Soft Robotic Modular and Reconfigurable Actuator

Related Applications

[001] The present invention claims priority to Singapore patent application no. 10202112568Y filed on 11 November 2021, the disclosure of which is incorporated in its entirety.

Field of Invention

[002] The present disclosure relates to soft robotic actuators; these robotic actuators are made of modular components and are thus reconfigurable. Each of the modular components may differ in mechanical and/or dimensional properties from one another; different units of these modular components can be freely combined into subassemblies and are reconfigured to form the soft robotic actuators, which controllably perform a desired motion of extension and/or bending, and to deliver a desired force output.

Background

[003] Soft Robotics is a class of robotics that involves creating compliant designs by use of either compliant mechanisms or materials. Soft pneumatic actuators are a major class of soft actuators that use compliant materials; they are gaining popularity due to their utility in healthcare, wearable robotics, surgery, locomotion, soft manipulation for delicate objects, and so on. Conventional Soft Pneumatic Actuators are manufactured from three primary materials, namely silicone polymers, thermoplastic polyurethane (TPU) and fabrics; these known pneumatic actuators use TPU for hermetic sealing of the pneumatic chambers. In isolation, each of these materials poses challenges. FIG. 1 shows the conventional materials that have been popular for designing soft pneumatic actuators and their properties. Each material has its advantages in terms of mechanical properties and manufacturability, but it comes with trade-offs. Silicone has been the most used material for manufacturing soft pneumatic actuators. It possesses high deformation properties due to its high strain limit, but its low Young's Modulus tends to limit force output in isolation. Methods of using fibre-reinforcement and external constraints have tried to improve the force output or programmability, but this leads to use of higher input pressure. TPU-based actuators are usually manufactured by 3D printing, making them more repeatable than other techniques

for soft robot manufacturing. However, the increased stiffness of TPU leads to very high-pressure requirements, although TPU actuators provide large force output. These actuators also have the highest energy losses due to their high stiffness. The third class of actuators are made from TPU-backed fabrics; the fabrics provide conformance, while the TPU acts as a hermetic seal. The fabric actuators are usually manufactured by heat sealing TPU-TPU contact sides on two sheets back-to-back via ironing or ultrasonic welding. These designs have lower energy losses than TPU actuators, but their design complexity is limited due to their manufacturing technique. Heat seals are also prone to rupture at the seam, and thus, these actuators usually cannot tolerate pressures above substantially 150 kPa. In view of these limitations, there presents a need to develop soft robotics actuator carrying features and/or properties capable of addressing at least some of the shortcoming inherently exhibited in the prior arts discussed above.

Summary

[004] The following presents a simplified summary to provide a basic understanding of the present invention. This summary is not an extensive overview of the present invention, and is not intended to identify key features of the invention. Rather, it is to present some of the inventive concepts of this invention in a generalised form as a prelude to the detailed description that is to follow.

[005] The present invention seeks to provide soft robotic actuators which perform a desired motion of extension and/or bending, and to deliver a desired force output.

[006] In one embodiment, the present invention provides a robotic actuator comprising: a corrugated sleeve formed with corrugating folds extending from a first end to a second end and defining an interior passageway; and a bladder being detachably disposed inside the interior passageway of the corrugated sleeve; wherein, when a fluid medium is supplied into the bladder, the bladder is inflated, thereby compressing against the interior passageway, deforming the corrugated sleeve and providing a force output at the robotic actuator, and the bladder is reversible deflated when the fluid medium is released.

[007] In one embodiment, the corrugated sleeve is cylindrically shaped; in another embodiment, the corrugated sleeve is substantially hemi-cylindrical shaped and comprises a

flat surface, resulting in the interior passageway being substantially hemi-cylindrical. Preferably, the bladder is shaped to fit substantially snugly into the interior passageway.

[008] Preferably, the corrugating folds are spaced apart at a regular pitch distance. Preferably, a wall of each corrugating fold at both an outside surface and the inner passageway is curved or arched shaped. In another embodiment, a wall of each of the corrugating fold at the inner passageway is substantially flat. It is possible that a width of each corrugating fold at the outside surface has a bigger dimension than a width of the corrugating fold at the inner passageway. It is possible to vary a tensile stiffness of a material along the flat surface to control bending of the corrugated sleeve; alternatively, a fabric strip can be attached along the flat surface to control the bending.

[009] Preferably, radial fissures are formed radiating from the inner passageway and extending to both ends of the corrugated sleeve.

[0010] Preferably, the robotic actuator further comprises a lock member to removeably secure the bladder inside the corrugated sleeve. In one embodiment, the lock member comprises a female connector being connected to an end of the corrugated sleeve and a male connector being connected to an end of the bladder, so that the female and male connectors are engageable or dis-engageable by a rotatory motion. In another embodiment, the lock member comprises a female connector being connected to an end of the corrugated sleeve and a male connector being connected to an end of the bladder, so that the female and male connectors are engageable or dis-engageable by a sliding motion.

[0011] Preferably, the bladder is made of a material of lower stiffness that a material of the corrugated sleeve, so that the bladder is hermetically sealed and is inflatable by the fluid medium, whilst the corrugated sleeve controls extension or bending of the robotic actuator caused by inflating the bladder. In one embodiment, the bladder material is silicone rubber, whilst the material of the corrugated sleeve is thermoplastic urethane (TPU).

[0012] In another embodiment, the present invention provides a method for configuring extension or bending of a robotic actuator, the method comprises: configuring a corrugated sleeve by forming corrugating folds to extend from a first end to a second end, and defining an interior passageway; and removeably securing a bladder inside the corrugated sleeve, wherein the bladder is hermitically sealed to receive a fluid medium, wherein the bladder is

formed from a material of lower stiffness compared to a material of the corrugated sleeve; wherein, when the fluid medium is supplied into the bladder, inflation of the bladder acts on the interior passageway, thereby causing a force output and extension of the robotic actuator.

[0013] Preferably, the method further comprises forming fissures along the corrugated sleeve to alter the stiffness of the corrugated sleeve, so that the force output is increased and the robotic actuator bends towards location of the fissures. Additionally or alternatively, the method further comprises forming the corrugated sleeve with a flat surface to obtain a semi-cylindrical passageway, so as to reduce the bending stiffness of the corrugated sleeve towards the flat surface and the robotic actuator responds by bending towards the flat surface.

[0014] Preferably, removeably securing the bladder inside the corrugated sleeve comprises connecting a lock member to an end of the corrugated sleeve and an end of the bladder.

[0015] In yet another embodiment, the present invention provides a method for configuring an assistive mechanism using the above robotic actuator; the method comprises: inserting a bladder inside a corrugated sleeve, wherein the bladder is hermitically sealed to receive a fluid medium and forming the bladder from a material of lower stiffness compared to a material of the corrugated sleeve; removeably securing one end of the bladder to an associated end of the corrugated sleeve with a lock member; mounting an opposite end of the corrugated sleeve with another lock member; and securing each of the lock members to a limb constituting a joint; wherein inflating the bladder creates a force output, and resulting extension and bending of the robotic actuator creates an assistive motion about the joint, whilst deflating the bladder reverses motions of the robotic actuator.

[0016] Preferably, the joint is constituted with a prothesis or an exoskeleton.

Brief Description of the Drawings

[0017] This invention will be described by way of non-limiting embodiments of the present invention, with reference to the accompanying drawings, in which:

[0018] FIG. 1 illustrates characteristics of various materials usable for manufacturing a soft robotic actuator;

[0019] FIG. 2 illustrates a subassembly of a robotic actuator according to an embodiment of the present invention for extension actuation; FIG. 3 illustrates a cross-sectional view of the subassembly shown in FIG. 2;

[0020] FIG. 4 illustrates a subassembly of a robotic actuator according to another embodiment for bending and extension actuation; FIG. 5 illustrates a cross-sectional view of the subassembly shown in FIG. 4;

[0021] FIG. 6 illustrates a robotic actuator according to another embodiment of the present invention;

[0022] FIG. 7 illustrates a robotic actuator according to yet another embodiment;

[0023] FIG. 8 is a graph illustrating relative extension ratios of robotic actuators constituted by corrugated sleeves of TPU Shore hardness 60A, 85A and 95A;

[0024] FIGs. 9-10 are graphs illustrating bending profiles of the robotic actuators constituted by corrugated sleeves of TPU Shore hardness 85A and 95A, with pressure being incremented at a rate of 5 kPa;

[0025] FIG. 11 is a graph illustrating pressure-curvature relationship of bending of the robotic actuators constituted by corrugated sleeves of TPU Shore hardness 60A, 85A and 95A;

[0026] FIG. 12 is a graph illustrating blocked force output by bending the robotic actuators constituted by corrugated sleeves of TPU Shore hardness 60A, 85A and 95A with cylindrical bladders;

[0027] FIG. 13 is graph illustrating comparative blocked force output by bending the robotic actuators constituted by corrugated sleeves of TPU Shore hardness 60A and 85A with cylindrical and hemispherical bladders;

[0028] FIG. 14 is a graph illustrating blocked force output by extending the robotic actuators constituted by corrugated sleeves of TPU Shore hardness 85A and 95A; and

[0029] FIGs. 15 and 16 are pictures illustrating a use of the robotic actuator as an elbow assistive mechanism.

Detailed Description

[0030] One or more specific and alternative embodiments of the present invention will now be described with reference to the attached drawings. It shall be apparent to one skilled in the art, however, that this invention may be practised without such specific details. Some of the details may not be described at length so as not to obscure the invention. 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.

[0031] The terms "skin" and "corrugated sleeve" are used to refer to a component disposed external to a bladder to constrain deformation, movement, and/or operation of the soft robotic actuator of the present invention;

[0032] The term "bladder" is used to refer to an internal component of the soft robotic actuator that receives a fluid medium to controllably deform the skin or corrugated sleeve surrounding the bladder;

[0033] FIGs. 2 to 7 show various embodiments of soft robotic actuators **300**,**400** and subassemblies **100**,**200** of components that make up the soft robotic actuators. In general, each of the robotic actuators **300**,**400** or subassemblies **100**,**200** include two modules, namely, a corrugated sleeve **110**,**210** and a bladder **120**,**220**. The bladder **120**,**220** is made of a low stiffness material (such as, silicone rubber) and is hermetically sealed, whilst the corrugated sleeve **110**,**210** is made of a higher stiffness material (such as, thermoplastic urethane (TPU)) than the bladder material and serves as an external skin to constrain deformations (extension and/or bending) of the bladder **120**,**220** when a fluid medium is supplied into the bladder. With the corrugated sleeve **110**,**210** and the bladder **120**,**220** being modular components, the robotic actuators thus obtained become reconfigurable according to a desired motion and a desired output force by inflating/deflating the bladder and deforming the corrugated sleeve.

[0034] As shown in FIGs. 2 and 3, the corrugated sleeve **110** is formed by a plurality of circular folds **112**, like that of an accordion, and form a corrugated, cylindrical body with a substantially interior passageway **111**. The passageway **111** extends from a first end **113** to a second end **114** of the corrugated sleeve **110**, with the folds **112** of the corrugated sleeve **110** being fabricated with dimensions and being arranged in a geometrical configuration. The bladder **120** is detachably inserted inside the passageway **111** and, preferably, extends from the first end **113** to the second end **114** inside the corrugated sleeve **110**. In a use application, a fluid medium is supplied into the bladder **120** under pressure through a tubing opening located at one end of the hermetically sealed bladder **120** to reversibly inflate the bladder **120**; inflation by the fluid medium causes the bladder **120** to press against and to deform the corrugated sleeve **110**, thereby generating a force output and extension of the robotic actuator, which is constituted by the corrugated sleeve **110** and the bladder **120**. The fluid medium can be pneumatic- or hydraulic-based. The pneumatic medium may be atmospheric air, nitrogen, carbon dioxide, argon, helium, or any gas, employed to inflate the bladder **120**. The hydraulic medium may be water, glycol, oil and so on.

[0035] As shown in FIGs. 2 and 3, the outmost edges **118** of the folds **112** are curved or arched in shape and collectively define the outer surface of the corrugated, cylindrical sleeve **110**; likewise, the innermost edges **119** of the folds **112** are curved or arched and collectively define the passageway **111**. In one embodiment, each fold **112** has a wall **152** thickness of substantially 0.5 to 2 mm, which is relatively lower than that of known actuators; for example, the corrugated folds **112** are 3D printed and the wall **152** thickness is substantially 2 x the size of the 3D printing nozzle. In another embodiment, the inner most edges **119** of the folds **112** are flat and thus provide a larger area of contact with the bladder **120**.

[0036] In one embodiment, the folds **112** are formed at a regular pitch **p**; the pitch **p** may be substantially 8 mm, but this is not so restricted; the pitch **p** may vary with the wall **152** thickness and may depend on characteristics of a 3D printer that is employed to fabricate the corrugated sleeve **110**. When the pitch **p** is regular, the widths of the folds **112** along the outer surface and along the passageway **111** may be substantially the same; in another embodiment, even when the pitch **p** is regular, the widths of the folds **112** along the outer surface and along the passageway **111** may differ; preferably, the width of the folds **112** along the outer surface of the corrugated sleeve **110** is larger than the fold width along the passageway **111**. An annular height **h** of the folds, as seen in FIG. 3, may be about 12 mm,

or range from about 10 to 15 mm, depending on the application of the robotic actuator **300**,**400**.

[0037] In FIG. 3, the first end **113** of the corrugated sleeve **110** is shown to be open, whilst the second end **114** is closed. An edge **116** around the open first end **113** of the corrugated sleeve **110** is raised, for example, to reinforce the open first end 113 of the corrugated sleeve **110**.

[0038] The bladder **120** shown in FIGs. 2 and 3 is elongate and is dimensioned to fit snugly inside the passageway **111** of the corrugated sleeve **110**. The bladder wall thickness may range from substantially 2 to 4 mm.

[0039] The bladder **120** is made of a low stiffness material (such as, silicone rubber) and is hermitically sealed; the corrugated sleeve **110** is made of a higher stiffness, to provide an outer skin to constrain inflation of the bladder **120**; in this manner, the corrugated sleeve **110** of the robotic actuators **300**,**400** thus configured is free from the need of being hermitically sealed, hence permitting the corrugated sleeve **110** to be fabricated at a reduced thickness, compared to known robotic actuators formed with a single thermoplastic polyurethane (TPU). The reduced thickness subsequently renders the assembled robotic actuator **300**,**400** to be operable under lower fluid pressures as the corrugated sleeve of lower wall **152** thickness requires less energy for deformation.

[0040] In another embodiment, the folds **112** are formed with longitudinal fissures **151** to form another geometric configuration of a corrugated sleeve **110a** for constituting a robotic actuator. In one embodiment, the fissures **151** radiate radially from the passageway **111**, are spaced regular and divide the corrugated sleeve **110a** into regular sectors **150**; the fissures **151** reduce the stiffness of extension of the corrugated sleeve **110a**; with this geometric configuration, when the bladder **120** is inflated, the corrugated sleeve **110a** deforms by extending in a substantially longitudinally direction at a lower fluid pressure than compared to a corrugated sleeve **110** without the fissures. In another embodiment, the fissures **151** are formed in a non-regular array about the passageway **111** and a corrugated sleeve **110b** thus obtained is configured to both extend and bend, where bending is towards the side where the fissures **151** are located (but this is not illustrated in a figure).

[0041] FIG. 4 shows a subassembly **200** obtained by combining a corrugated sleeve **210** and a bladder **220**, whilst FIG. 5 shows a cut-section to show the interior arrangements. A robotic actuator using the subassembly **200** is configured to produce a greater degree of bending compared with the robotic actuator employing the above corrugated sleeve **110**,**110a**,**110b**. As shown in FIGs. 4 and 5, the corrugated sleeve **210** is a substantially semi-cylindrical in shape and forms a semi-cylindrical corrugated sleeve **210**, with outmost edges 218 of the folds 212 are curved or arched in shape and collectively define the outer surface of the semi-cylindrical corrugated sleeve with wall thickness 252 and innermost edges 219 of the folds 112 define an interior passageway 211. A flat planar surface **260** runs lengthwise along the corrugated sleeve **210** rendering the interior passageway **211** inside the corrugated sleeve also semi-cylindrical in shape. As the corrugated sleeve **210** with folds **212** forming the corrugations can flex more in relation to the flat surface **260**, deformation of the corrugated sleeve **210** leads to bending towards flat surface **260** upon inflation of a bladder **220** disposed in the interior passageway **211**.

[0042] In another embodiment of the corrugated sleeve **210a**, longitudinal fissures **251** are formed, like the fissures described above, to reduce the extension stiffness of the corrugated sleeve **210a** or to increase the flexibility of the resulting subassembly **200a**. The nature of fabricating the folds and the fissures are as described above, and no further description is provided.

[0043] In a variation, the flat surface **260** of the corrugated sleeve **210**,**210a** is slightly curved. In a further variation, the flat surface **260** may be fabricated with varied thickness or stiffness at different portions for regulating the ratio and degree of bending motion. According to the above embodiment and variations, a cylindrically shaped bladder **120** as described above can be fitted inside the passageway **211**. Preferably, a bladder **220** with a semi-cylindrical shape is used; the bladder **220** that is semi-cylindrical shaped with a flat facade is able to fit snugly into the passageway **211** and thus provides more effective control on the extension and/or bending of the corrugated sleeve **210**,**210a**.

[0044] FIG. 6 shows a robotic actuator **300** according to an embodiment of the present invention. The robotic actuator **300** is made up of the above subassembly **200**,**200a** and a lock member **370** located at a first end **213**, with a second end **214** of the corrugated sleeve **210**,**210a** being closed (similarly shown in FIG. 3). In a use configuration, two or more

corrugated sleeves **210**,**210a** may be connected in series and a distal end may be equipped with an end effector.

[0045] The lock member **370** is provided to removably secure the bladder **220** inside the corrugated sleeve **210**,**210a**. As shown, the lock member **370** is made up of a male connector **371** in rotatory engagement with a female connector **372**. Preferably, the female connector **372** is a substantially semi-annular member located on an end wall of the corrugated sleeve **210**,**210a** and is formed with an annular trench **373**. The male connector **371** is a semi-circular member **376**, connected to an end of the bladder **220**, and has a part-circular arm **377** that engages with the annular trench **373**. The part-circular arm **377** has a fixed end extending from the semi-circular member **376** and the part-circular arm **377** hovers along part of the circular edge of the semi-circular member **376**; as a result, a rift is formed between the semi-circular member **376** and the part-circular arm **377**; a width of the rift is larger than a thickness of an inner sidewall **375** around the annular trench **373** so that the part-circular arm **377** can be rotatably engaged inside the annular trench **373** to facilitate the removeable securing of the bladder **220** inside the corrugated sleeve **210**,**210a**. In one embodiment, both the male connector **371** and the female connector **372** are formed from the thermoplastic polyurethane (TPU) material used to form the corrugated sleeve **210**,**210a**. It is also possible the male connector and the female connector are formed with a TPU with a higher Shore hardness value.

[0046] As shown in FIG. 6, the male connector **371** is provided with a through opening **378**, which receives a tubing for supplying a pressurised fluid medium into the bladder **220**. In a variation, the opening **378** is arranged to coincide with an opening of the bladder **220** for supplying the fluid medium during operation of the robotic actuator **300**. It is also possible that the opening **378** is provided to receive both a tubing conveying the fluid medium and wires from sensors that may be used to monitor extension and bending of the robotic actuator **300** or any accompanying end effector.

[0047] FIG. 7 shows a robotic actuator **400** according to another embodiment of the present invention. The robotic actuator **400** is made up of the above subassembly **200**,**200a** and a lock member **480** disposed at each of two ends of the subassembly. In another embodiment, a robotic actuator may be configured with two or more subassemblies connected in series

and the lock member **480** is connected to one end, whilst the opposite end may be equipped with an end effector.

[0048] Each lock member **480** is made up of a male connector **481** being connected to the bladder **220** and a female connector **482** being connected to an end the corrugated sleeve **210**,**210a**. The female connector **482** is U-shaped and is formed with a tough **484**. The tough **484** is accessible via a side opening for slidingly receiving and engaging a matching plate member **485** of the male connector **481**. Whilst not shown, the plate member **485** is connected to the bladder **220**, so that the male connector **481** slidingly engageable with the female connector **482** to form an assembly of the robotic actuator **400**.

[0049] In FIG. 7, the male connector **481** is shown substantially as a triangular block **487** with the plate member **485** being located at a face edge. On another face edge of the male connector **481**, a through hole **489** is provided for communicating a fluid medium into the bladder **220** or for running sensor wires into the passageway **211**. For example, in an application, such as an elbow assistive mechanism for patient rehabilitation, the male connectors **481** are used as mounting points to a patient's limbs, a prothesis or an exoskeleton.

[0050] Performance tests of the above robotic actuators:
Conventional robotic actuators using a single TPU material require high input pressure to generate deformation due to the high elastic modulus of TPU. Although this enables the generation of higher output forces, a large amount of energy is taken up in the deformation of the known robotic actuator itself. In the present invention, this limitation is circumvented by using the corrugated sleeve **110**,**110a**,**110b**,**210**,**210a** based on TPU with the internal bladder **120**,**220** serving as a hermetic seal for containing the fluid medium. Thus, the bladder **120**,**220** is configured for transferring the force onto the corrugated sleeve **110**,**110a**,**110b**,**210**,**210a**, which serves as a programmable or controllable constraint. The corrugated sleeve **110**,**110a**,**110b**,**210**,**210a** can thus be manufactured in much more complex configurations and can be separated due to the modular configuration. This allows a user to change the bladder **120**,**220** and the corrugated sleeve **110**,**110a**,**110b**,**210**,**210a** combinations to alter the properties of the robotic actuators **300**,**400**. The present invention illustrates bending and extension as two actuation modes of the robotic actuators. These two modes are the most used actuation modes for soft robotics applications, which may range from robotic locomotion to healthcare and rehabilitation. As described above, each robotic

actuator **300**,**400** is made up of combinations of at least three modular components. The first component is the corrugated sleeve body **110**,**110a**,**110b**,**210**,**210a** manufactured using 3D-printed thermoplastic polyurethane (TPU). The corrugated sleeve body controls the deformation profile of the robotic actuator **300**,**400**. The second component, the bladder **120**,**220**, is moulded from silicone rubber (obtainable from DragonSkin-10, Smooth-On, USA). The bladder **120**,**220** serves as a hermetic seal. The third component is a 3D printed TPU lock member **370**,**480** which enables the bladder **120**,**220** to be removeably secured inside the corrugated sleeve body **110**,**110a**,**110b**,**210**,**210a**; the lock member **370**,**480** also serves to route the fluid medium into the bladder; in addition, the lock member **480** also serves as a mounting point for the robotic actuator **400**. The TPU material filament is BCN3D TPU 95A (since discontinued), which can be obtained from Ninjaflex NinjaTek 85A or Polyflex Polymaker 95A, or X60, which can be obtained from Diabase Engineering, 60A.

[0051] Blue markers were placed on the corrugated sleeves of the robotic actuators **300**,**400** to capture deformation data on a tracking software. The robotic actuators were then mounted vertically on a retort stand. The fluid pressure was increased in 5 kPa increments. A tracker (Open-Source Physics) was used to process the video and extract coordinates of the robotic actuator deformations; the raw data thus obtained were then processed using Matlab to plot deformations (extension and bending) of the robotic actuator.

[0052] FIG. 8 shows extension ratios of the corrugated sleeve **110**,**110a** constituting the robotic actuators, with the corrugated sleeve being fabricated with TPU of Shore hardness 60A, 85A and 95A. Initially, the extension ratio changes of the three TPU materials are similar. This is likely due to the bladder **120** initially expanding to contact the corrugated sleeve at the passageway **111** when the pressure is about 45 kPa or less. From about 60 kPa pressure, the corrugated sleeve made of softer TPU materials start to deform more. Since the Young's Moduli of the TPU material increase in line with their Shore hardness, it is evident that extension of the 60A corrugated sleeve is the largest for a given pressure, while that of the 95A corrugated sleeve is the smallest.

[0053] The above robotic actuators **300**,**400** with the corrugated sleeve **210**,**210a** being also fabricated with TPU Shore hardness 60A, 85A and 95A are tested for bending performance. The fluid pressure was incremented at 5 kPa interval until the free end of the robotic actuator curled up and touched the end that is held at the retort stand. FIG. 9 shows the corrugated

sleeve made of 85A TPU and the bending maxes out at about 65 kPa. In contrast, FIG. 10 shows the robotic actuator made with corrugated sleeve of TPU 95A curled up and the bending maxes out at about 85 kPa, which is evident for the higher stiffness of the 95A TPU. Another plot of pressure-bending curvature characteristics of the 85A and 95A TPU are shown in FIG. 11; ignoring the initial inaccuracy at about 20 kPa and below, the robotic actuator made with 95A TPU exhibits higher stiffness and the 85A TPU maxes out at a lower pressure of about 50 kPa. The above test results show that the actuation pressure of the above robotic actuators is less than about 150 kPa, which is a desirable pressure for a wearable actuator system.

[0054] Force output of a robotic actuators also determines their applications; for example, a wearable assistive device represents its ability of the robotic actuator to perform a task. A Vertical Automatic Handy Tester (JSV H1000, Measuring Instrument Technology, Singapore) with a force gauge was used to measure the force output of the above robotic actuators. The robotic actuators made with corrugated sleeve **110**,**110a**,**110b** of 60A, 85A and 95A TPU and equipped with cylindrical bladders **120** were mounted in an inverted condition to apply a compressive force on the force gauge against the force of gravity. The robotic actuator is then pressurized in increments of 5 kPa; three data sets were taken for each robotic actuator. The mean and variance of the force output were plotted. FIG. 12 shows the blocked force output by actuating the robotic actuators in the bending mode. From FIG. 12, it is observed that the lower stiffness robotic actuator provided higher force output at the same pressure as compared to the higher stiffness ones. This is because less energy was used to bend the robotic actuator having a lower stiffness, thereby, allowing the robotic actuator of lower stiffness to transfer a higher proportion of the fluid pressure to useful work. The higher stiffness robotic actuators could tolerate higher pressures owing to their correspondingly higher Young's Moduli. Despite lacking the force output for the same pressures as their softer counterparts, the robotic actuator exhibiting higher stiffness of TPU 85A and 95A are routinely chosen for applications since they generate higher peak forces with less mechanical failure.

[0055] FIG. 13 shows the blocked force profiles of bending robotic actuators **300,400** using the cylindrical bladder **120** and semi-cylindrical bladders (Hemi-tube) **220**. In particular, 60A and 85A TPU corrugated sleeves **210**,**210a** are used and the blocked force curves are plotted. From the test results, the robotic actuators using the semi-cylindrical bladder **220** of

the same material generate about 20% higher force at the same pressure. This is because the cylindrical bladder **120** must first expand to contact the semi-cylindrical passageway **211**, and thus the initial force transfer does not perform useful work. Thus, a semi-cylindrical bladder **220** to fit snugly inside the corrugated sleeve **210**,**210a** is a better choice to use. This snug fit of the bladder also translated to lower variance between the tests using the semi-cylindrical bladder **220**.

[0056] FIG. 14 shows the blocked force profiles of extension robotic actuators **300**,**400** using the cylindrical bladder **120** and the cylindrical sleeve **110** made with 85A and 95A TPU. From FIG. 14, it is seen that 95A TPU higher stiffness robotic actuator transfer larger forces at pressures higher than 10 kPa. This is likely because the extension robotic actuator with the cylindrical bladder **120** has less transmission loss between the bladder and the cylindrical sleeve **110**, and 10 kPa is the initial pressure for the cylindrical bladder to expand and make close contact along the cylindrical passageway **111** inside the cylindrical sleeve **110**.

[0057] FIG. 7 shows the robotic actuator **400** which can be used to assist an elbow exoskeleton. FIGs. 15 and 16 illustrate an application of the robotic actuator **400** at an elbow where the lock members **480** at both the ends are used as mounting points. The ability of the robotic actuator **400** to generate sufficient high force is desirable in such an assistive mechanism. The elbow is an upper body joint that requires high assistive torque, usually as it is load bearing and experiences a large moment arm from the hand, where an object is grasped.

[0058] 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, a fabric strip can be attached to a side of the bladder **120**,**220** to control bending of the bladder; it is also possible that the fabric strip be attached to the flat surface **260** of the semi-cylindrical sleeve to control bending of the semi-cylindrical sleeve **210**,**210a**. The fabric strip is flexible but has a tensile stiffness higher than the TPU.

CLAIMS:

1. A robotic actuator comprising:

a corrugated sleeve formed with corrugating folds extending from a first end to a second end and defining an interior passageway; and

a bladder being detachably disposed inside the interior passageway of the corrugated sleeve by a lock member;

wherein, when a fluid medium is supplied into the bladder, the bladder is inflated, thereby compressing against the interior passageway, deforming the corrugated sleeve and providing a force output at the robotic actuator, and the bladder is reversible deflated when the fluid medium is released.

2. The robotic actuator according to claim 1, wherein the lock member comprises a female connector and a male connector being connected to the first or the second end of the corrugated sleeve, so that the female and male connectors are engageable or dis-engageable by a rotatory motion.

3. The robotic actuator according to claim 1, wherein the lock member comprises a female connector and a male connector being connected to the first or the second end of the corrugated sleeve, so that the female and male connectors are engageable or dis-engageable by a sliding motion.

4. The robotic actuator according to claim 1, wherein the corrugated sleeve is cylindrically shaped.

5. The robotic actuator according to claim 1, wherein the corrugated sleeve is substantially hemi-cylindrical shaped and comprises a flat surface, resulting in the interior passageway being substantially hemi-cylindrical.

6. The robotic actuator according to any one of the preceding claims, wherein the bladder is shaped to fit substantially snugly into the interior passageway.

7. The robotic actuator according to any one of the preceding claims, wherein the corrugating folds are spaced apart at a regular pitch distance.

8. The robotic actuator according to any one of the preceding claims, wherein a wall of each corrugating fold at both an outside surface and the interior passageway is curved or arched shaped.

9. The robotic actuator according to any one of the preceding claims, wherein a wall of each of the corrugating fold at the interior passageway is substantially flat.

10. The robotic actuator according to claim 8, wherein a width of each corrugating fold at the outside surface has a bigger dimension than a width of the corrugating fold at the interior passageway.

11. The robotic actuator according to any one of the preceding claims, wherein radial fissures are formed radiating from the interior passageway and extending to both ends of the corrugated sleeve.

12. The robotic actuator according to any one of claims, wherein the bladder is made of a material of lower stiffness than a material of the corrugated sleeve, so that the bladder is hermetically sealed and is inflatable by the fluid medium, whilst the corrugated sleeve controls extension or bending of the robotic actuator caused by inflating the bladder.

13. The robotic actuator according to claim 12, wherein the bladder material is silicone rubber, whilst the material of the corrugated sleeve is thermoplastic urethane (TPU).

14. The robotic actuator according to any one of the preceding claims, further comprising a fabric strip that is attachable along a side of the bladder to control a direction of bending of the bladder.

15. The robotic actuator according to any one of claims 5-13, further comprising a fabric strip that is attachable onto the flat surface of the hemi-cylindrical sleeve.

16. The robotic actuator according to any one of claims 5-15, wherein a material along the flat surface is formed with a varied stiffness, so as to control bending of the hemi-cylindrical sleeve.

17. A method for configuring extension or bending of a robotic actuator, the method comprises:

configuring a corrugated sleeve by forming corrugating folds to extend from a first end to a second end, and defining an interior passageway; and

removeably securing a bladder inside the corrugated sleeve by connecting a lock member to the first or the second end of the bladder and a corresponding end of the corrugated sleeve, wherein the bladder is hermitically sealed to receive a fluid medium, wherein the bladder is formed from a material of lower stiffness compared to a material of the corrugated sleeve;

wherein, when the fluid medium is supplied into the bladder, inflation of the bladder acts on the interior passageway, thereby causing a force output and extension of the robotic actuator.

18. The method according to claim 17, further comprises forming a fissure along the corrugated sleeve to alter the stiffness of the corrugated sleeve, so that the force output is increased and the robotic actuator bends away from location of the fissure.

19. The method according to claim 17, further comprises forming the corrugated sleeve with a flat surface to obtain a hemi-cylindrical passageway, so as to control the bending stiffness of the corrugated sleeve towards the flat surface.

20. The method according to claim 19, wherein controlling the bending stiffness about the flat surface of the corrugated sleeve is implemented by varying a material stiffness along the flat surface or attaching a fabric strip along the flat surface.

21. A method for configuring an assistive mechanism using the robotic actuator according to any one of claims 1-16 comprises:

inserting a bladder inside a corrugated sleeve, wherein the bladder is hermitically sealed to receive a fluid medium and forming the bladder from a material of lower stiffness compared to a material of the corrugated sleeve;

removeably securing one end of the bladder to an associated end of the corrugated sleeve with a lock member;

mounting an opposite end of the corrugated sleeve with another lock member; and

securing each of the lock members to a limb constituting a joint;

wherein inflating the bladder creates a force output, and resulting extension and bending of the robotic actuator creates an assistive motion about the joint, whilst deflating the bladder reverses motions of the robotic actuator.

22. The method according to claim 21, wherein the joint is constituted with a prothesis or an exoskeleton.