the one or more first hollow elastic tubes.

17. The selectively actuated textile of claim 10, wherein the selectively actuated textile is fixed on a first end, wherein a second end is actuated in response to the working fluid being selectively provided to or removed from the one or more first hollow elastic tubes.

18. The selectively actuated textile of claim 10, further including:

a strain sensor positioned in close proximity to the one or more hollow elastic tubes, wherein the strain sensor provides feedback regarding force or displacement applied by the selectively actuated textile.

19. The selectively actuated textile of claim 10, further including:

a passive layer of stiff material that is stitched to the actuated textile, wherein the passive layer enables out-of-plane bending.

20. The selectively actuated textile of claim 10, further including one or more second hollow elastic tubes oriented at an angle with respect to the one or more first hollow elastic tubes.

21. A haptic feedback garment comprising:

one or more soft actuators embedded within the haptic feedback garment, wherein each actuator includes a hollow elastic tube configured to receive a working fluid;

one or more tubes, wherein each tube is connected on a first end to an input associated with each of the soft actuators; and

one or more pumps, wherein each pump is configured to provide a working fluid to one of the one or more soft actuators via one of the one or more tubes, wherein application of the working fluid to the soft actuator provides a haptic response to a user wearing the haptic feedback garment.

22. The haptic feedback garment of claim 21, wherein the one or more soft actuators include a channel constrained in a circumferential direction, wherein the hollow elastic tube is positioned within the channel.

23. The haptic feedback garment of claim 21, wherein the haptic feedback garment is a glove having a plurality of fingers, wherein each finger includes one or more embedded soft actuators.

24. The haptic feedback garment of claim 21, wherein the haptic feedback garment is a sleeve or band and wherein each of the soft actuators is positioned circumferentially around the sleeve or band, wherein removal of fluid from the one or more soft actuators provides a compressive force to the sleeve or band.

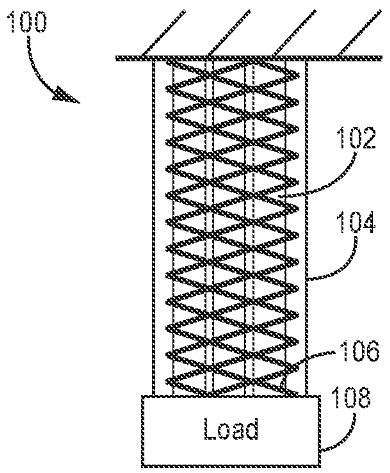


FIG. 1A

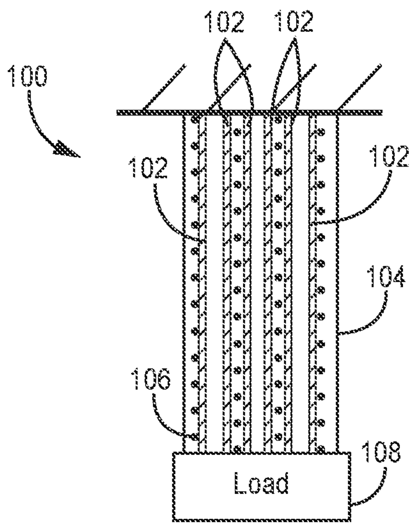


FIG. 1B

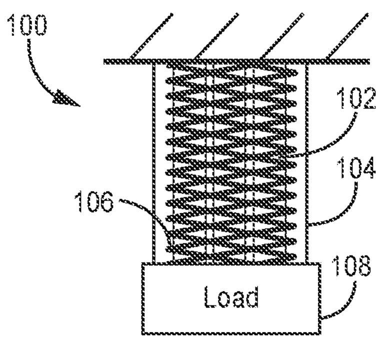


FIG. 1C

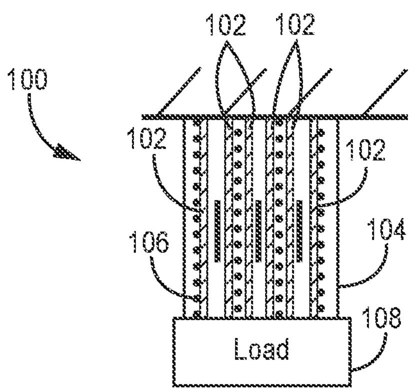


FIG. 1D

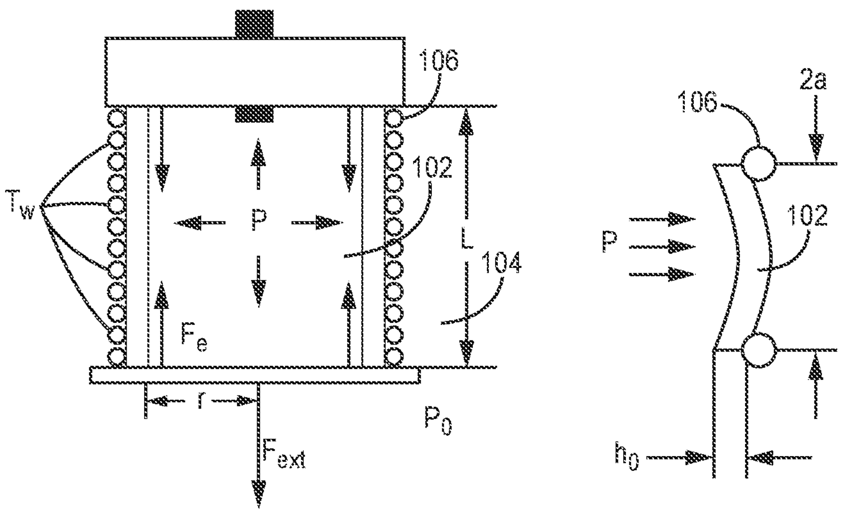


FIG. 2A FIG. 2B

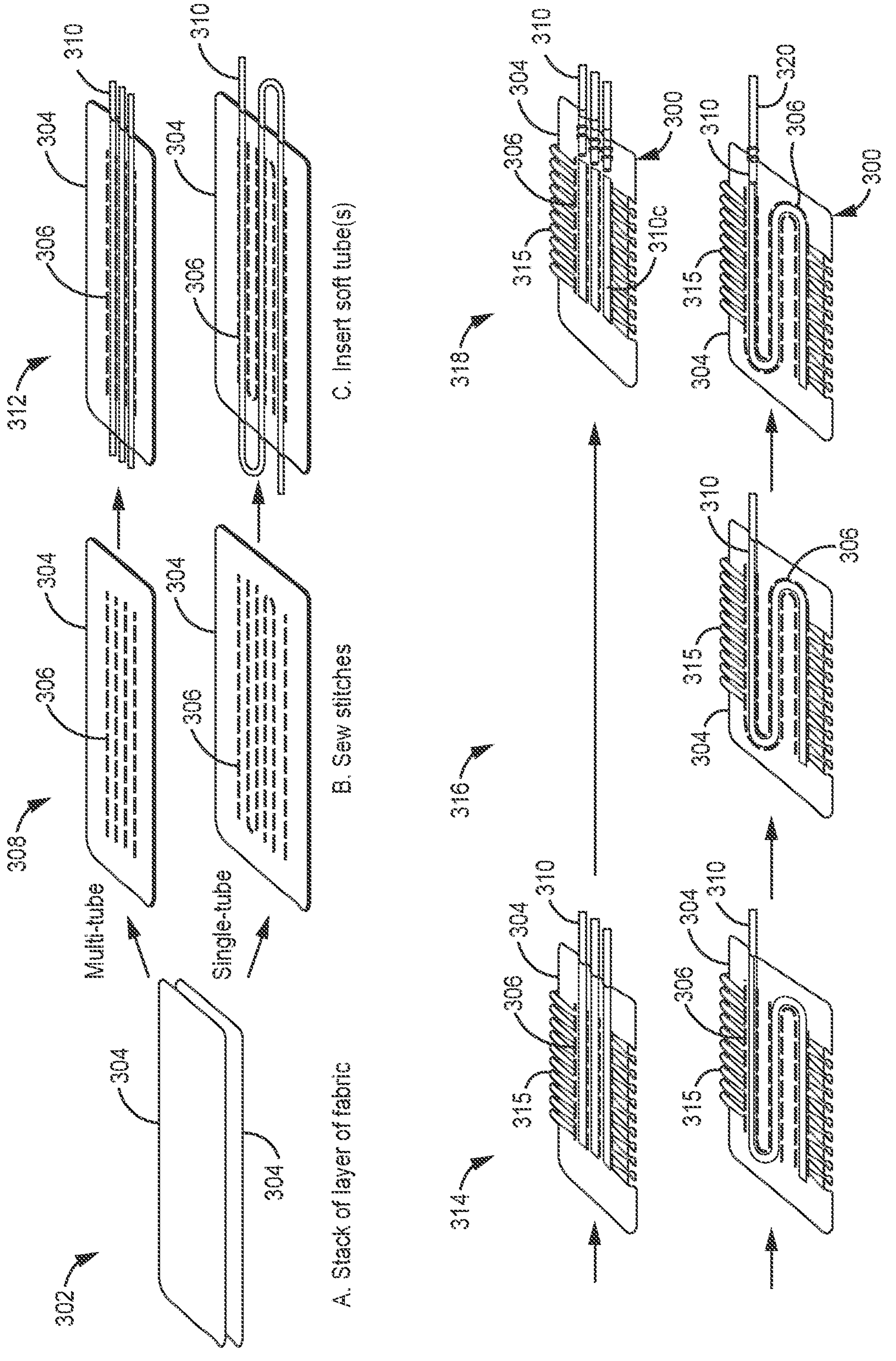

302
304
304
A. Stack of layer of fabric
Multi-tube
Single-tube
308
306
304
306
304
B. Sew stitches
312
306
304
310
306
304
310
C. Insert soft tube(s)
314
315
306
304
310
315
306
304
310
316
315
304
310
306
318
315
306
304
310
300
310c
315
304
310
306
320
300

FIG. 3

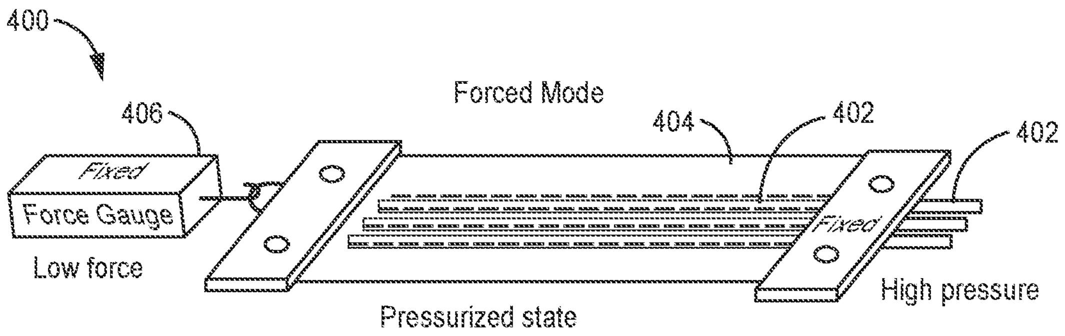

400
Forced Mode
406
404
402
402
Fixed
Force Gauge
Fixed
Low force
High pressure
Pressurized state

FIG. 4A

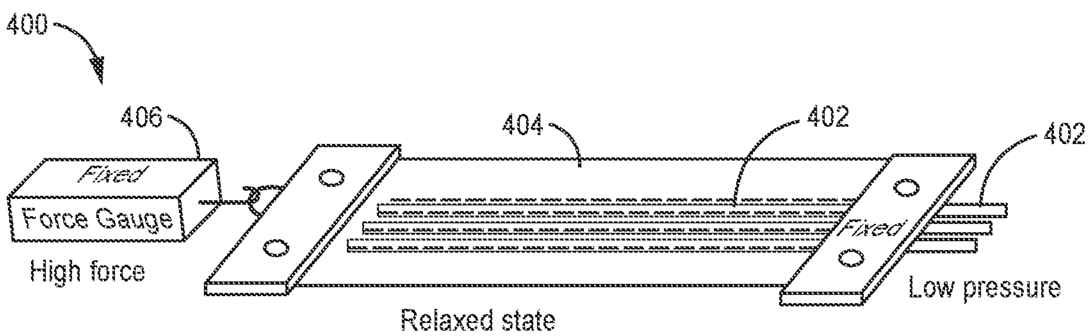
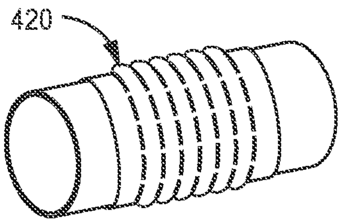
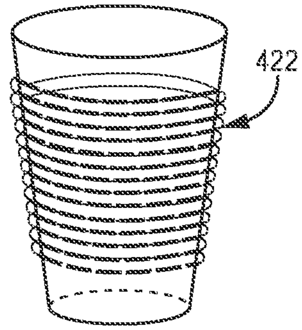

400
406
404
402
402
Fixed
Force Gauge
Fixed
High force
Low pressure
Relaxed state

FIG. 4B



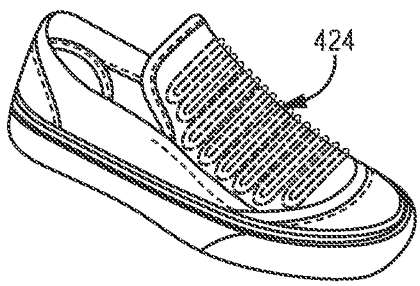
Uniform structure

FIG. 4C



Tapered structure

FIG. 4D



Arbitrary structure

FIG. 4E

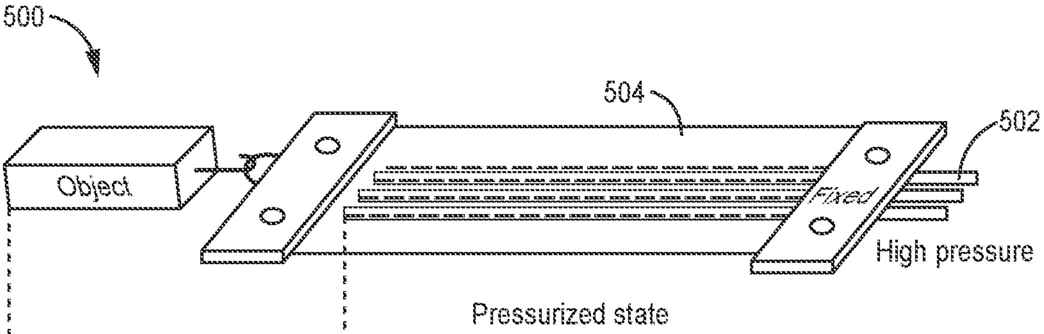

500
504
502
Object
Fixed
High pressure
Pressurized state

FIG. 5A

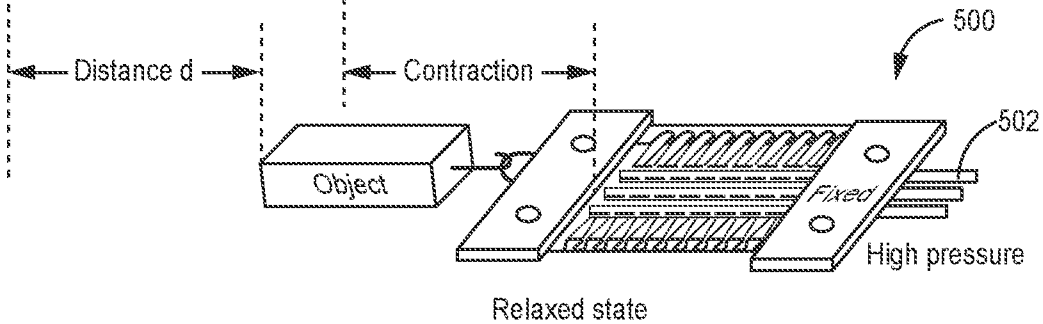
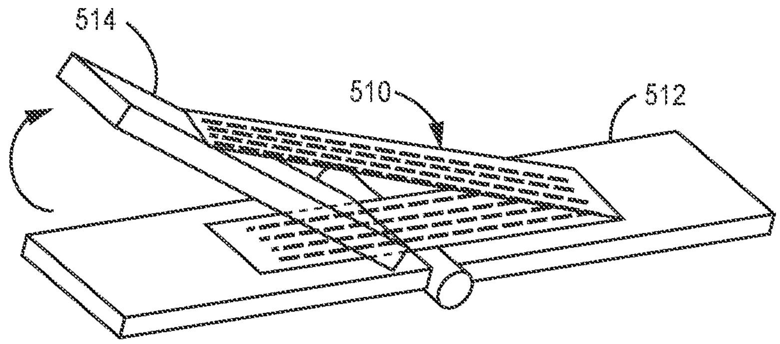
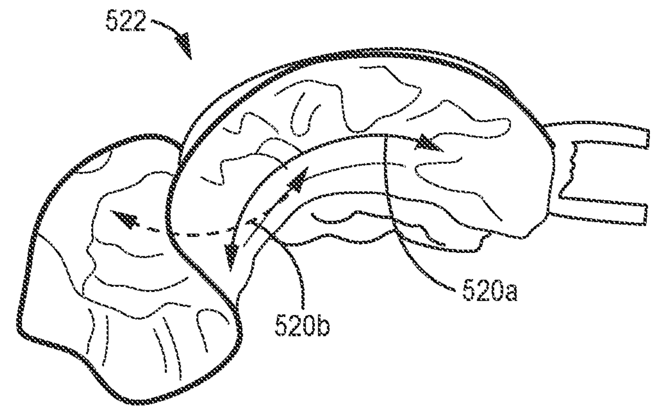

Distance d
Contraction
500
502
Object
Fixed
High pressure
Relaxed state

FIG. 5B



Linear actuation

FIG. 5C



Surface actuation

FIG. 5D

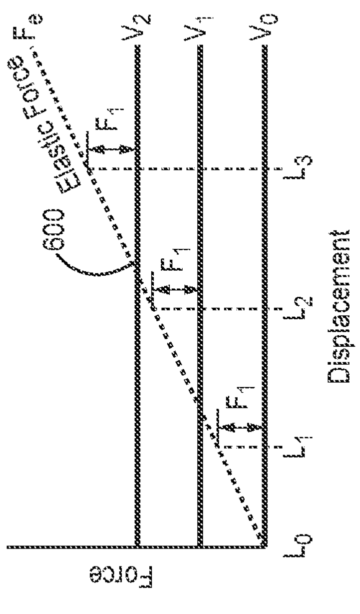


FIG. 6A

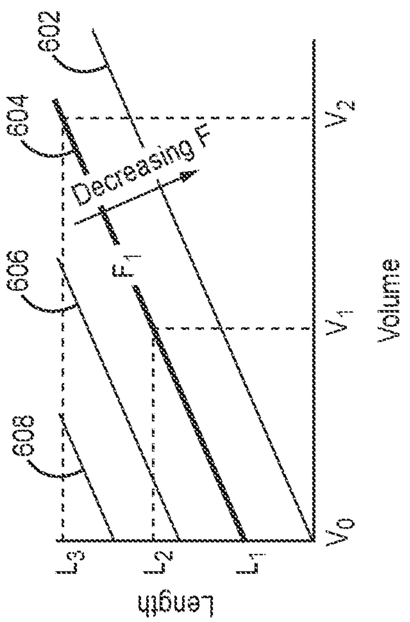


FIG. 6B

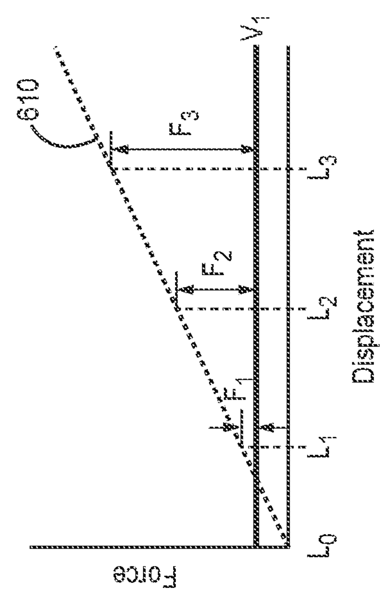


FIG. 6C

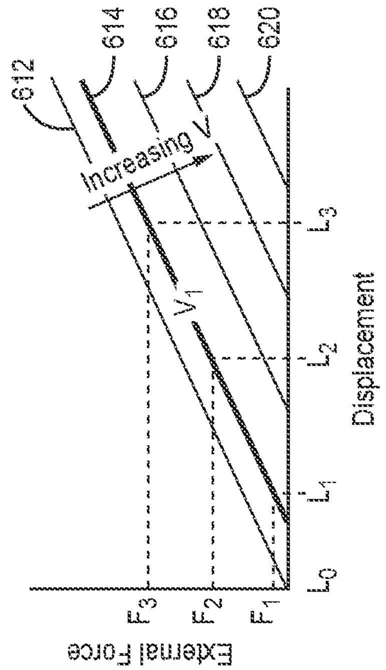


FIG. 6D

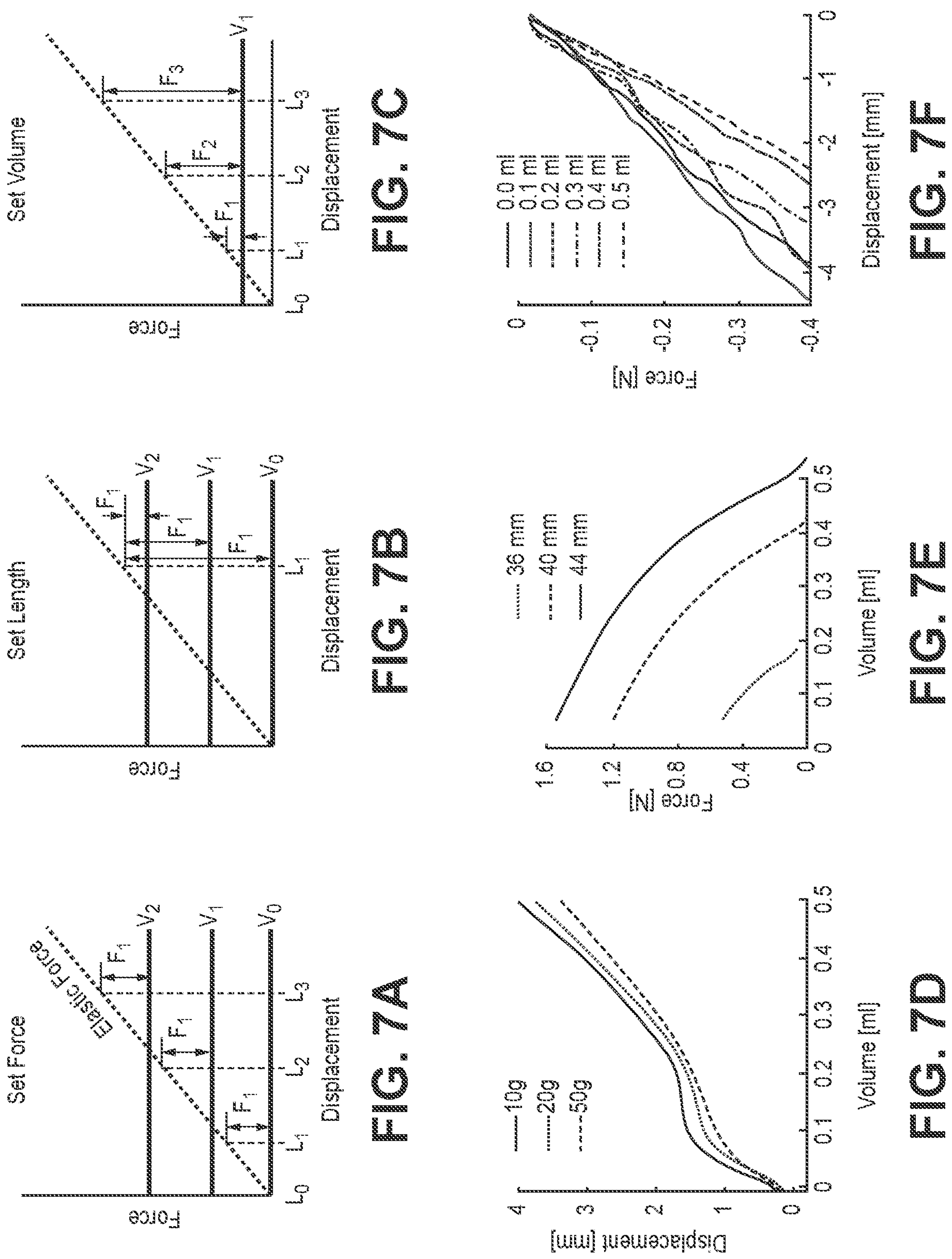


FIG. 7A FIG. 7B FIG. 7C FIG. 7D FIG. 7E FIG. 7F

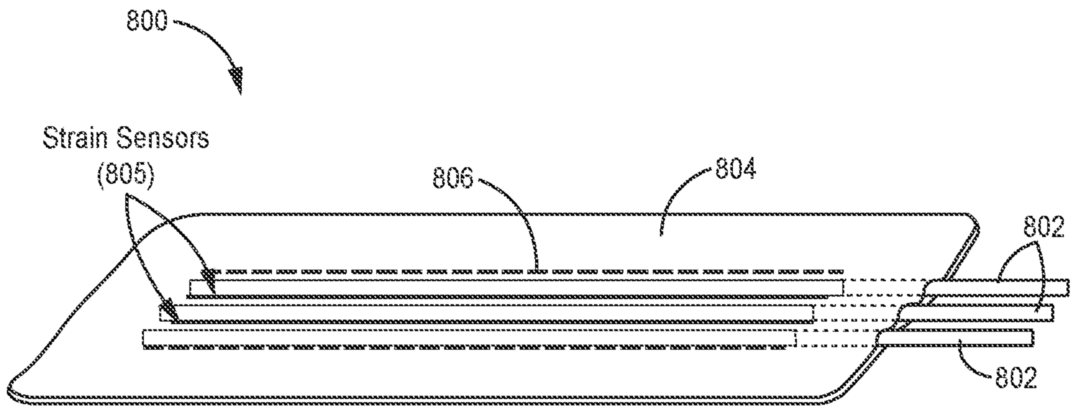

800
Strain Sensors
(805)
806
804
802
802

FIG. 8A

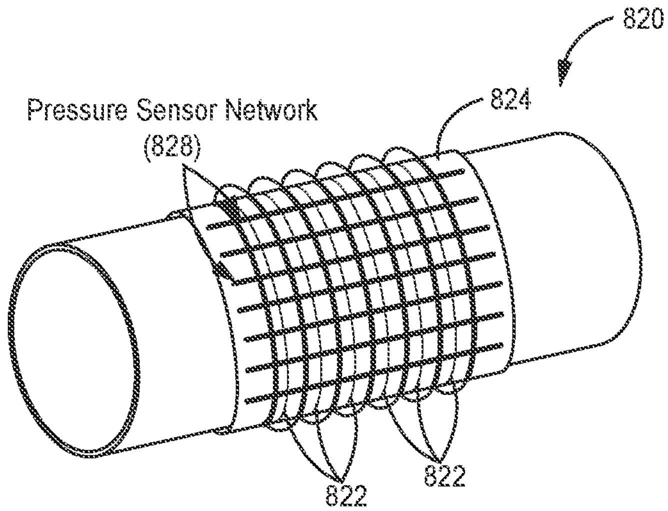

820
Pressure Sensor Network
(828)
824
822
822

FIG. 8B

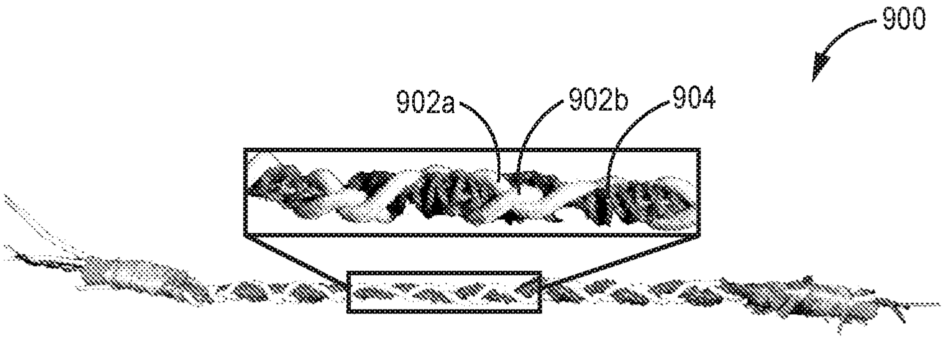


FIG. 9A

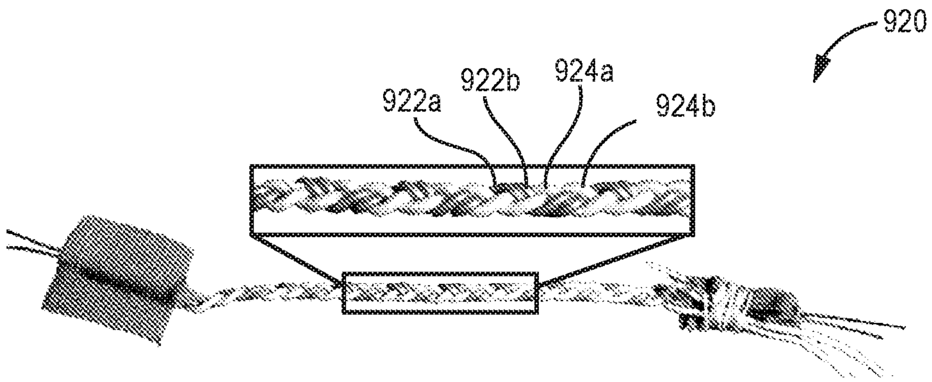


FIG. 9B

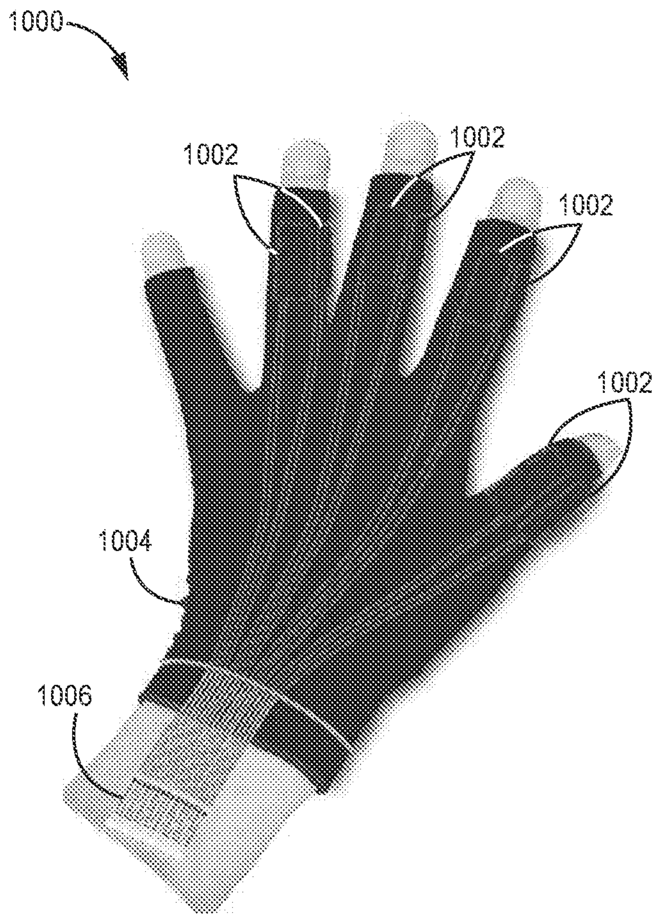


FIG. 10

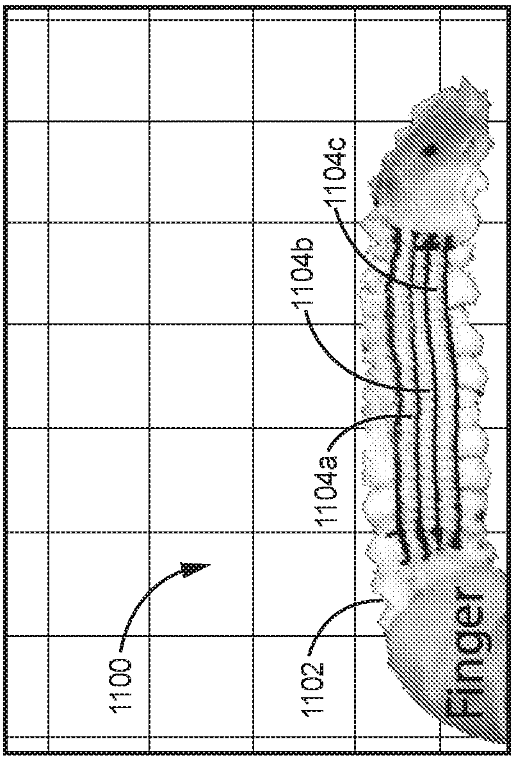


FIG. 11A

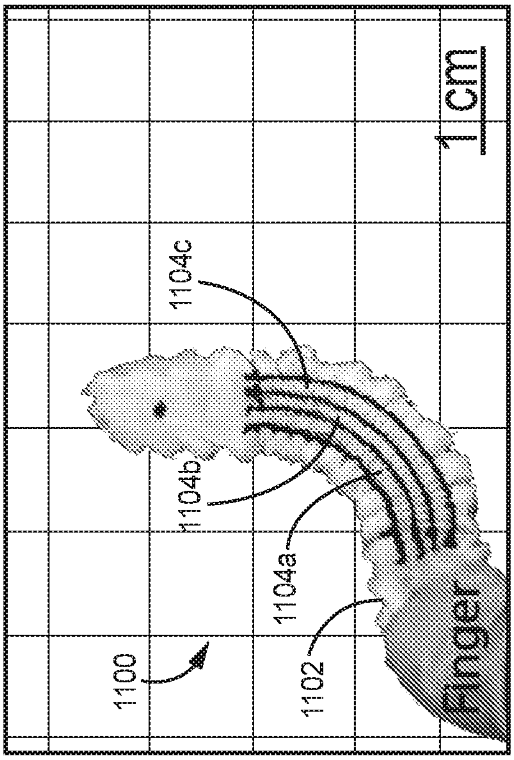


FIG. 11B

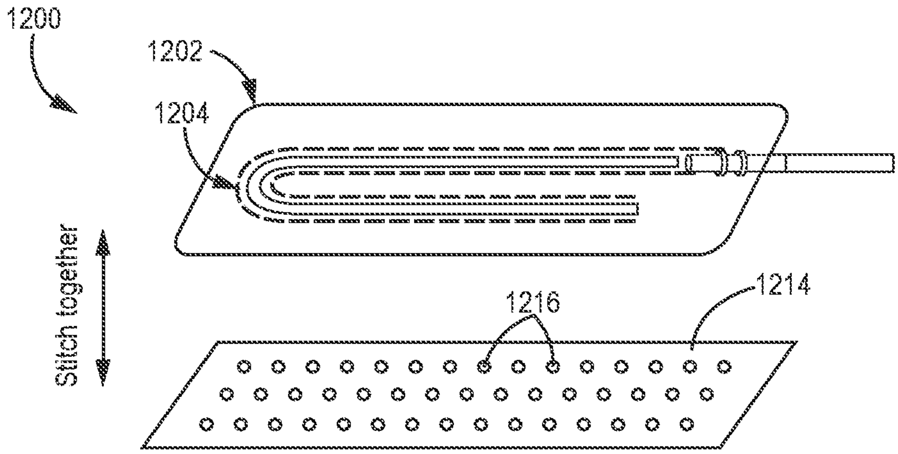


FIG. 12A

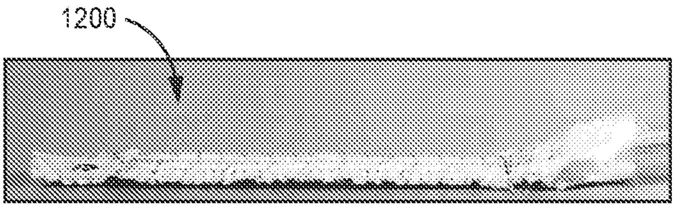


FIG. 12B

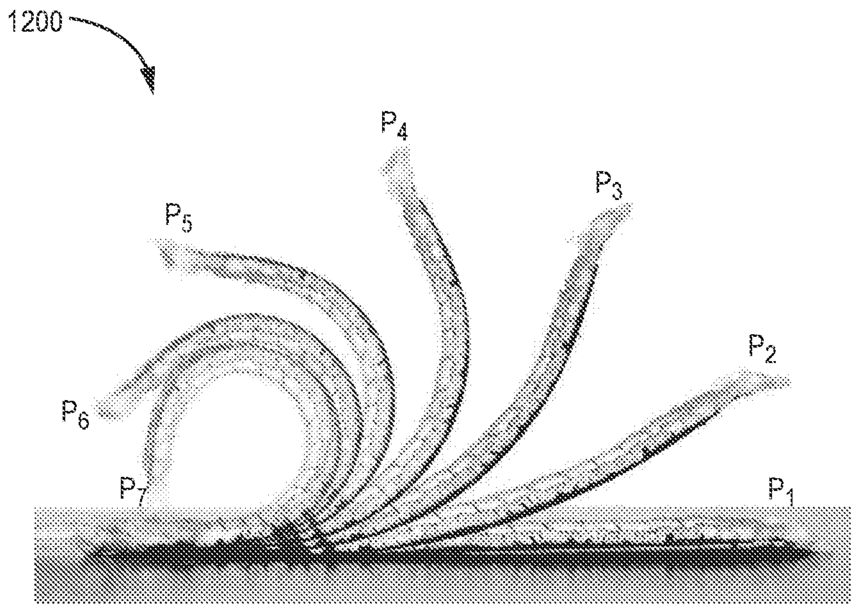


FIG. 12C

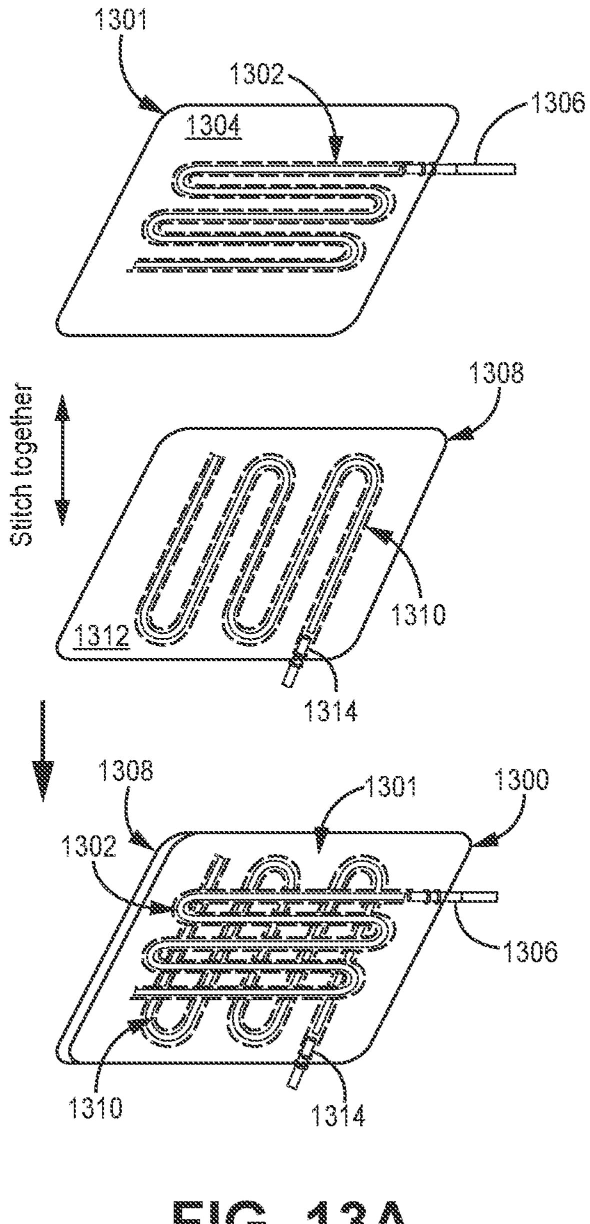

1301
1302
1304
1306
Stitch together
1308
1310
1312
1314
1308
1301
1300
1302
1306
1310
1314

FIG. 13A

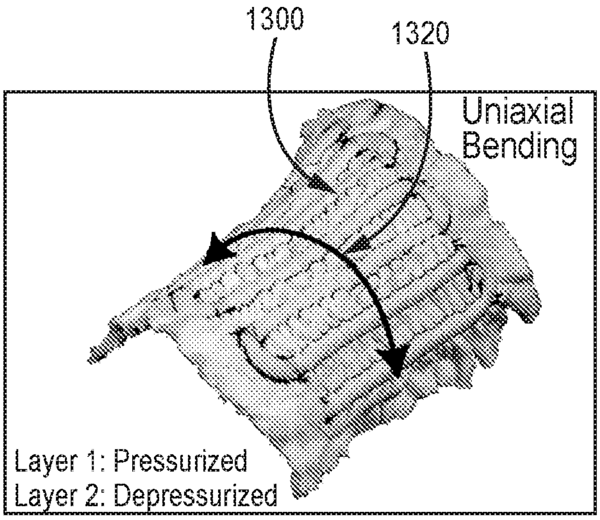


FIG. 13B

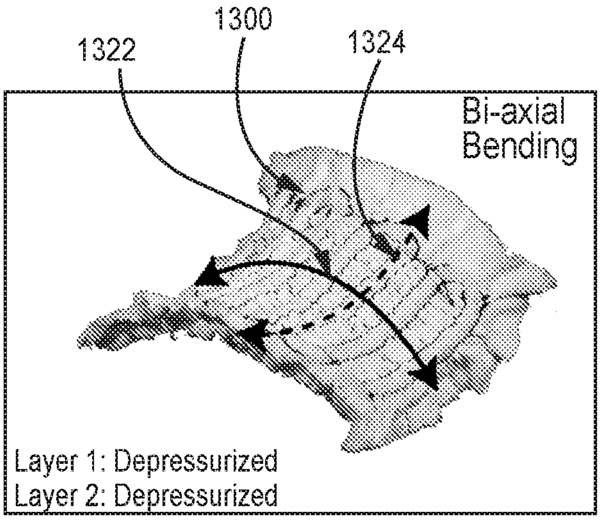


FIG. 13C

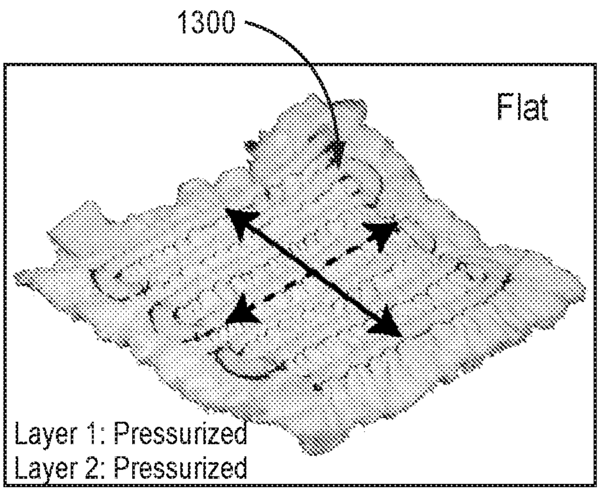


FIG. 13D

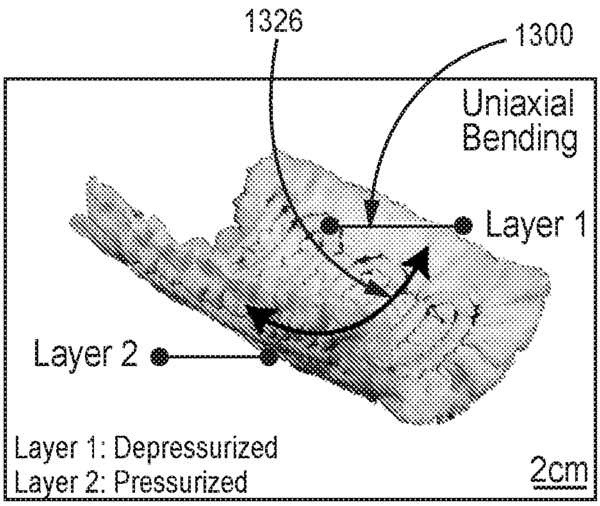


FIG. 13E

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US19/51032

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.:
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:

-***-Continued Within the Next Supplemental Box-***-

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.:
1-20

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.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US19/51032

A. CLASSIFICATION OF SUBJECT MATTER

IPC - A61B 17/135; A61F 2/50, 5/01; A61H 9/00 (2019.01)

CPC - A61B 17/135; A61F 2/50, 5/012, 5/013, 5/05816; A61H 9/0078

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)
See Search History document

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	WO 2017/120314 A1 (PRESIDENT AND FELLOWS OF HARVARD COLLEGE) 13 July 2017; figures 21-25; page 4, lines 20-25; page 11, lines 10-15; page 14, lines 9-26	1-2, 5-8, 10-16, 18-20 --- 3
X	US 2005/0081711 A1 (KEREKES L et al) 21 April 2005; abstract; figures 1a-1c; paragraphs [0044]-[0046]	1-2, 4, 9-10, 13-14, 17, 20
Y	GB 2515155 A (ANEURIN BEVAN LOCAL HEALTH BOARD CLINICAL EDUCATION CENTRE) 17 December 2014; figures 5A-5C; page 11, lines 20-25; page 12, lines 5-15; page 13, lines 10-15	3
A	US 2014/0109560 A1 (ILIEVSKI F et al) 24 April 2014; entire document	1-20
A	WO 2018/129521 A2 (THE REGENTS OF THE UNIVERSITY OF MICHIGAN) 12 July 2018; entire document	1-20

☐ 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
"D" document cited by the applicant in the international application
"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	Date of mailing of the international search report
2 December 2019 (02.12.2019)	14 JAN 2020

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Shane Thomas Telephone No. PCT Helpdesk: 571-272-4300

-***-Continued from Box No. III Observations where unity of invention is lacking-***-

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I: Claims 1-20 are directed toward a method of fabricating a soft actuator and selectively actuated textile comprising: stacking two or more layers of fabric adjacent to one another; forming one or more channels between the stacked layers of fabric, wherein the channels provide a circumferential constraint.

Group II: Claims 21-24 are directed toward a haptic feedback garment comprising: one or more pumps, wherein application of the working fluid to the soft actuator provides a haptic response to a user wearing the haptic feedback garment.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons.

The special technical features of Group I include stacking two or more layers of fabric adjacent to one another; forming one or more channels between the stacked layers of fabric, wherein the channels provide a circumferential constraint; placing one or more hollow elastic tubes within the one or more channels; and connecting at least a first end of each of the one or more hollow elastic tubes to a delivery system capable of providing a working fluid to the one or more hollow elastic tubes; wherein working fluid is selectively provided to or removed from the one or more first hollow elastic tubes to actuate the selectively actuated textile (which is not present in Group II).

The special technical features of Group II include one or more soft actuators embedded within the haptic feedback garment, one or more tubes, wherein each tube is connected on a first end to an input associated with each of the soft actuators; and one or more pumps, wherein each pump is configured to provide a working fluid to one of the one or more soft actuators via one of the one or more tubes, wherein application of the working fluid to the soft actuator provides a haptic response to a user wearing the haptic feedback garment (which is not present in Group I).

The common technical features of Groups I and II include an actuator including a hollow elastic tube configured to receive a working fluid.

These common technical features are disclosed by US 2014/0109560 A1(Ilievski): an actuator (soft robotic device; abstract) including a hollow elastic tube (channel in flexible body defines a hollow elastic tube; abstract) configured to receive a working fluid (a pressurized inlet is in fluid communication with channels and so is capable of receiving a working fluid; abstract).

Because the common technical features are disclosed by Ilievski, the inventions are not so linked as to form a single general inventive concept. Therefore, Groups I-II lack unity.