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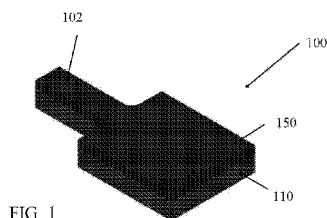


FIG. 1

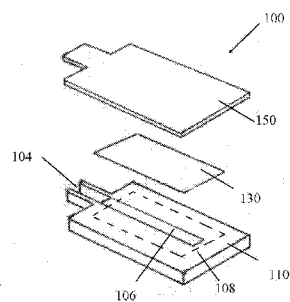


FIG. 2

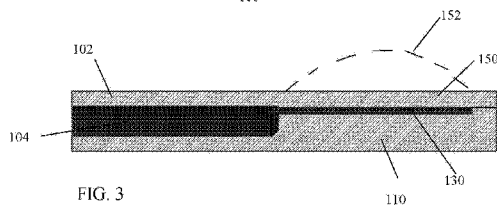


FIG. 3

(57) Abstract: The invention provides a seamless chamber actuator (100,100a,100b) which comprises a base layer (110,110a), a second layer (150,150a) and a substantially zero-volume actuation chamber (108) formed between the base and the second layers. In another embodiment, a torsion housing (220) is mounted on the seamless chamber actuator (100b) to provide a jamming actuator (200). The jamming actuator (200) is further configured with a glove to provide a wrist jamming actuator (200a). In another embodiment, a bending actuator (300) is formed by a base layer (310), a flat groove, a perforated membrane (330), a corrugated layer (350) and a substantially zero-volume actuation chamber (308,308a) is formed between the base and the corrugated layers. These seamless chamber actuators (100,100a,100b), jamming actuators (200,200a) or bending actuators (300) can be configured for force feedback, haptic sensation, force assistive or force resistive devices, such as, in VR, AR or body rehabilitation.

LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE,
SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN,
GQ, GW, KM, ML, MR, NE, SN, TD, TG).

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SEAMLESS CHAMBER ACTUATOR

Related Patent Application

[001] The present invention claims priority to Singapore patent application no. 10202250083P filed on 7 June 2022, the disclosure of which is incorporated in its entirety.

Field Of Invention

[002] The invention relates to seamless chamber actuators to provide force feedback for virtual reality (VR), augmented reality (AR), haptics, resistance training or rehabilitation applications; these seamless chamber actuators have substantially near-zero fluid inflation volume and are thus very compact, relative small in size, easy to customise into a wearable device, fast to actuate, provide high-force output from a small, compact size, and so on. When configured for VR, AR or haptic feedback, these seamless chamber actuators may be used to simulate point forces, vibrations or impact; these seamless chamber actuators may be used to pinch a moveable member for resistance training or to perform a movement for rehabilitation; performing a movement can also be achieved by forming a bending seamless chamber actuator.

BACKGROUND OF THE INVENTION

[003] Haptic technology, also known as haptics, refers to the science and technology of creating tactile sensations or haptic feedback through the use of actuators. These actuators are utilized in various industries and applications to enhance user experiences, improve safety, and enable realistic touch sensations.

[004] In the field of consumer electronics, haptic actuators are widely adopted and have become an integral part of numerous devices. These actuators can be found in everyday gadgets such as smartphones, tablets, gaming controllers, smartwatches, fitness trackers, as well as virtual reality (VR) or augmented reality (AR) devices and other wearable devices. A purpose of haptic actuators in consumer electronics is to provide users with tactile feedback, thereby enhancing overall user sensation or experience. By simulating various sensations like vibrations, texture, or physical resistance, haptic actuators add an extra dimension of interaction and immersion to consumer electronic devices. Wearable devices,

such as smartwatches and fitness trackers, utilize haptic actuators to deliver notifications, alerts, and feedback to users. For example, a gentle vibration on the wrist can notify the wearer about incoming messages, calls, or reminders without the need to check the device's screen constantly. Additionally, haptic feedback can be utilized during fitness activities to provide users with cues or reminders, such as vibrations indicating progress towards fitness goals or specific exercise durations.

[005] In virtual reality (VR) and augmented reality (AR) devices, haptic actuators play a pivotal role in creating a sense of presence and realism. VR headsets and controllers incorporate haptic feedback to simulate various sensations, such as the feel of touching virtual objects, experiencing the impact of virtual interactions, or perceiving the texture of virtual surfaces. This integration of haptics heightens the overall immersion and engagement in virtual environments, making the experiences more lifelike and compelling.

[006] In the medical and healthcare fields, haptic actuators have diverse applications in a range of devices and systems. Surgical simulators and training tools employ haptic feedback to replicate the tactile sensations encountered during surgical procedures. Surgeons and medical professionals can practice and refine their skills in a virtual environment with realistic touch sensations, allowing them to develop better surgical precision and proficiency. Furthermore, haptic actuators are utilized in rehabilitation equipment and prosthetic devices. For individuals undergoing physical therapy or rehabilitation programs, haptic feedback can assist in motor skill development, gait training, and sensory stimulation. By providing tactile cues and responses, haptic actuators aid in the rehabilitation recovery process and may help improve mobility and coordination.

[007] Haptic technology significantly contributes to the field of assistive technology as well. Haptic actuators are incorporated into assistive devices designed for individuals with disabilities, such as prosthetics or mobility aids. These actuators provide sensory feedback, enabling users to perceive and interact with their environment more effectively. Haptic feedback can enhance the overall quality of life for individuals with disabilities by facilitating better control, improving spatial awareness, and enabling a more natural and intuitive interaction with assistive devices.

[008] However, despite the advantages of these haptic actuators, there remain challenges when incorporating the actuators into the devices. One key challenge associated with haptic actuators is the size and form factor for portable feedback devices. Portable feedback devices have limited and compact space, therefore there is a need to develop haptic actuators that are compact, relatively small in size, easy to customise into an application, fast to actuate, provide high-force output from a small, compact size, and so on, and to fit snugly into these devices while still providing sufficient feedback and sensation.

SUMMARY OF INVENTION

[009] The present invention seeks to provide actuators with substantially zero-volume actuation chamber for creating force feedback or haptic sensation. Preferably, the actuators can be used to help patient rehabilitation or be used in or with a wearable apparel for body haptic sensation in VR or AR.

[0010] In one embodiment, the present invention provides a seamless chamber actuator comprising: a base layer wherein an inside face is formed with a flat groove; a membrane or tape is disposed over the flat groove, with the membrane/tape having a surface area; and a second layer is fusedly formed over the base layer and the membrane/tape, so that a substantially zero-volume fluid actuation chamber is formed by the flat groove and the surface area of the membrane/tape; wherein, when a fluid pressure is supplied into the flat groove, the substantially zero-volume fluid actuation chamber is inflated and the fluid pressure acts on the surface area of the membrane/tape, the second layer responds by deforming and bulging out to provide a haptic sensation, and the second layer returns to its unactuated state when the fluid pressure is released. Preferably, a port that is fluidly connected to the flat groove for supplying a fluid pressure for actuation.

[0011] Preferably, the seamless chamber actuator further comprises a top layer fusedly formed over the second layer, with the top layer having an aperture such that when the second layer responds to a fluid pressure, the second layer deforms and bulges out through the aperture to provide a haptic sensation. Preferably, the second layer is made from a material with stiffness or hardness that is lower than a material stiffness of the base layer or the top layer.

[0012] Preferably, the seamless chamber actuator further comprises: a torsion housing being mounted onto the top layer, with the torsion housing comprising a strip of cloth being wound up by a torsion spring and an end of the cloth is disposed between the torsion housing and the top layer of the seamless chamber actuator; wherein, when a fluid pressure is supplied to the port, the second layer responds by deforming through the aperture and jamming the cloth against the torsion housing, and a resulting induced friction holds the end of the cloth in position.

[0013] Preferably, the seamless chamber actuator further comprises: integrating a plurality of the torsion housing in parallel to form a wrist housing, wherein the wrist housing is configured with a glove and ends of the cloths extending from the wrist housing are weaved into the respective fingers of the glove.

[0014] In another embodiment, the seamless chamber actuator comprises: a base layer; a flat groove, a perforated membrane/tape and a corrugated layer formed over the base layer and the perforated membrane/tape; and a substantially zero-volume fluid actuation chamber is formed between the base layer and the corrugated layer; wherein, when a fluid pressure is supplied into the substantially zero-volume fluid actuation chamber, the seamless chamber actuator responds by bending towards the base layer. Preferably, a port is fluidly connected to the substantially zero-volume fluid actuation chamber for actuation.

[0015] Preferably, each corrugation of the corrugated layer is configured with an interior actuation chamber, which is fluidly connected to the substantially zero-volume fluid actuation chamber.

[0016] Preferably, the base layer and the corrugated layer are formed from a single material of a predetermined stiffness or hardness, or the base layer and the corrugated layer are formed from two materials of different predetermined stiffness or hardness. Preferably, the corrugated layer is formed with a material of lower stiffness or hardness than that of the base layer.

[0017] In another embodiment, the present invention provides a method for providing haptic sensation comprises actuating the above seamless chamber actuators to provide force or

vibration force sensation in a virtual reality or augmented reality application, or force feedback or assistive force for patient rehabilitation.

[0018] In another embodiment, the present invention provides a method for controlled bending about a joint or joints; Preferably, the above torsion housing or wrist housing is attached on a side of the joint or joints and the end of the cloth attached to a side opposite the joint or joints; and actuating the second layer to jam a position of the end of the cloth, so that an angle of bending about the joint or joint is held in position for force feedback or to maintain an assistive force. This method for controlled bending about a joint or joints can also be used with the above bending actuator.

[0019] Preferably, the above seamless chamber actuators can be configured as part of or with a wearable apparel for providing haptic sensation or for providing force feedback or assistive force for patient rehabilitation. Preferably, components of these seamless chamber actuators may be formed by 3D printing.

[0020] One skilled in the art will readily appreciate that the present invention is well adapted to carry out the objects and obtain the ends and advantages mentioned, as well as those inherent therein. The embodiments described herein are not intended as limitations on the scope of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] To facilitate an understanding of this invention, there is illustrated in the accompanying drawings the preferred embodiments from an inspection of which when considered in connection with the following description, the invention, its construction and operation and many of its advantages would be readily understood and appreciated.

[0022] FIG. 1 illustrates a seamless chamber actuator according to a first embodiment, whilst FIG. 2 illustrates an exploded view of the seamless chamber actuator, and FIG. 3 illustrates a sectional side view of the seamless chamber actuator;

[0023] FIGs. 4-6 illustrate a seamless chamber actuator according to a second embodiment;

[0024] FIG. 7 illustrates the above seamless chamber actuator being configured for connection with a barb connector;

[0025] FIG. 8 illustrates the above seamless chamber actuator being configured for direct connection with a fluid tubing;

[0026] FIGs. 9-10 illustrate the above seamless chamber actuator being configured with an elongate actuator area for generating a higher force sensation or feedback;

[0027] FIG. 11 illustrates the above seamless chamber actuator being configured in an apparel for body force sensation;

[0028] FIGs. 12-13 illustrate the above seamless chamber actuator being integrated with a torsion housing according to a third embodiment;

[0029] FIG. 14 illustrates the seamless chamber actuator shown in FIG. 12 for flexing a lower arm about an elbow joint; whilst FIG. 15 illustrates jamming motion control of arm flexion at different flexing positions;

[0030] FIGs. 16-19 illustrate the seamless chamber actuators shown in FIG. 12 being configured with a glove;

[0031] FIG. 20 illustrates a seamless chamber actuator being configured as a bending actuator according to a fourth embodiment;

[0032] FIG. 21 illustrates the bending actuator shown in FIG. 20 being formed in 3 different stiffness materials; whilst FIGs. 22-24 illustrate performance of three bending actuators when actuated with compressed air, and FIG. 25 is a graph showing the bending performance; and

[0033] FIG. 26 illustrates the bending actuator shown in FIG. 20 being applied for controlled or assistive bending of a finger.

DETAILED DESCRIPTION OF THE INVENTION

[0034] From hereon, spatially relative terms, such as “top”, “bottom”, “left”, “right”, and the like, may be used herein for ease of description to describe one technical element or feature's relationship to another technical element or feature as illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the technical features in use or operation in addition to the orientation depicted in the figures.

[0035] For example, if a technical feature within the figures is turned over, its elements described as “top” of other elements or features would then be oriented “bottom” of the other elements or features. Thus, the exemplary term “top” can encompass both an orientation of above and below. The device may be otherwise oriented and the spatially relative descriptors used herein are interpreted accordingly.

[0036] For example, if a technical feature within the figures is flipped horizontally, its elements described as “left” of other elements or features would then be oriented “right” of the other elements or features. Thus, the exemplary term “left” can encompass both an orientation of left and right. The device may be otherwise oriented and the spatially relative descriptors used herein are interpreted accordingly.

[0037] The present invention will now be described in greater detail, by way of examples, with reference to the figures. For ease of reference, common reference numerals or series of numerals will be used throughout the figures when referring to the same or similar features common to the figures.

[0038] **FIG. 1** shows a seamless chamber actuator **100** according to a first embodiment of the present invention, whilst **FIG. 2** shows an exploded view of the seamless chamber actuator **100** and **FIG. 3** shows a sectional side view of the seamless chamber actuator **100**.

[0039] The seamless chamber actuator **100** is made up of a base layer **110** and a second layer **150** of pliable materials being fused over the base layer **110**, with a substantially zero-volume fluid actuation chamber **108** formed therebetween according to a first embodiment. Preferably, the base layer **110** and the second layer **150** of pliable materials are fabricated by

a three-dimensional (3D) printer, preferably a Fused Deposition Modelling (FDM) 3D printer or Stereolithography (SLA) 3D printer. Preferably, the base layer **110** is fabricated using a 3D printing material with 75D Shore hardness (which is obtainable from Ninjatek Armadillo), whilst the second layer **150** is fabricated using a 3D printing material X60 with Shore hardness 60A (which is obtainable from Diabase); in other words, the base layer **110** is configured with a higher material stiffness than the second layer **150**. The second layer **150** deforms under a load and returns to its unactuated shape upon release of the load.

[0040] In FIGs. 1-2, one edge of the seamless chamber actuator **100** has a material extension **102**, and a fluid supply port **104** is configured within the material extension **102**. Now referring to FIG. 2, an inside surface of the base layer **110** is formed with a flat groove **106**; preferably, the flat groove **106** is substantially 0.2 to 0.3 mm in depth; the flat groove **106** is fluidly connected from the port **104**, to which a fluid tubing T supplies fluid power, such as, compressed air for actuating the seamless chamber actuator **100**. To 3D print the second layer **150** onto the base layer **110** and over the flat groove **106**, a membrane or tape **130** is disposed over the groove **106** before 3D printing. After 3D printing, materials of the base layer **110** and the second layer **150** around the membrane/tape **130** are fused together to form an air-tight fluid actuation chamber, ie. the substantially zero-volume fluid actuation chamber **108** thus formed has an air gap of substantially 0.2 to 0.3 mm provided by the groove **106** and a surface area of the membrane/tape **130**. When an air pressure is supplied through the port **104**, the air pressure exerts (from below, as seen in FIG. 2) on the membrane/tape **130** and the second layer **150** responds by deforming, extending or bulging out, as illustrated by the dashed line **152** in FIG. 3; when the air pressure in the port **104** is released, the second layer **150** returns to its unactuated state; in this way, the bulging of the second layer **150** by supplying compressed air to the port **104** is used to simulate a sensory or haptic sensation, for example, in a VR or AR application. In one embodiment, the second layer **150** can be configured with a dimension of substantially 10 mm x 10 mm, or with lower or higher dimensions according to desired haptic sensations; with such a small size of the second layer **150**, the seamless chamber actuator **100** can be provided to simulate a substantially point force sensation. It is also possible to supply the air pressure to the port **104** according to a fluctuating pattern and the elastic response of the second layer **150** can thus simulate some vibration sensations. As can be realised, the sensing force created by deforming and bulging of the second layer **150** is determined by the surface area of the membrane/tape **130**, the air pressure supply at the port **104** and elasticity of the second layer

150. Preferably, the base layer **110** is made of a higher stiffness or hardness material and thicker material so that the seamless chamber actuator **100** is dimensionally stable.

[0041] FIGs. 4-6 show a seamless chamber actuator **100a** according to a second embodiment of the present invention. The seamless chamber actuator **100a** is made up of a base layer **110a**, a second layer **150a**, a membrane/tape **130a** and a top layer **170**; the base layer **110a**, the second layer **150a** and the membrane/tape **130a** are correspondingly similar to those used in the above seamless chamber actuator **100**. As seen from FIGs. 4-6, the top layer **170** is provided with an aperture **172**, which may be substantially similar in area or shape to the membrane/tape **130a**. Preferably, the base layer **110a** and the top layer **170** are formed of the same material of stiffness or hardness which is higher than that of the second layer **150a**. Preferably, the base layer **110a** and the top layer **170** being similar to the materials of the base layer **110** described in the above embodiment, and the second layer **150a** being similar to the above second layer **150**. The seamless chamber actuator **100a** is also similar provided with a port **104a** for supplying fluid pressure for actuating this seamless chamber actuator **100a**; when air is supplied to the port **104a**, air pressure acts from below the membrane/tape **130a** and the second layer **150a** responds by deforming and bulging up through the aperture **172**, as indicated by the dashed line **152a** in FIG. 6. By providing the top layer **170**, the area of the second layer **150a** to provide haptic sensation is now determined by the shape and dimensions of the aperture **172**, which can be visually distinguished (as compared to the first embodiment); in addition, the top layer **170** adds rigidity to the seamless chamber actuator **100a**. It is possible that a material extension **102** of the top layer **170** disposed substantially above the port **104a** (ie. an area denoted by **174**) be provided with a higher thickness; thus, the thickened area **174** of the top layer **170** further adds rigidity around the port **104a**.

[0042] In FIGs. 1-2 and 4-5, the seamless chamber actuator **100,100a** are shown with a rectangular or quadrilateral shape, but the shape is not so limited. For example, the seamless chamber actuator **100,100a** can also be polygonal or round in shape, as can be seen in FIG. 11 when a plurality of the seamless chamber actuators **100,100a** are configured in an apparel **190** to provide haptic sensation. Preferably, the second layer **150,150a** has a thickness of substantially 0.4 to 0.8mm, and more preferably, substantially 0.6 mm. Preferably, the top layer **170** is also 3D printed, with a material of substantially 75D Shore hardness, and a thickness of substantially 1 mm or more. The top layer **170** may be fabricated with a flat surface or with the thickened area **174** above the port **104**. The base layer **110,110a** may be thick relative to the second layer **150,150a**, and may be substantially 5 mm, or more; the

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thickness of the seamless chamber actuator **100,100a**, at least at the material extension **102**, may also depend on a selected size of the port **104,104a**, associated fitting **120** and pneumatic tubing **T** size.

[0043] FIG. 7 shows the above seamless chamber actuator **100,100a** being provided with the port **104,104a** and an associated barb fitting **120** for pneumatic tubing **T** connection. In another embodiment, the material extension **102** is configured with a reduced cross-sectional area, so that the pneumatic tubing **T** can be inserted directly over the material extension **102** and this dispenses away with the use of any fitting at the port **104,104a**; this direct tubing connection at the port **104,104a** is shown in FIG. 8.

[0044] FIGs. 9 and 10 show a seamless chamber actuator **100b** being configured with an elongate actuator body, when compared with the above seamless chamber actuator **100,100a**. The actuator body refers to the seamless chamber actuator excluding the material extension **102**, and may be substantially 25 mm long x 10 mm wide. The structure and arrangement of the base layer **110**, the second layer **150**, the membrane/tape **130** and the top layer **170** are as described for the corresponding components in the above actuators **100,100a**.

[0045] FIGs. 12-13 show the above seamless chamber actuator **100b** is mounted with a torsion housing **220** to form a jamming actuator **200**, which provides another embodiment of the present invention. The torsion housing **220** may be separately formed and then mounted onto the above seamless chamber actuator, preferably with the seamless chamber actuator **100b**, by a mounted means; for example, a mounting means may be by way of an adhesive, such as, a curable epoxy.

[0046] As seen from FIG. 13, the torsion housing **220** is made up of a shell **220** having an extension body **221**. The shell **220** and the extension body **221** is open at a bottom side, as seen in FIG. 13. Disposed inside the shell **220** is a strip of cloth **242** being wound up by a torsion spring **240**, so that a free end of the cloth **242** can be pulled through the open bottom and out at the right-hand end, as seen in FIGs. 12 or 13. The cloth **242** is chosen for its flexibility but is relatively inextensible. The torsion spring **240** keeps the cloth **242** in a substantially constant tension. Preferably, the torsion housing **220** is made up of two parts; these two parts may snap into place by known means and be taken apart for fixing or adjusting the strip of cloth **242** and the torsion spring **240**. The torsion housing **220** is also provided with a pair of holes **222** for securing the jamming actuator **200** at a point of

application, for example, about a joint or joints. In use, the free end of the cloth **242** is pulled out and connected to a body part; to keep the body part in position, the seamless chamber actuator **100b** component is actuated so that the second layer **150** is deformed or extended and the extended second layer **150** pinches the cloth **242** against the extension body **221**, and induced friction thus keeps the cloth **242** in position; the pinching force on the cloth **242** can thus be varied by controlling the fluid pressure connected to the port **104** or by varying the length of the extension body **221**. In practice, jamming actuator **200** is provided with the extension body **221** having predetermined dimensions, a predetermined torsion spring **240** force, and the pinch force desired at the second layer **150** is controlled by varying the fluid pressure.

[0047] FIG. 14 shows an application of the above jamming actuator **200** for controlling an angle of flexing of an arm about an elbow joint. As shown in FIG. 14, the jamming actuator **200** is fixedly located on an upper arm (by using the securing holes **222**) whilst the free end of the cloth **242** is connected to a lower arm (LA) below the elbow joint; when the jamming actuator **200** is not actuated, the lower arm can flexed up and down freely; upon actuation, the second layer **150** pinches or jams the cloth **242** against the extension body **221**, thereby maintaining the position of the arm at various angles of flexion, as shown in FIG. 15. This application can be used to provide force feedback on the arm; this application can also be applied to the fingers (as will be described with a variation of this jamming actuator), to the legs, neck or torso, which are made up of joints; for example, when a load is applied on the arm and the jamming force of the second layer **150** is slowly released until the arm is held in force equilibrium at a fluid pressure at the port **104**, and with a known friction coefficient at the surface of the second layer **150**, a force feedback can be calibrated with the fluid pressure. In another application, the jamming actuator **200** applies a jamming force on the cloth **242** to provide assistive force, for example, for holding an item in the hand or pushing against a wall, or measuring a force resistance during a rehabilitation exercise. In yet another application, the jamming actuator **200** can be used to provide passive rehabilitation by allowing a patient to stretch the arm in a jammed position to improve muscle memory.

[0048] The above jamming actuators **200** can be configured in parallel to form a glove jamming actuator **200a** according to another embodiment of the present invention. For example, FIG. 16 shows five parallel jamming actuators **200** are integrated into a wrist housing **220a** and each strip of the cloth **242** is weaved onto the glove for each finger. When

the glove jamming actuator **200a** is not actuated, the fingers in the glove can move freely; upon actuation, for example on selected fingers, the associated second layers **150** of the glove jamming actuator **200a** jam the associated strips of cloths **242** against the wrist housing **220a** and induced friction on the respective strip of cloth **242** controls bending of the respective finger. As described above, the glove jamming actuator **200a** can also be used to provide force feedback, assistive force or motion, or passive rehabilitation of muscles. FIG. 17 shows the glove jamming actuator **200a** is in the non-actuated state, whilst FIGs. 18-19 show the glove jamming actuator **200a** are in the actuated states.

[0049] In addition, the above jamming actuator **200** and the glove jamming actuator **200a** can also be integrated with electronic controls and fluid pressure sensing to provide force feedback and haptic sensation in VR or AR applications.

[0050] FIG. 20 shows a bending actuator **300** according to yet another embodiment of the present invention. The bending actuator **300** is 3D printed according a variation of the above embodiments. As shown in FIG. 20, the bending actuator **300** is formed with a base layer **310**, a flat groove **306**, a perforated membrane (or tape) **330**, a corrugated layer **350**, with a fluid chamber **308** formed between the base layer **310** and the perforated membrane **330** but the fluid chamber **308** is fluidly connected via the flat groove **306** to a port **304**. As in the above embodiments, the fluid chamber **308** is narrow, for example of substantially 0.2 to 0.3 mm gap, and is described as a substantially zero-volume actuation chamber, which is also identified by similar series numeral as **108**. In another embodiment, each fold of corrugation of the corrugated layer **350** is formed with a narrow component fluid chamber **308a**, which is fluidly connected to the substantially zero-volume actuation chamber **308** via apertures **332** located on the perforated membrane **330**. The width of the component fluid chamber **308a** may be substantially 0.2 to 0.5 mm and this width depends on the nozzle size for 3D printing. The folds of the corrugations are spaced apart at a pitch of **p**, which may be substantially 3 mm, for example; preferably, the apertures **332** are also spaced apart at pitch **p**. In FIG. 20, the walls **351** of the folds of the corrugated layer **350** are shown to be straight; however, it is not so limited; the walls **351** of the folds of the corrugated layer **350** may be serpentine.

[0051] In a first configuration, the base layer **310** is formed with a material of higher stiffness or hardness (such as, NF 85A Shore hardness, which is obtainable from NinjaFlex, whilst

the corrugated layer **350** is formed with an elastic material of lower stiffness or hardness (such as, X60 with a Shore hardness of 60D, which is obtainable from Diabase) to provide a bending actuator being made of two-composite materials; in a second configuration, both the bottom layer **310** and the corrugated layer **350** are formed with a relatively hard material (such as, NF 85A with Shore hardness 85A, which is obtainable from NinjaFlex); in a third configuration, both the bottom layer **310** and the corrugated layer **350** are formed with an elastic material (such as, X60 with a Shore hardness of 60D, which is obtainable from Diabase). FIG. 21 shows three bending actuators **300** formed according to these three configurations.

[0052] FIGs. 22-24 show these three bending actuators **300** after being actuated with fluid pressure supplied to the respective ports **104**. As can be seen from FIGs. 22-24, when the fluid chambers **308** are inflated in 20 kPa increment to substantially 300 kPa, side-walls of the corrugations of the corrugated layers **350** become extended and the bending actuators **300** respond by bending towards the base layer **310**. As observed from FIGs. 22-24, the bending actuator **300** formed with stiffer NF bend the least, possibly due to the hardness of the NF material.

[0053] Finite element models (FEM) of the bending actuators **300** were carried out to study stresses caused by bending of the actuators. From FIG. 23, the bending actuator **300** made of X60 elastic material has the highest bending angle at 300 kPa, compared to that made of X60-NF composite bending actuator shown in FIG. 24. From finite element analysis (FEA), the bending actuator **300** made with X60 single elastic material showed the higher Von Mises stress at the bend areas compared to the X60-NF composite materials bending actuator. Laboratory testing of these bending actuators **300** were also carried out and the results are shown in FIG. 25. These laboratory testing results show that the X60-NF composite-materials bending actuator **300** may provide longer reliability.

[0054] The results of bending performance suggest the bending actuator **300** made with X60-NF composite materials can be useful for a wearable application. FIG. 26 shows an application of the bending actuator **300** being employed as an assistive device for rehabilitating a finger of a stroke or hemiparetic patient. The bending actuator **300** can also be applied over other joints, such as, an elbow or knee. Still further, the bending actuator **300** can be configured as part of a wearable apparel for providing haptic sensation.

[0055] While specific embodiments have been described and illustrated, it is understood that many changes, modifications, variations and combinations of variations disclosed in the text description and drawings thereof could be made to the present invention without departing from the scope of the present invention. For example, the torsion housing **220** and the wrist housing **220a** may not be formed by 3D printing. In the above description, the torsion housing **220** and wrist housing **220a** are mounted on the seamless chamber actuator **100b**; in another embodiment, it is also possible that the torsion housing **220** or wrist housing **220a** is mounted on the seamless chamber actuator **100**.

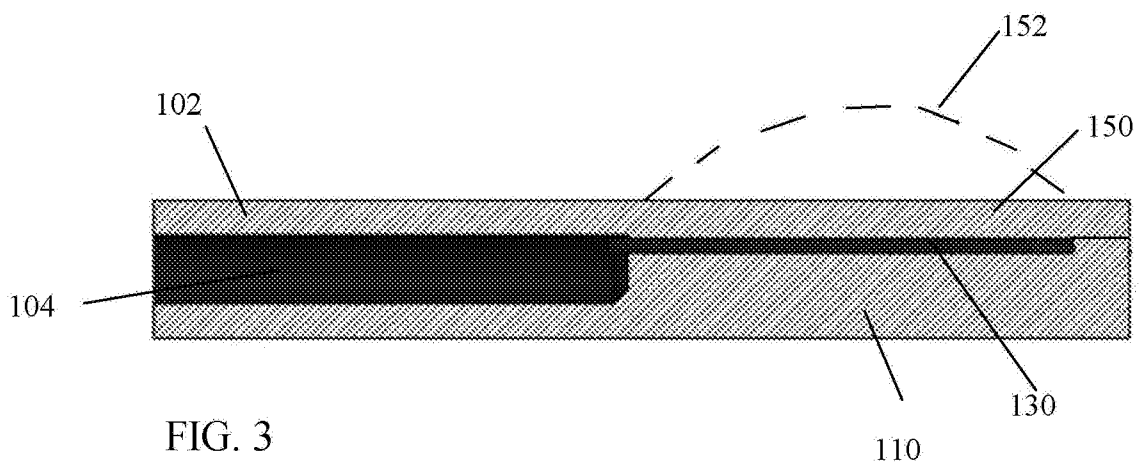
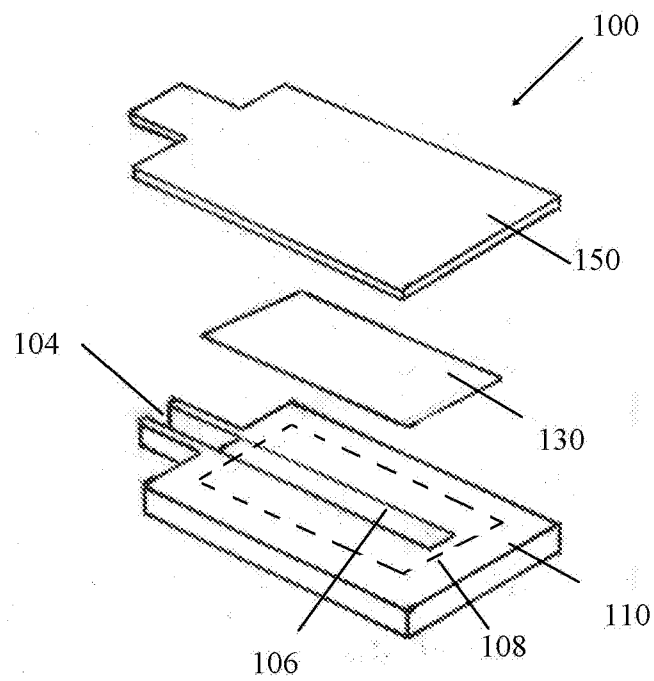
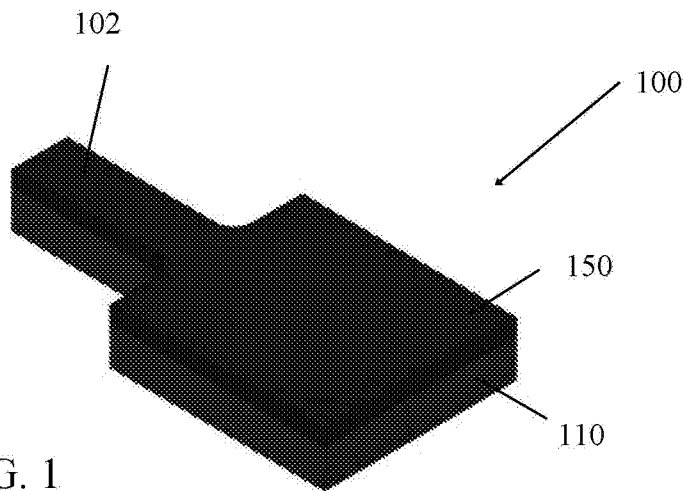
CLAIMS:

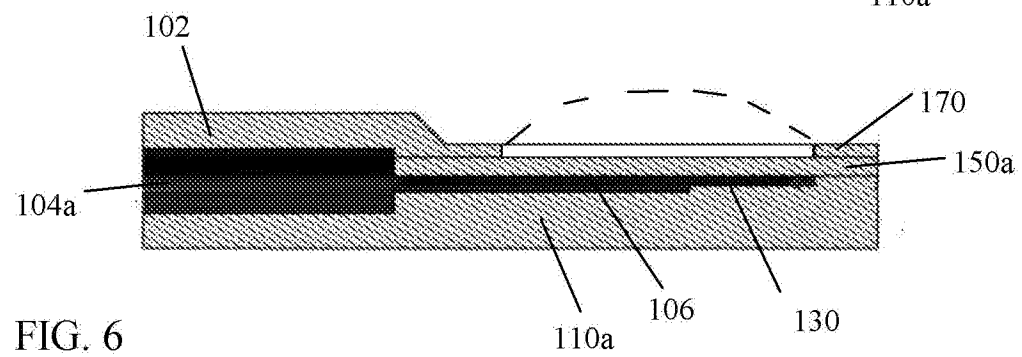
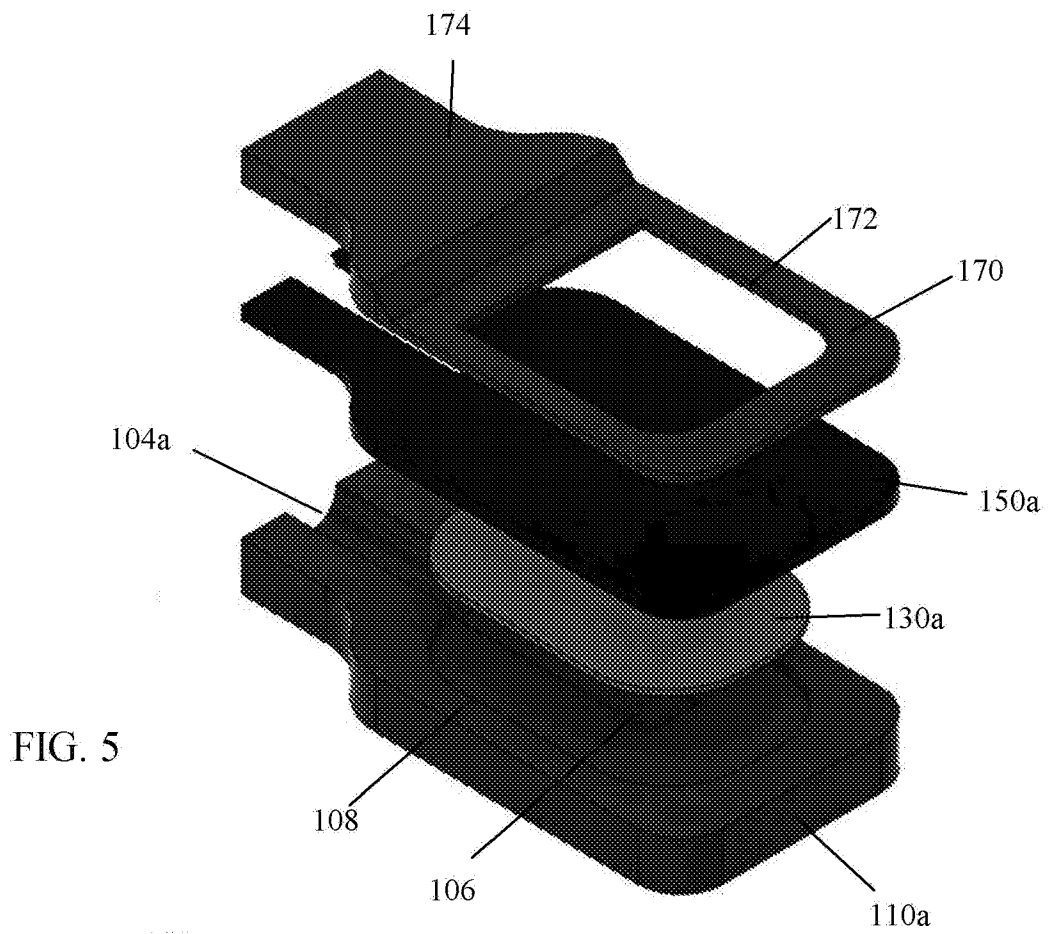
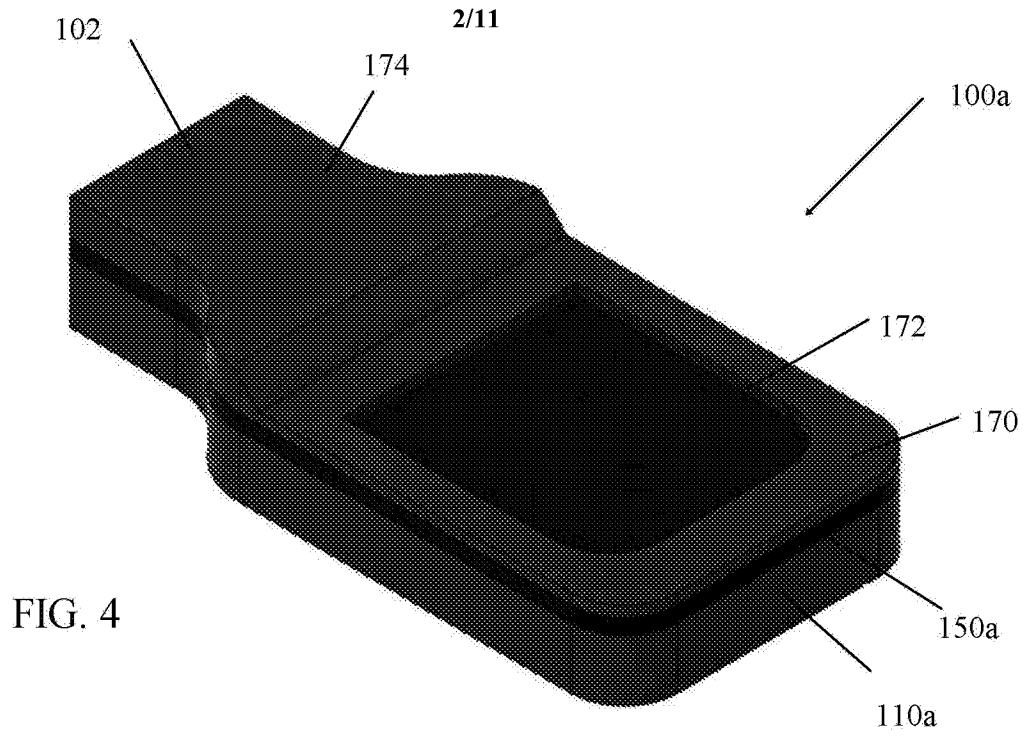
1. A seamless chamber actuator comprising:
 - a base layer wherein an inside face is formed with a flat groove;
 - a membrane or tape is disposed over the flat groove, with the membrane/tape having a surface area; and
 - a second layer is fusedly formed over the base layer and the membrane/tape, so that a substantially zero-volume fluid actuation chamber is formed by the flat groove and the surface area of the membrane/tape;
 - wherein, when a fluid pressure is supplied into the flat groove, the substantially zero-volume fluid actuation chamber is inflated and the fluid pressure acts on the surface area of the membrane/tape, the second layer responds by deforming and bulging out to provide a haptic sensation, and the second layer returns to its unactuated state when the fluid pressure is released.
2. The actuator according to claim 1, further comprises:
 - a top layer fusedly formed over the second layer, with the top layer having an aperture such that when the second layer responds to a fluid pressure, the second layer deforms and bulges out through the aperture to provide a haptic sensation.
3. The actuator according to claim 2, wherein the second layer is made from a material with stiffness or hardness that is lower than a material stiffness of the base layer or the top layer.
4. The actuator according to any one of claims 1-3, further comprises:
 - a port that is fluidly connected to the flat groove.
5. The actuator according to claim 4, further comprises:
 - a torsion housing being mounted onto the top layer, with the torsion housing comprising a strip of cloth being wound up by a torsion spring and an end of the cloth is disposed between the torsion housing and the top layer of the seamless chamber actuator;
 - wherein, when a fluid pressure is supplied to the port, the second layer responds by deforming through the aperture and jamming the cloth against the torsion housing, and a resulting induced friction holds the end of the cloth in position.

6. The actuator according to claim 4, further comprises:
integrating a plurality of the torsion housings in parallel to form a wrist housing, wherein the wrist housing is configured with a glove and ends of the cloths extending from the wrist housing are weaved into the respective fingers of the glove.
7. The actuator according to claim 1, wherein the second layer is formed as folds of corrugations, with the folds being spaced apart at a pitch p and a component fluid chamber is formed within each fold of the corrugation; and
the membrane or tape is perforated with apertures, with the apertures being spaced apart also at pitch p and in register with the folds;

wherein, when a fluid pressure is supplied into the substantially zero-volume fluid actuation chamber, the seamless chamber actuator responds by bending towards the base layer.
8. The actuator according to claim 7, wherein the base layer and the corrugated layer are formed from a single material of a predetermined stiffness or hardness, or the base layer and the corrugated layer are formed from two materials of different predetermined stiffness or hardness.
9. The actuator according to claim 8, wherein the corrugated layer is formed with a material of lower stiffness or hardness than that of the base layer.
10. A method for providing haptic sensation comprises:
actuating the seamless chamber actuator recited in claims 1-9 to provide force or vibration force sensation.
11. A method for controlled bending about a joint or joints comprises:
attaching the actuator recited in claim 5 or 6 about the joint or joints, with the torsion housing or wrist housing being attached on a side of the joint or joints and the end of the cloth or ends of the cloth are attached to a side opposite the joint or joints; and
actuating the second layer to jam a position of the respective cloth, so that an angle of bending about the joint or joint is held in position for force feedback or to maintain an assistive force.

12. A method for controlled bending about a joint or joints comprises:
attaching the bending actuator recited in claims 7-9 about the joint or joints, and
actuating the bending actuator to provide force feedback or to maintain an assistive force.





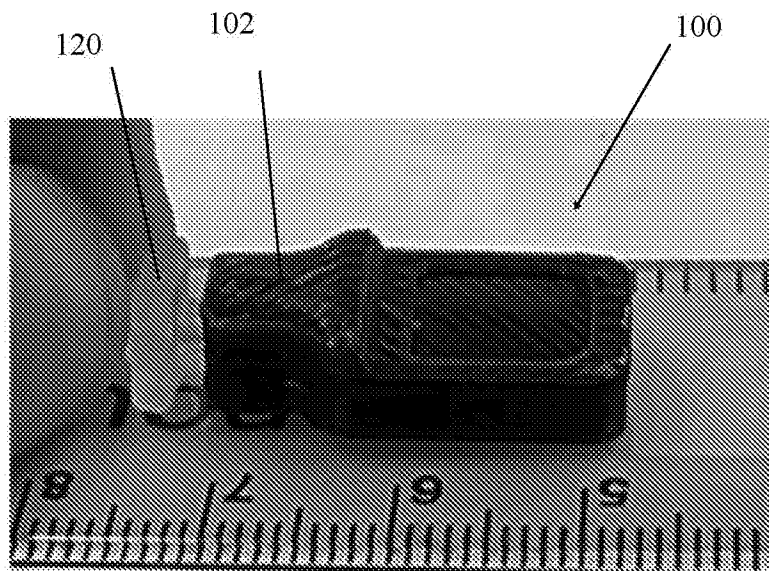


FIG. 7

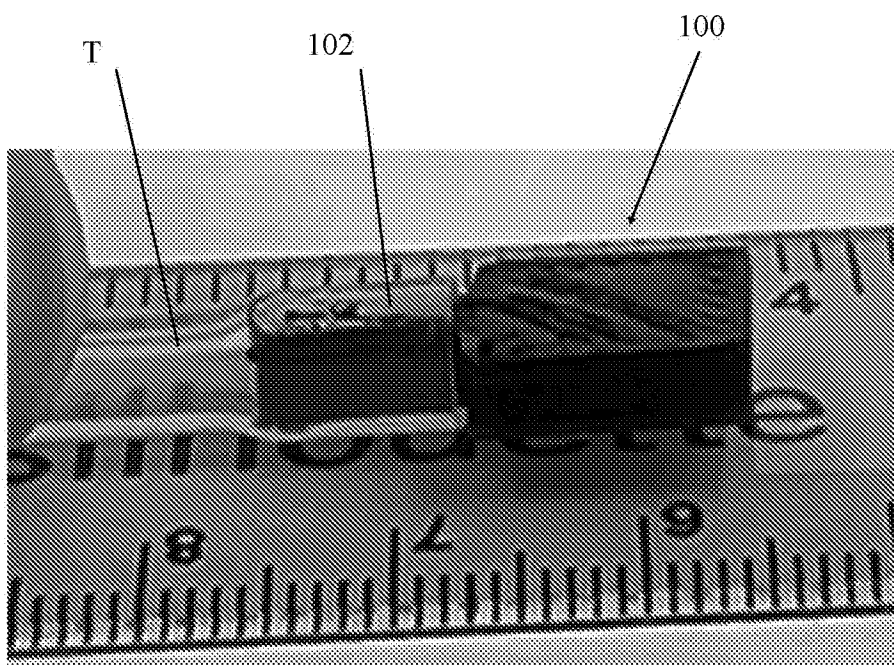


FIG. 8

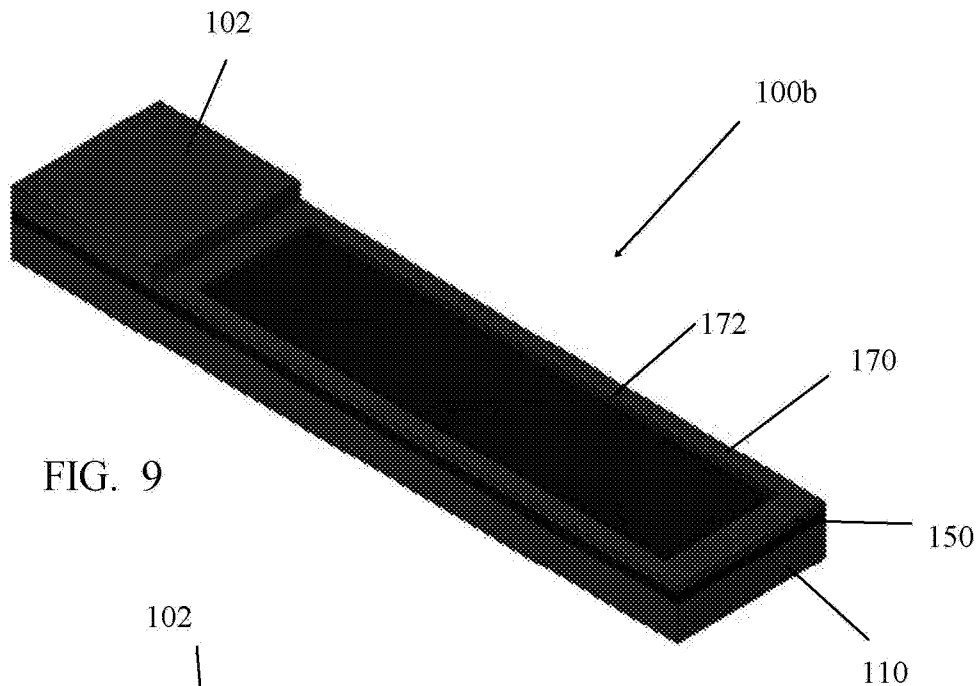


FIG. 9

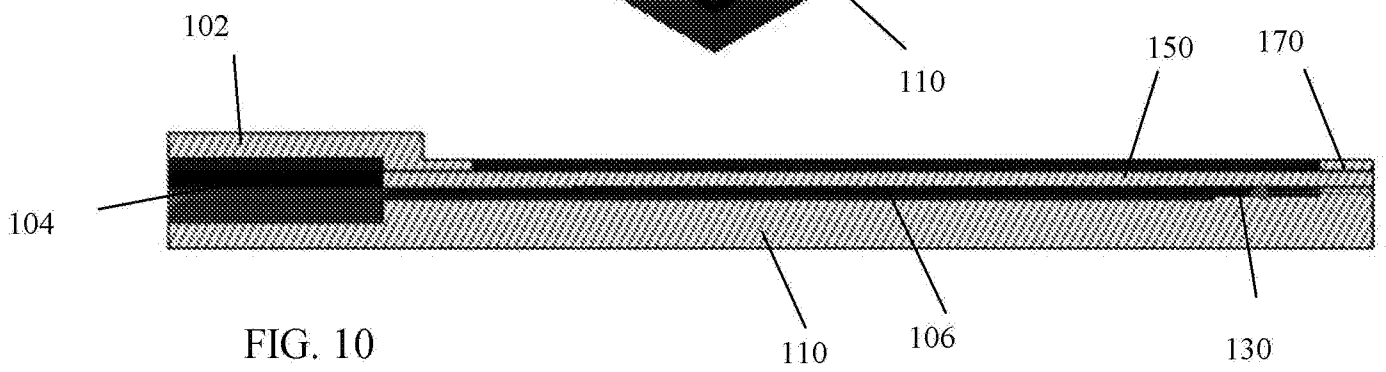


FIG. 10

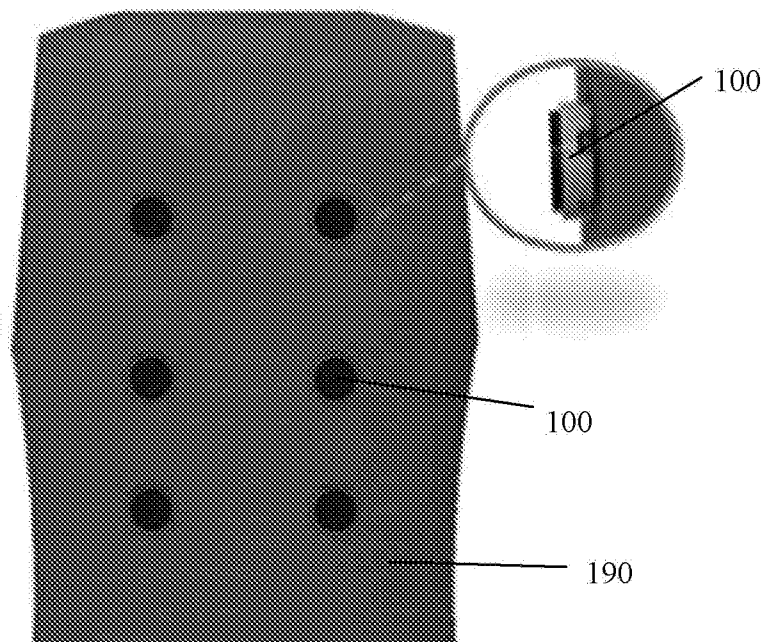
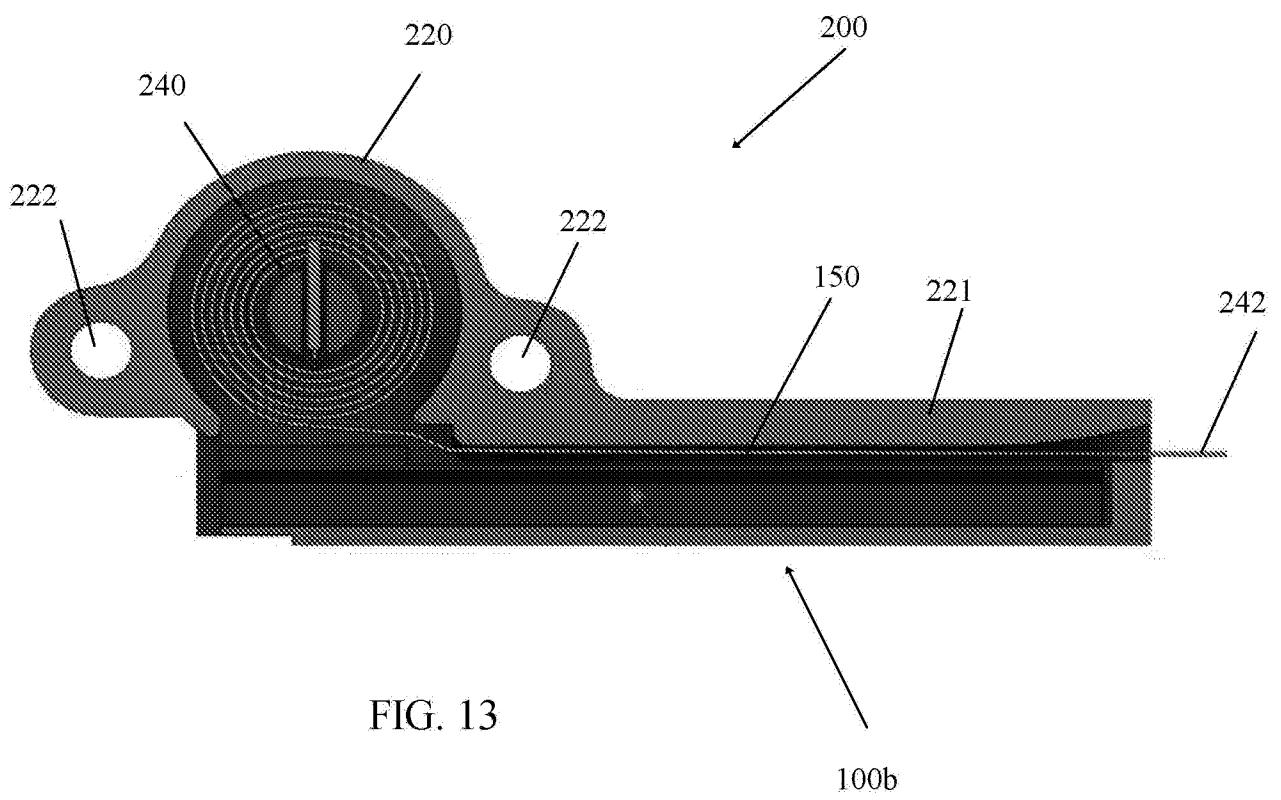
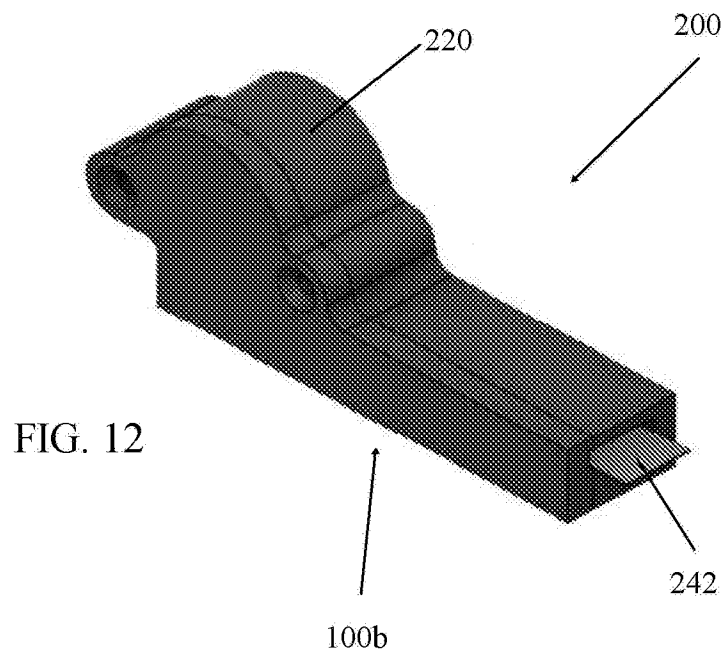


FIG. 11



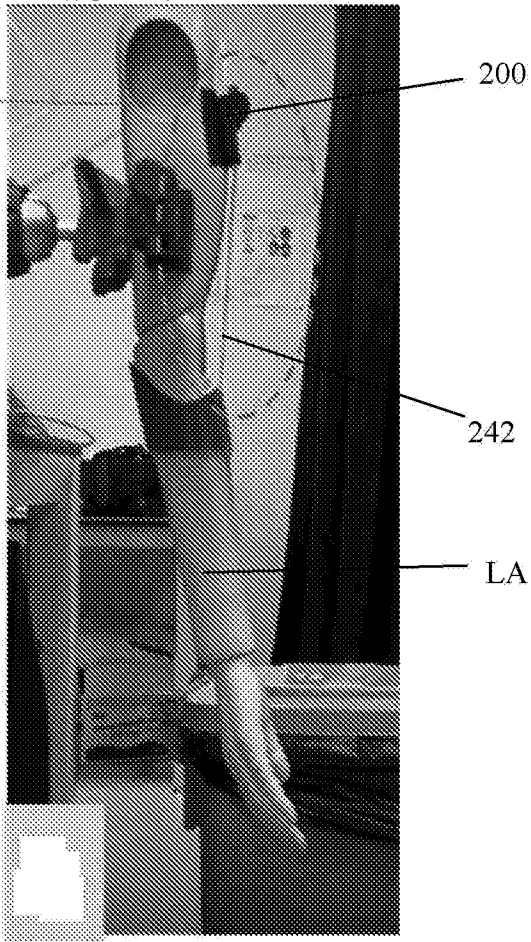


FIG. 14

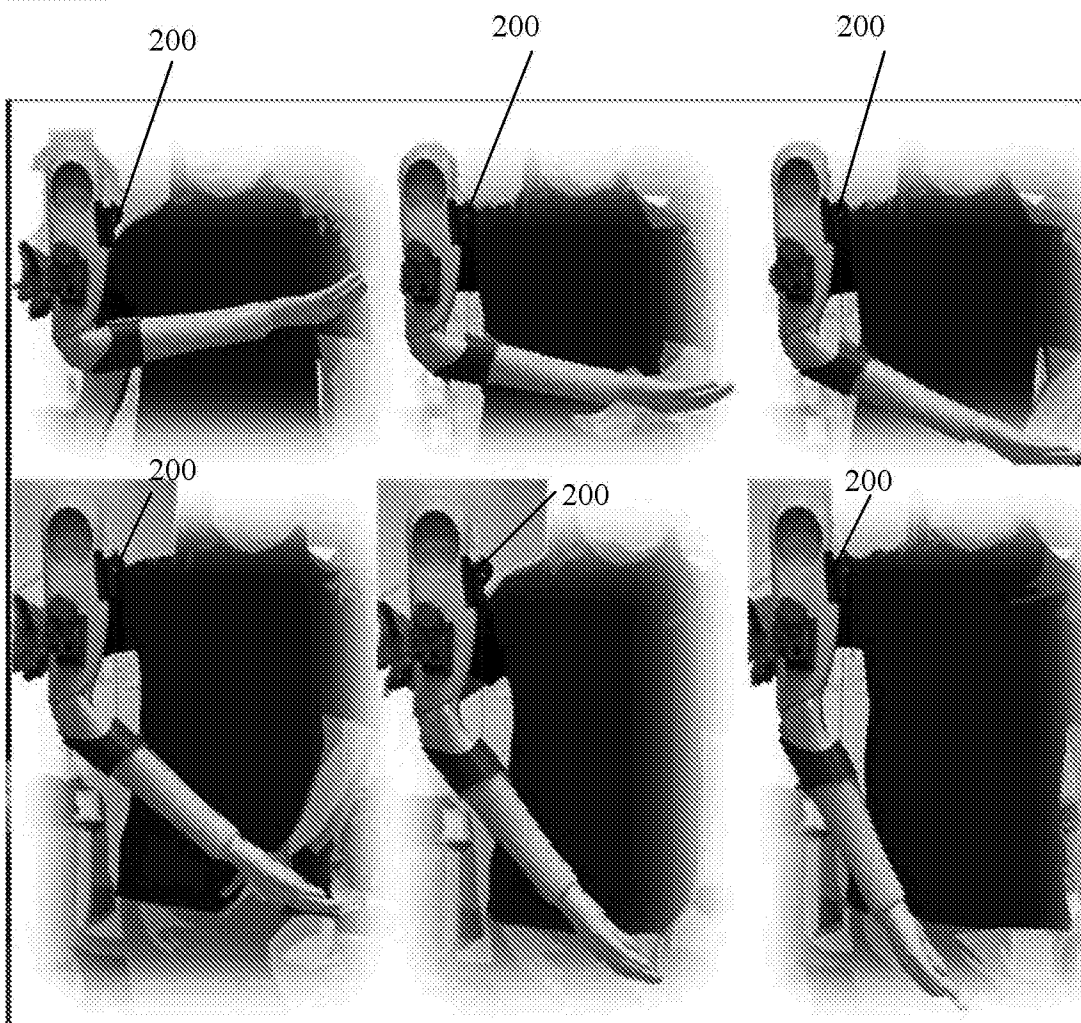


FIG. 15

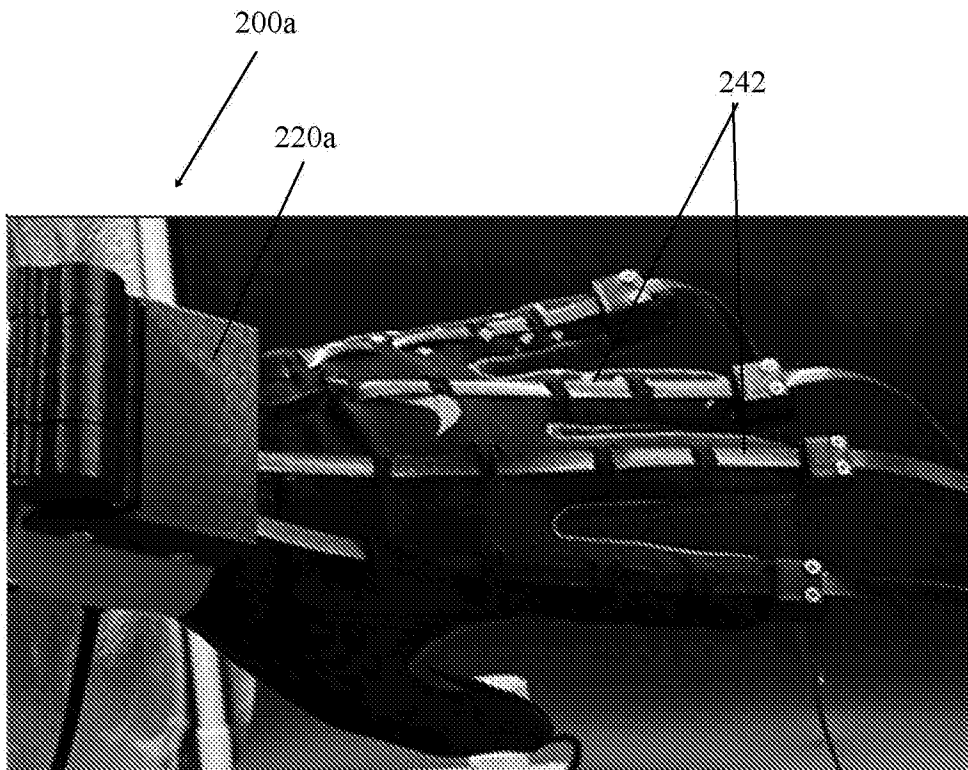


FIG. 16

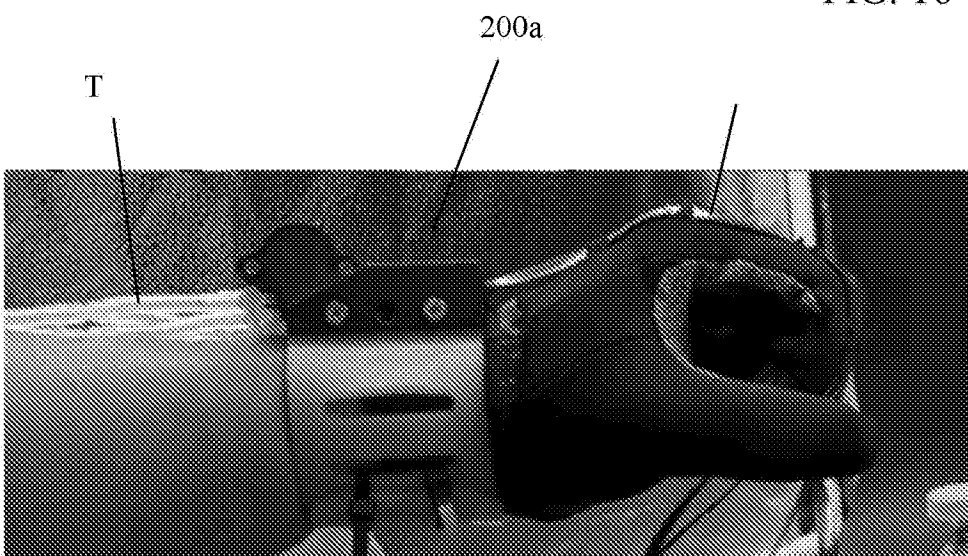


FIG. 17

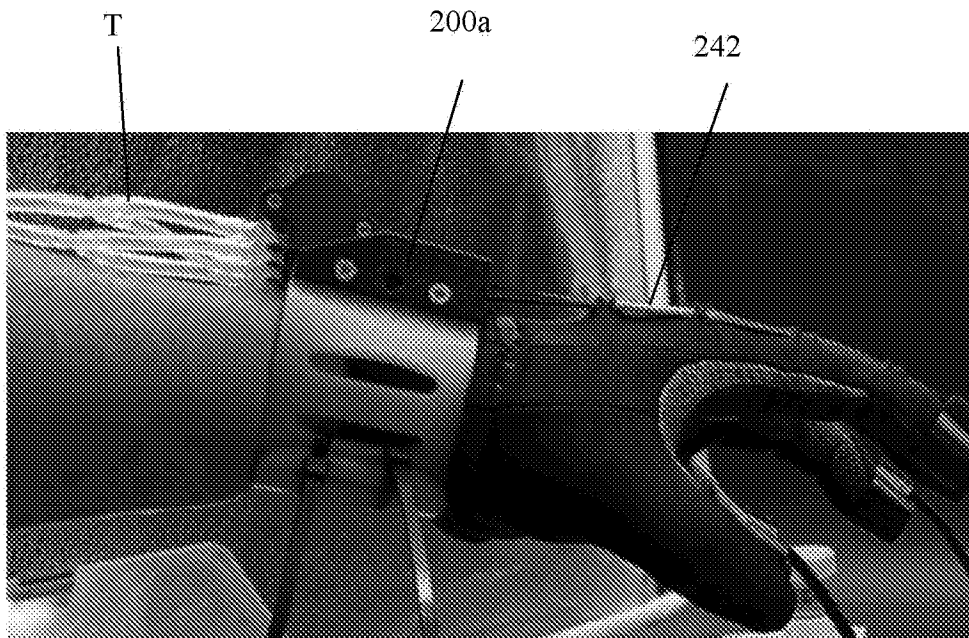


FIG. 18

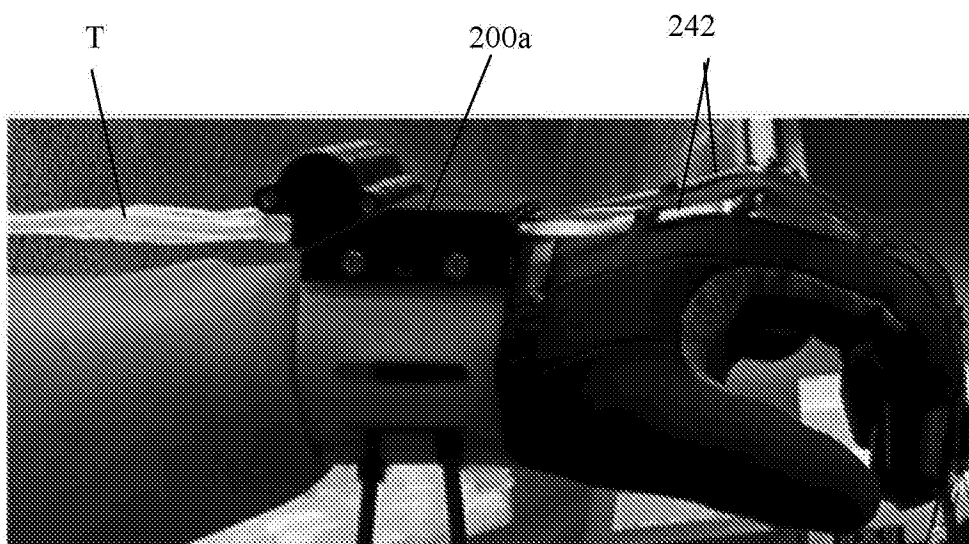
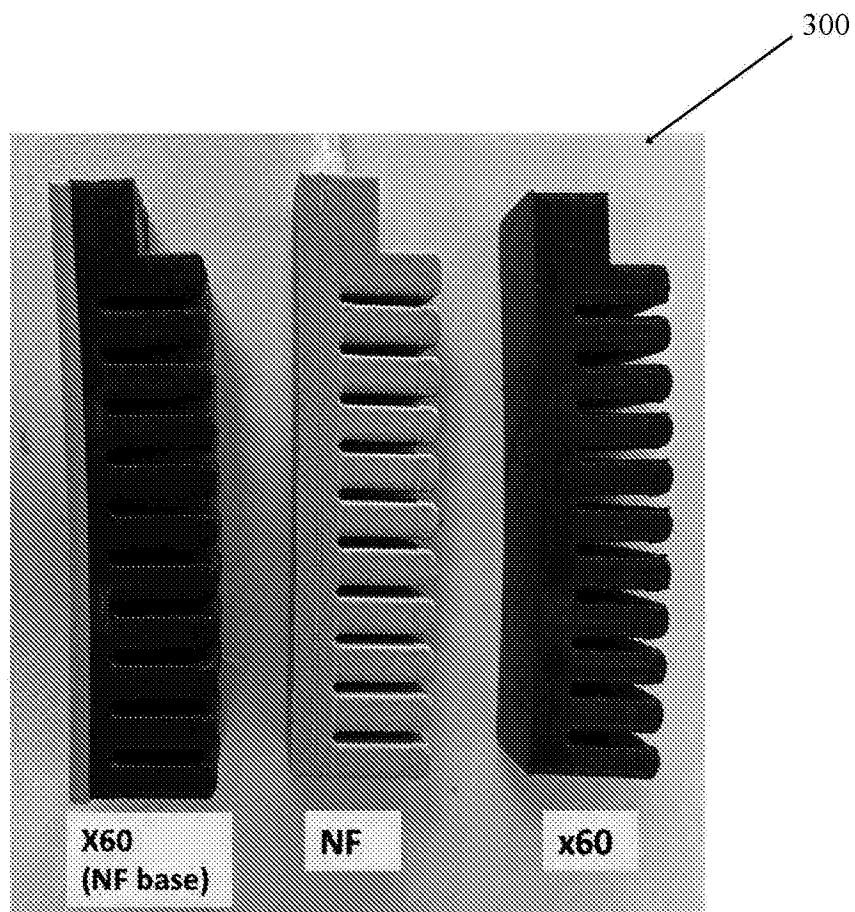
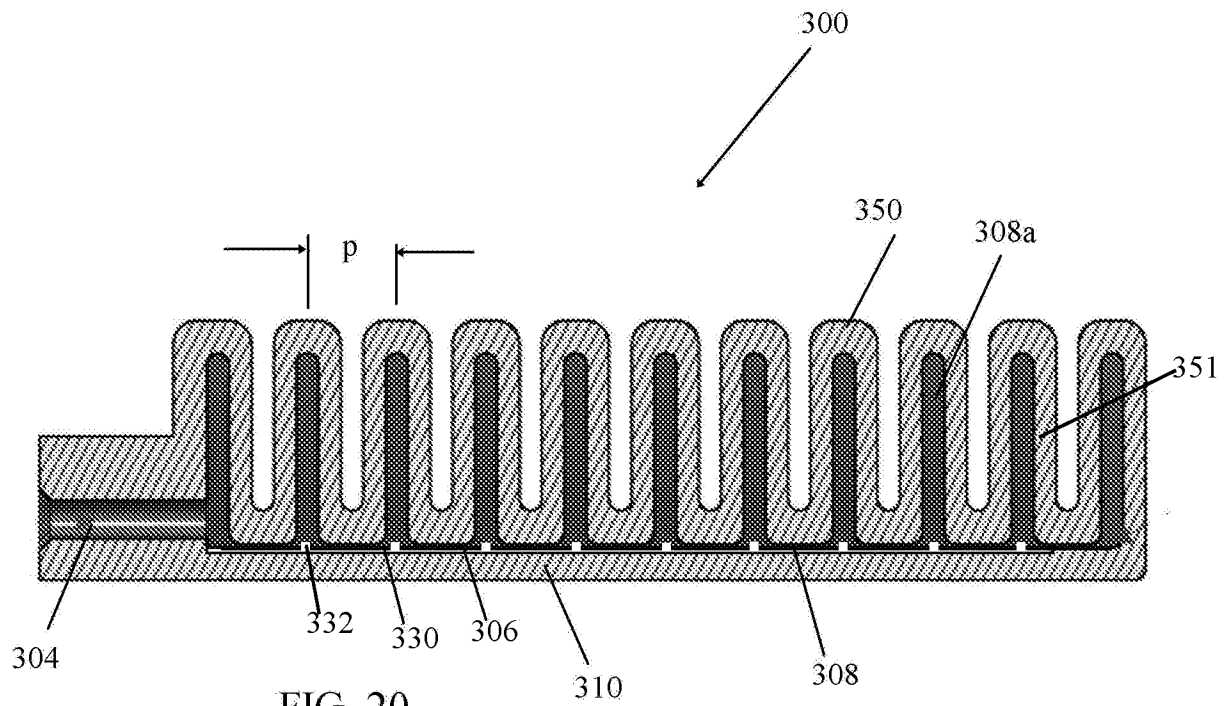
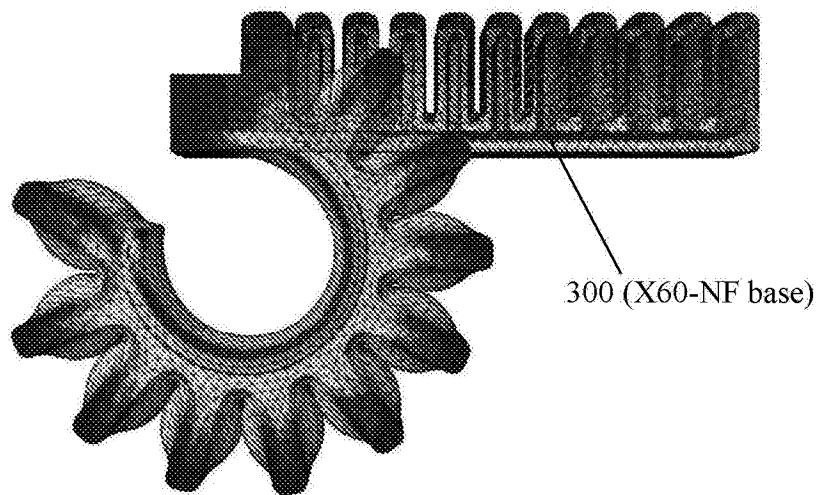
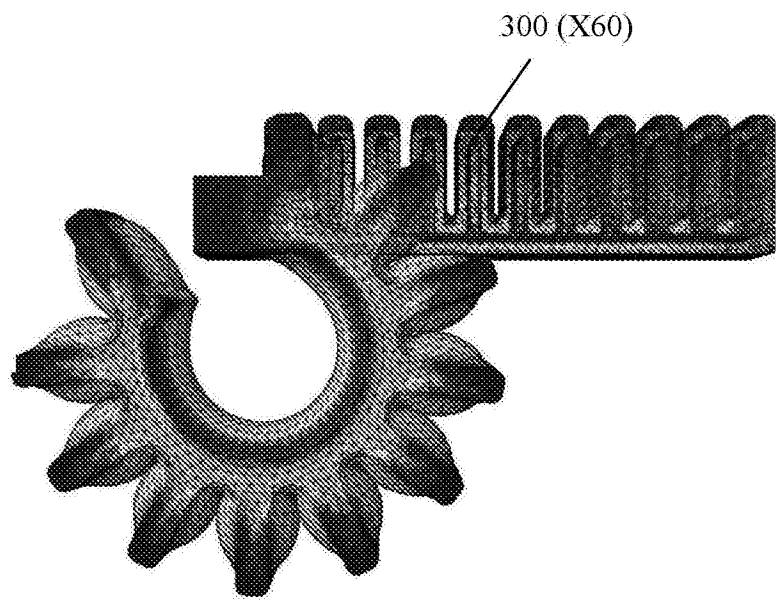
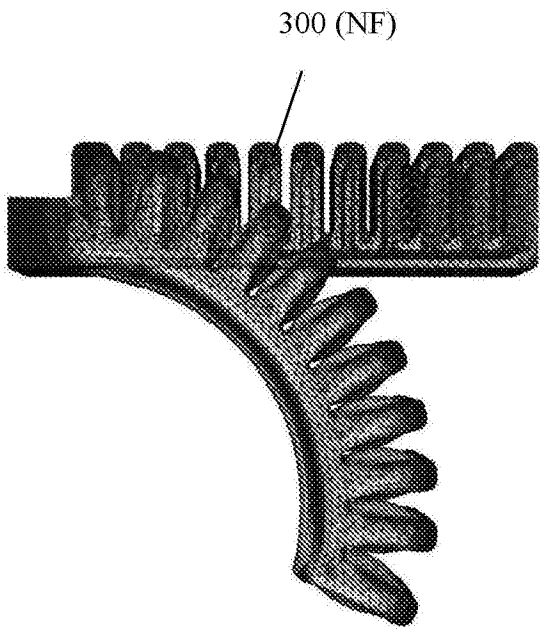


FIG. 19





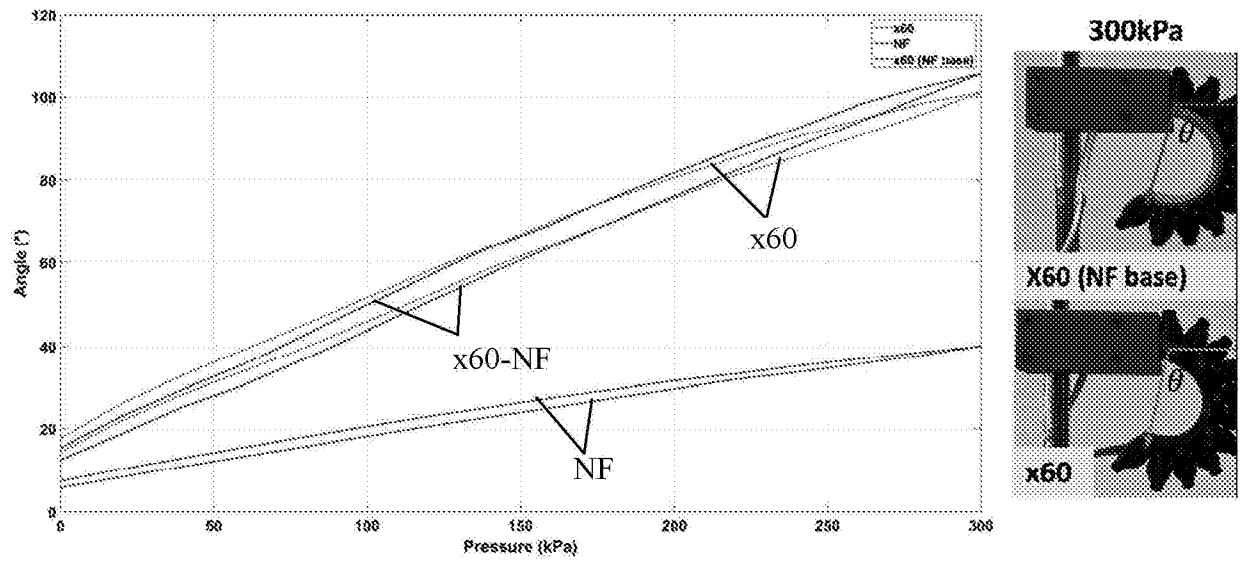


FIG. 25

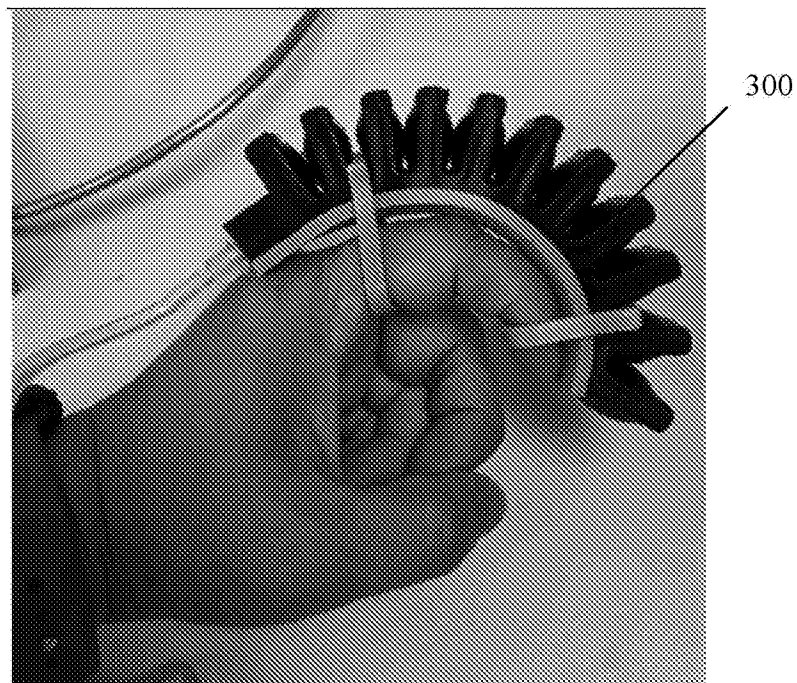


FIG. 26

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2023/050407

A. CLASSIFICATION OF SUBJECT MATTER

See Supplemental Box

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F15B, B25J

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)

FAMPAT: actuator, robotic, automation, chamber, hollow, groove, cavity, trench, compartment, membrane, tape, film, sheet, diaphragm, inflate, deform, bulge, deflate, stretch, expand, bend, twist, torsion, haptic, vibrate, tactile, tactual, sensation, sense, detect, transducer, feedback, and related terms

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 2021/0203021 A1 (MENICOVICH, D. ET AL.) 1 July 2021 Figures 1-4; paragraphs [0044]-[0047]	1-6, 10-11 7-9, 12
A	US 2017/0083085 A1 (RUBIN, J. A. ET AL.) 23 March 2017 Whole document, particularly Figures 16-19; paragraphs [0194]-[0199]	
A	WO 2018/212971 A1 (HAPTX INC) 22 November 2018 Whole document, particularly Figures 1-3; page 25, line 24 – page 28, line 29	

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*Special categories of cited documents:

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"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

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Date of the actual completion of the international search

12/10/2023

(day/month/year)

Date of mailing of the international search report

30/10/2023

(day/month/year)

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2023/050407

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

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WO 2018/212971 A1	22/11/2018	NONE	

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2023/050407

Supplemental Box

(Classification of Subject Matter)

Int. Cl.

F15B 15/10 (2006.01)

F15B 7/06 (2006.01)

B25J 9/14 (2006.01)

F15B 15/00 (2006.01)

B25J 11/00 (2006.01)