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(56) Documents Cited:
WO 2012/148472 A2 **CN 110236880 A**
US 20180296419 A1 **US 20170119614 A1**

(58) Field of Search:
INT CL **A61F, A61H, B25J, F04B**
Other: **WPI, EPODOC, XPI3E**

(54) Title of the Invention: **Soft robotic assistive device**
Abstract Title: **An assistive or rehabilitative device**

(57) An assistive or rehabilitative device 201 comprising a soft pneumatic actuator 203 and a piezoelectric resonant acoustic gas pump. The soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part. The soft pneumatic actuator is in fluid communication with the gas pump and the gas pump is for pressurising and/or depressurising the soft pneumatic actuator. The device may comprise a pressure sensing means, the soft pneumatic actuator may be a bending actuator.

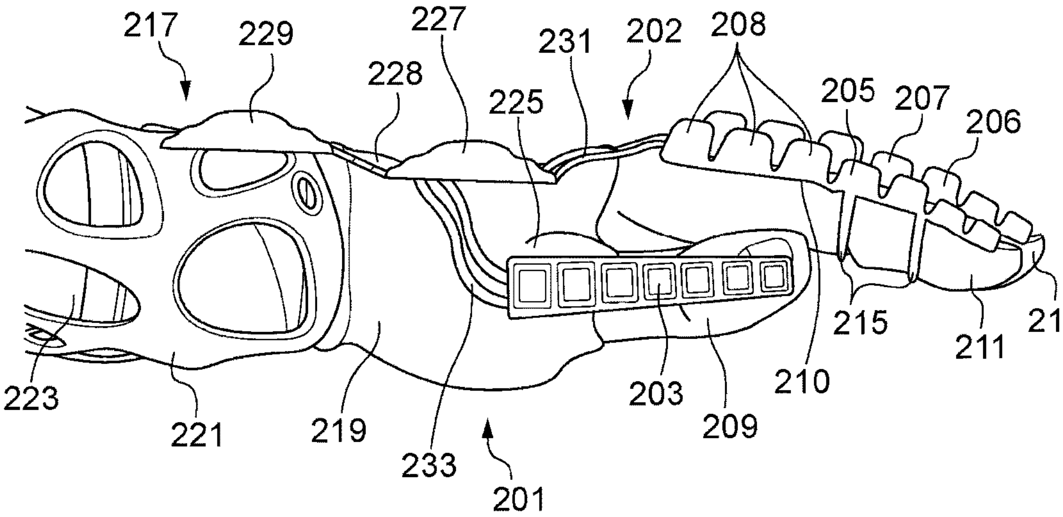

Figure 2

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

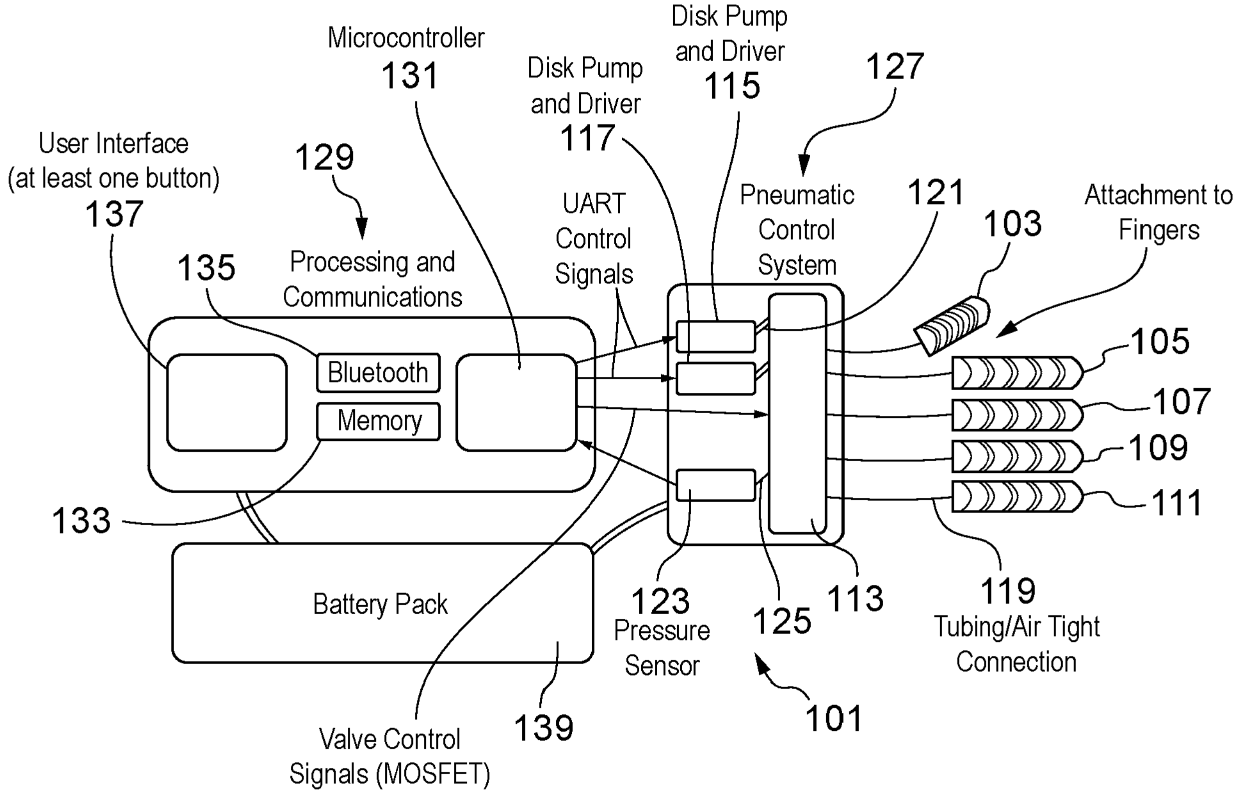

Figure 1

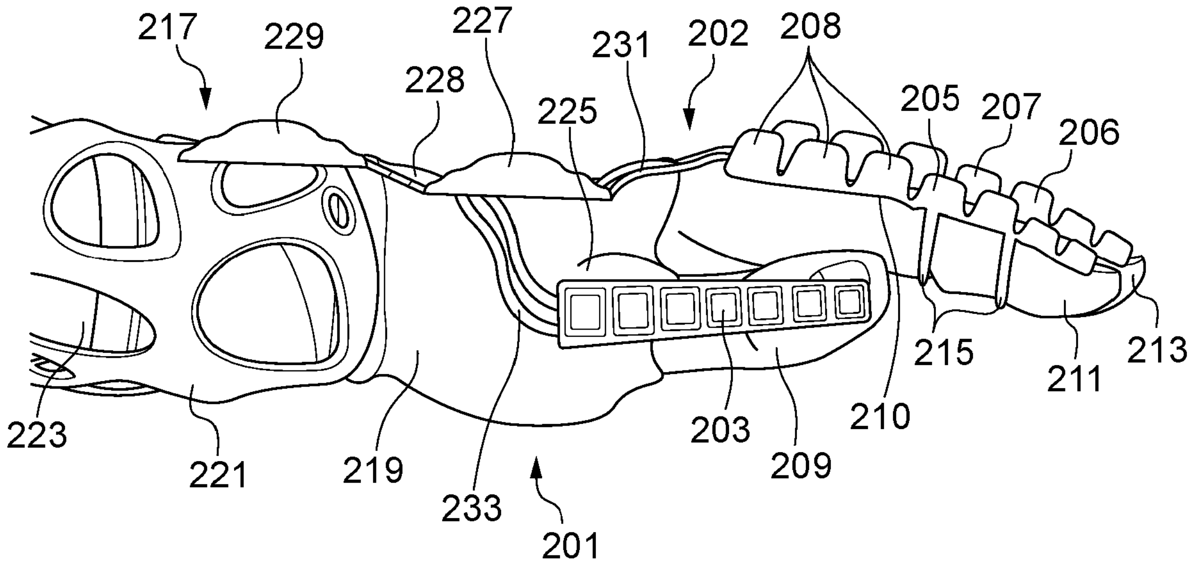

Figure 2

02 02 23

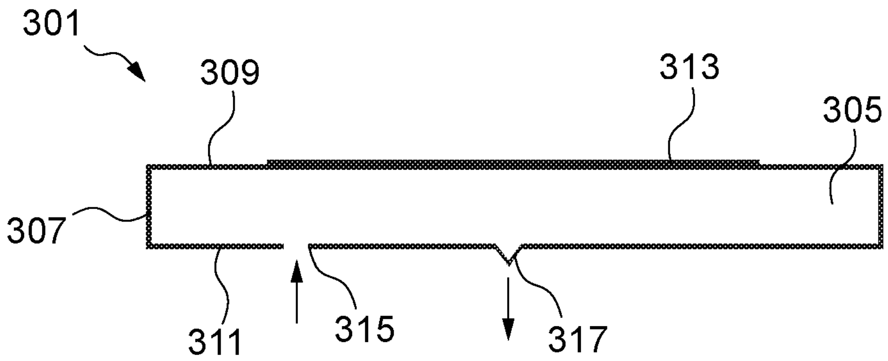

Figure 3A

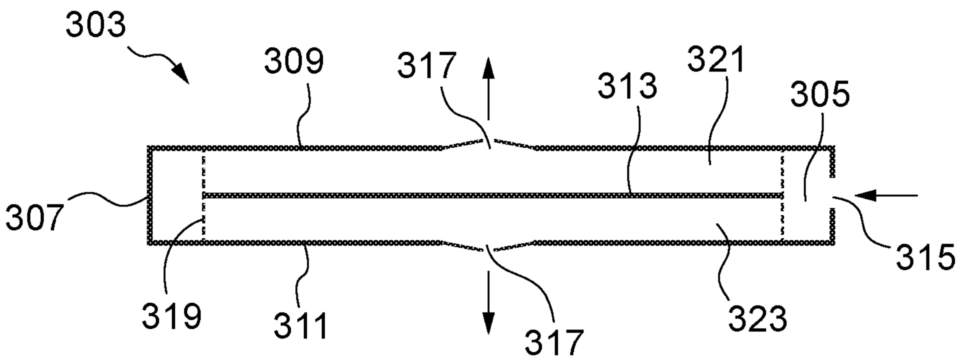

Figure 3B

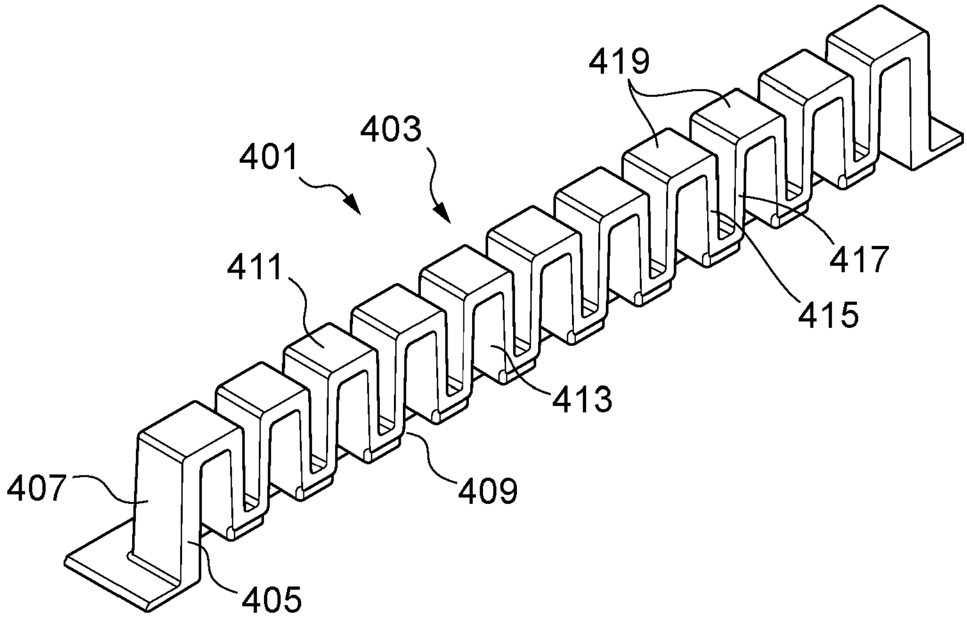

Figure 4

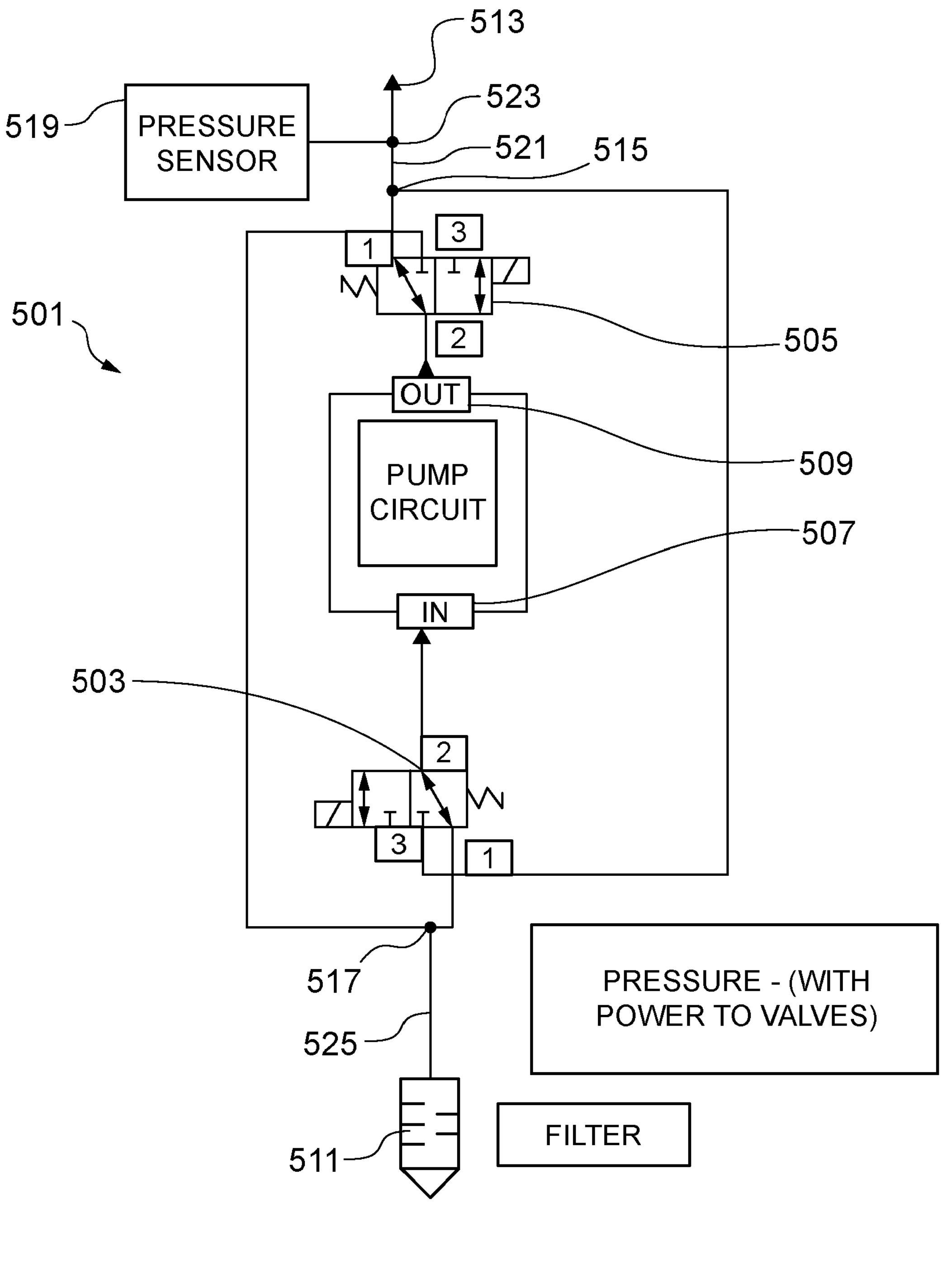

Figure 5A

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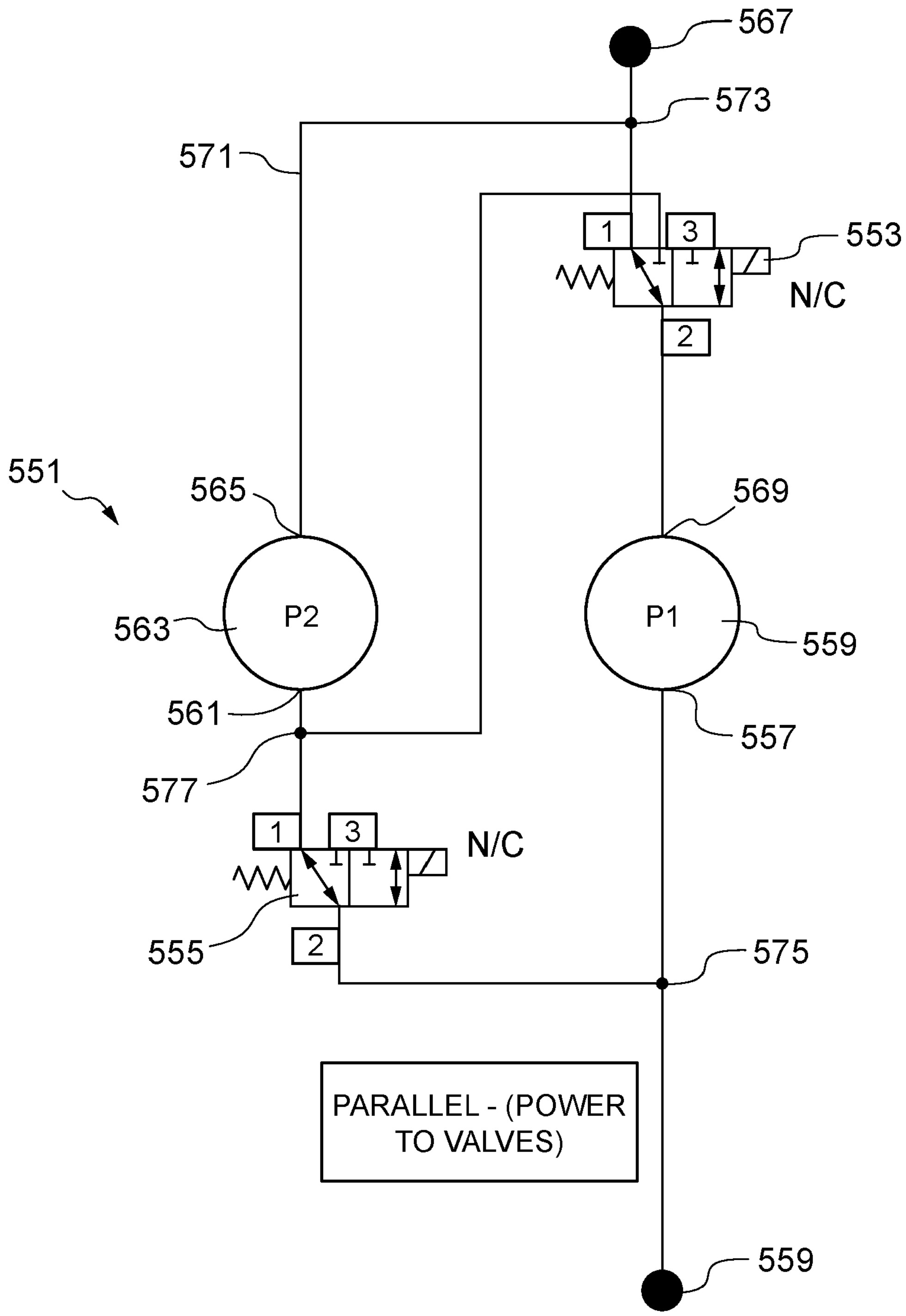


Figure 5B

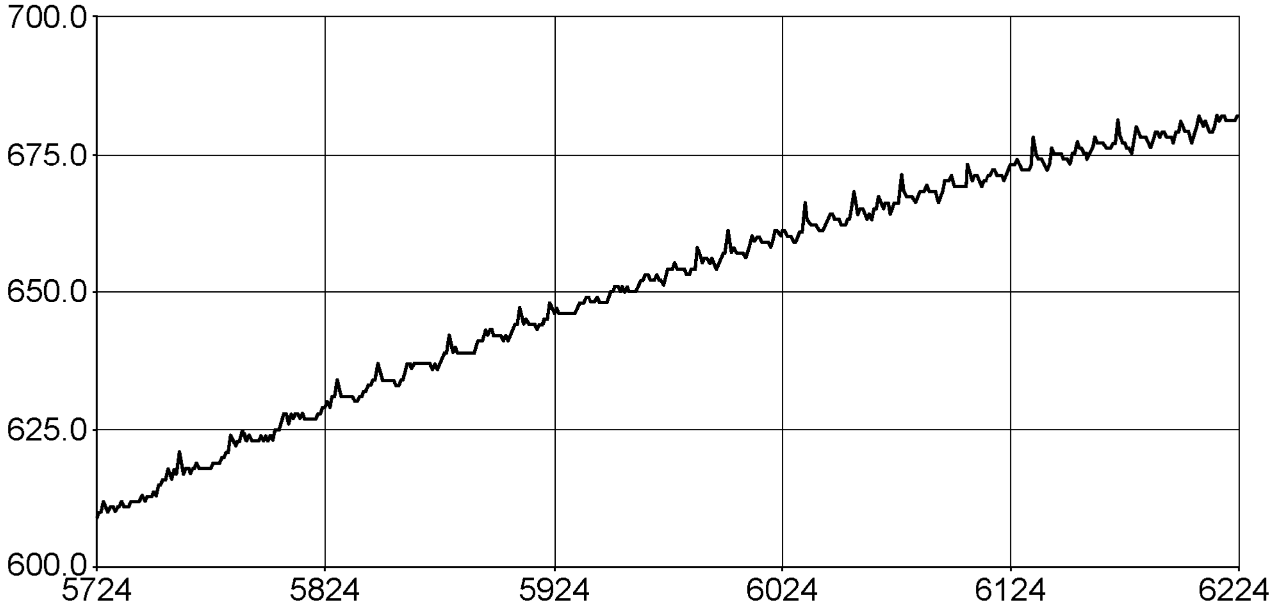


Figure 6A

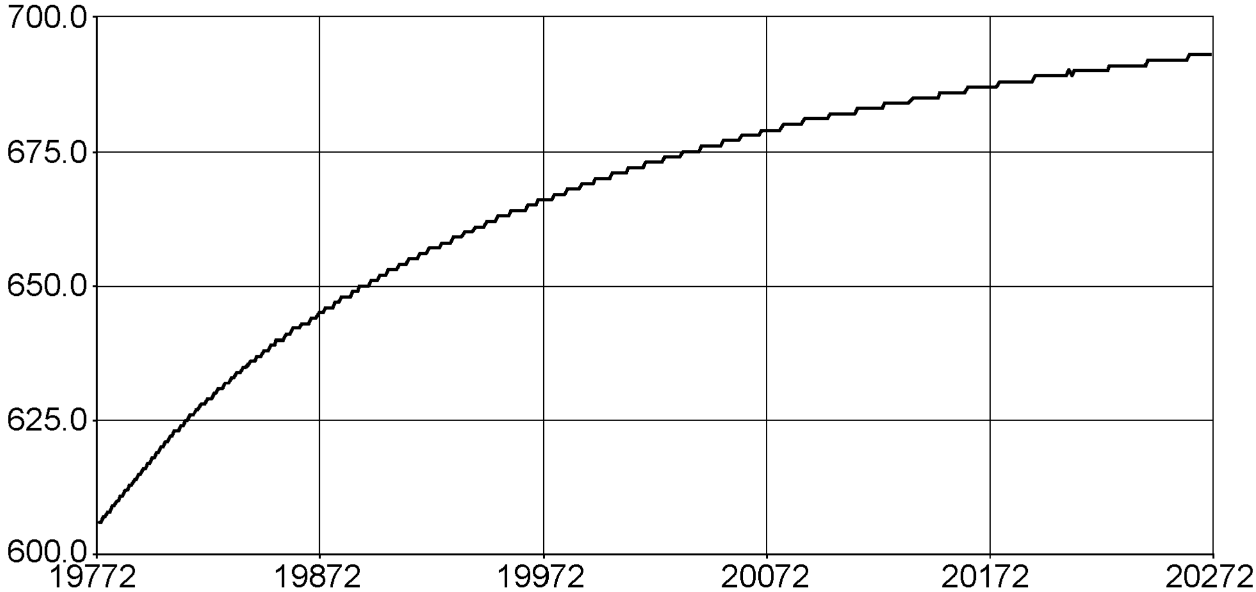
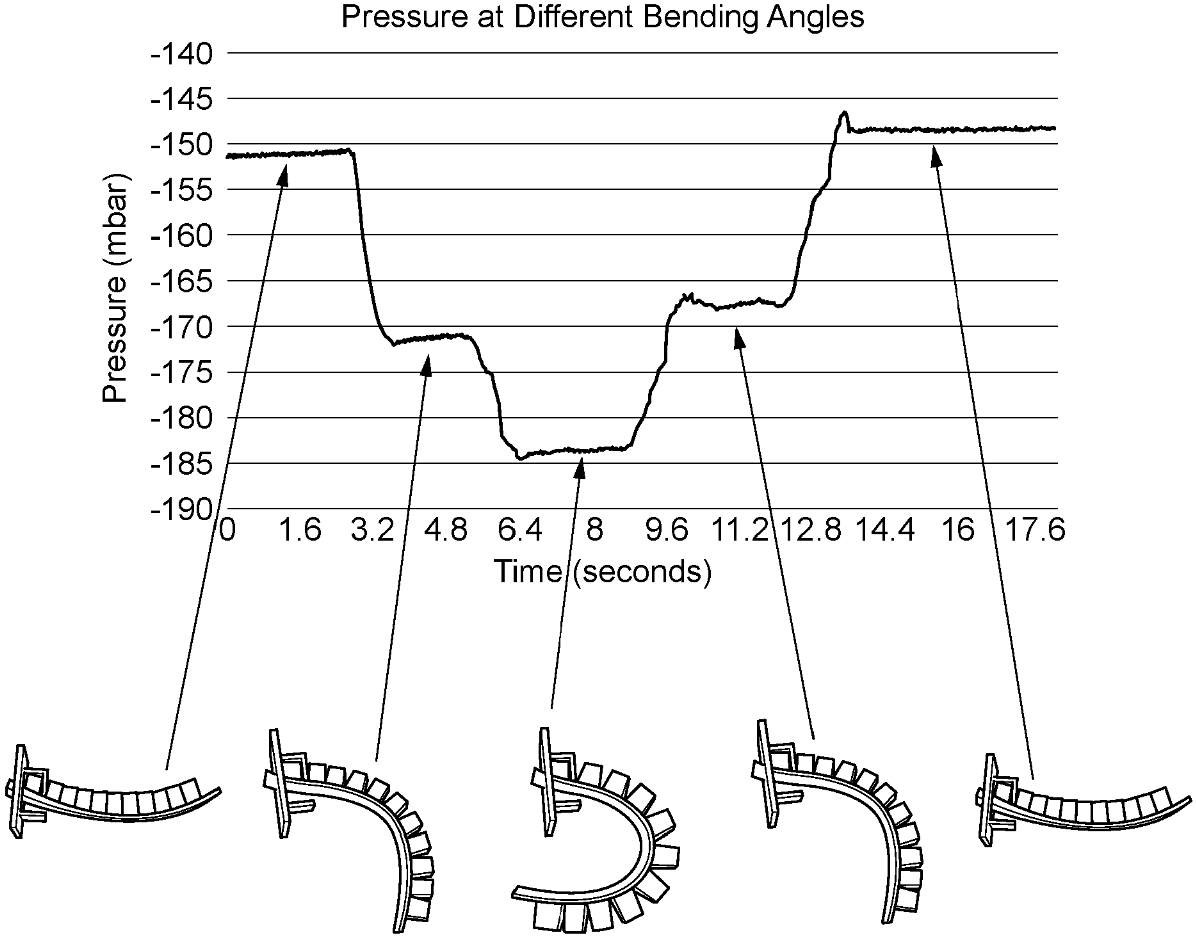


Figure 6B



Pressure at Different Bending Angles
Pressure (mbar)
-140
-145
-150
-155
-160
-165
-170
-175
-180
-185
-190
0
1.6
3.2
4.8
6.4
8
9.6
11.2
12.8
14.4
16
17.6
Time (seconds)

Figure 7

Soft Robotic Assistive Device

FIELD OF THE INVENTION

The present invention relates to assistive and rehabilitative devices comprising a soft pneumatic actuator.

BACKGROUND OF THE INVENTION

Assistive and rehabilitative devices comprising soft actuators are known. For example, Panagiotis, P. et al (2015) 'Soft robotic glove for combined assistance and at-home rehabilitation', *Robotics and Autonomous Systems*, Vol 73, p135-143 discloses a soft robotic glove designed to augment hand rehabilitation for individuals with functional grasp pathologies. A single hydraulic (water) pump was used to actuate five multi-segment soft hydraulic actuators. Hydraulic power supply and supporting electro-mechanical components, including mechanical switches for manual control and a water reservoir, were integrated into a waist belt pack. An electromagnetic tracking system, external to the soft robotic glove, was employed to track hand position.

The present inventors have found a solution to shortcomings in the state of the art.

PROBLEM TO BE SOLVED BY THE INVENTION

There is a need for improvements to the control of assistive and rehabilitative devices that comprise a soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part. Further, there is a need for improvements to the monitoring of the underlying range of motion, accuracy and/or strength of the body part when using such a device. Still further, there is a need for improved methods of assisting, monitoring and rehabilitating movement of a paralysed or weakened body part, such as the digits (i.e. fingers and thumb) of a hand.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the invention, there is provided an assistive or rehabilitative device comprising a soft pneumatic actuator and a gas pump, the soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part, wherein the soft pneumatic actuator is in fluid communication with the gas pump, the gas pump for pressurising and/or depressurising the soft pneumatic actuator.

In accordance with a second aspect of the invention, there is provided a gas pump manifold for directing and/or controlling gas flow from and/or to a gas pump (or gas pumps) of an assistive or rehabilitative device. Preferably, the device comprises a soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part. Preferably, the soft pneumatic actuator is in fluid communication with the gas pump and/or the gas pump is for pressurising the soft pneumatic actuator.

In accordance with a third aspect of the invention, there is provided a method of using an assistive device of the first aspect, the assistive device configured to actuate, assist and/or resist a movement of a body part, the method comprising: donning the device; and using the device to actuate, assist or resist the movement of the body part.

In accordance with a fourth aspect of the invention, there is provided a method of using a rehabilitative device of the first aspect, wherein the rehabilitative device is configured to actuate, assist, resist and/or monitor a movement of a body part, the method comprising: donning the device; and using the device to actuate, assist or resist the movement of the body part and/or using the device to monitor the underlying strength, accuracy and/or range of motion of the movement of the body part.

In accordance with a fifth aspect of the invention, there is provided a method of actuating, assisting, resisting and/or rehabilitating a movement of a body part.

ADVANTAGES OF THE INVENTION

The device and other aspects of the invention provide improved control and/or monitoring when assisting and rehabilitating the movement of a body part. The device is configured such that pressure measurements of an internal chamber of the soft pneumatic actuator may be used to accurately and precisely: track the three-dimensional position of the body part, determine when the gas pump should be turned on and off, and/or monitor the strength of the underlying body part.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of an assistive or rehabilitative device;

Figure 2 is a side view of an assistive or rehabilitative device;

Figures 3A and 3B are cross-sectional side views of piezoelectric resonant acoustic gas pumps;

Figure 4 is a cross-sectional side view of a soft pneumatic actuator;

Figures 5A and 5B are schematic diagrams of a valve arrangement;

Figures 6A and 6B are comparative soft pneumatic actuator pressure waveforms measured during gas pump operation; and

Figure 7 is an illustrative soft pneumatic actuator pressure waveform measured during manual manipulation of the soft pneumatic actuator.

DETAILED DESCRIPTION OF THE INVENTION

The invention concerns an assistive or rehabilitative device comprising a soft pneumatic actuator and a gas pump, the soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part, wherein the soft pneumatic actuator is in fluid communication with the gas pump, the gas pump for pressurising and/or depressurising the soft pneumatic actuator. Preferably, the gas pump is a piezoelectric resonant acoustic gas pump (or a gas pump that is configured to generate and rectify an acoustic standing wave to provide gas flow).

A piezoelectric resonant acoustic gas pump generates an acoustic standing wave, which acoustic standing wave is rectified to provide gas flow. Preferably, the gas pump is not a displacement pump. In one option (e.g. where the piezoelectric resonant acoustic gas pump generates an acoustic wrapped standing wave), an internal cavity of the gas pump has a substantially constant volume during pumping operation. Preferably, the acoustic standing wave is an acoustic wrapped standing wave. An acoustic wrapped standing wave is a standing wave that wraps around a piezoelectric actuator located centrally in the internal cavity of the gas pump.

In one option, the gas pump is a unidirectional gas pump. The direction of gas flow through a unidirectional gas pump cannot be reversed.

When a device comprising a soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part is in use, it is difficult to track the three-dimensional position of the body part (including monitoring range and accuracy of motion of the body part) and to monitor the underlying strength of the body part. For example, Panagiotis, P. et al (2015) (see above) used an electromagnetic tracking system, external to the soft robotic glove disclosed in that document, to track hand position. Furthermore, it is difficult to configure such a device to begin and to stop pressurising and/or depressurising the soft pneumatic actuator precisely when intended by a user or, for example, when a sufficient gripping force on an object is achieved.

However, it was surprisingly found that measuring gas pressure (discussed in further detail below) of the soft pneumatic actuator over time, i.e. by monitoring the pressure waveform of the soft pneumatic actuator, the three-dimensional position of the body part may be tracked, the underlying strength of the body part may be monitored, and/or it may be determined when pressurisation (and/or depressurisation) of the soft pneumatic actuator should start or stop. For example, where the body part is a finger and the soft pneumatic actuator is a bending actuator, the pressure waveform of the soft pneumatic actuator can be used to track the position (e.g. the degree of bending) of the finger. Continuing this example, a user of the device may begin to flex their finger which causes a sudden drop in gas pressure of the soft pneumatic actuator, signalling that the gas pump should be turned on to assist the continued flexion movement. Further continuing this example, the pressure waveform of the soft pneumatic actuator can be used to determine underlying resistance of the finger to actuation by the soft pneumatic actuator for monitoring the degree of spasticity of the finger.

It is advantageous to measure the gas pressure of the soft pneumatic actuator while the gas pump is in operation. However, during operation a gas pump may 'distort' the pressure waveform of the soft pneumatic actuator due to gas flow pulsation. Distortion of the pressure waveform causes inaccurate and imprecise control and monitoring when using the pressure waveform as described above.

It was found that a configuration using a piezoelectric resonant acoustic gas pump (or a gas pump that is configured to generate and rectify an acoustic standing wave to provide gas flow) for pressurising and/or depressurising the soft pneumatic actuator is surprisingly advantageous. This is because when the gas pump is in operation distortion of the pressure waveform of the soft pneumatic actuator is minimised such that the pressure waveform may be used as described above to accurately and precisely: track the three-dimensional position of the body part, determine when the pump should be turned on and/or off, and/or monitor the strength of the underlying body part.

Preferably, the gas pump is a generally disc-shaped gas pump. More preferably, an internal cavity or cavities of the gas pump is/are disc shaped. Disc-shaped means a cylinder shape, wherein the radius of the cylinder is significantly larger than the height of the cylinder. Preferably, a disc-shaped internal cavity has a radius greater than 1.2 times its height, more preferably at least 5 times its height, still more preferably at least 10 times its height, most preferably at least 15 times its height, for example around 20 times its height. It is preferred that an internal cavity of the gas pump is enclosed by a cylindrical side wall and two circular end walls. Preferably, the internal cavity (or cavities) of the gas pump is a resonant acoustic cavity (are resonant acoustic cavities).

Preferably, the gas pump comprises a piezoelectric actuator. Preferably, the piezoelectric actuator is configured to oscillate to generate an acoustic standing wave within an internal cavity of the gas pump (e.g. to drive radial oscillations of fluid pressure in an internal cavity of the gas pump). Preferably, the piezoelectric actuator is configured to flex at its mechanical resonance. Preferably, the piezoelectric actuator is a circular actuator and/or is disposed parallel to the end walls enclosing a disc-shaped internal cavity of the gas pump. Therefore, preferably, the piezoelectric actuator oscillates in a direction perpendicular to the end walls of the disc-shaped internal cavity.

In a first option, an end wall of a disc-shaped internal cavity comprises (or is attached to) a piezoelectric actuator. In this option, the gas pump comprises an internal cavity enclosed at one end by a driven end wall. In this option, the gas pump may comprise two disc-shaped internal cavities disposed adjacent to each other and sharing a driven end wall.

In a second option, a piezoelectric actuator is disposed within a disc-shaped internal cavity between (e.g. located centrally relative) two end walls enclosing the internal cavity. In this option, the actuator defines a first (e.g. upper) cavity portion and a second (e.g. lower) cavity portion. The first and second cavity portions are fluidically connected around a perimeter of the piezoelectric actuator to form a single continuous cavity which wraps around the piezoelectric actuator. Thus, in this option, the piezoelectric actuator may generate an acoustic wrapped standing wave within the disc-shaped internal cavity whereby the acoustic standing wave wraps around the piezoelectric actuator.

Preferably, the (or each) internal cavity of the gas pump is in fluid communication with a gas outlet comprising a valve (e.g. an ultrafast valve) for rectifying an acoustic standing wave to provide gas flow. i.e. the valve rectifies pressure oscillations within the internal cavity for providing a pumping effect. Preferably, the valved gas outlet is disposed through a generally central portion (e.g. at the centre) of a circular end wall enclosing the disc-shaped internal cavity or through a cylindrical side wall enclosing the disc-shaped internal cavity. Preferably, the valve is passive (e.g. undriven). For example, the valve may be the valve for controlling a flow of fluid disclosed in international patent application publication WO-A1-2021/152288, the entire contents of which are herein incorporated by reference.

Preferably, the gas pump comprises a gas inlet or inlets for supplying gas to the internal cavity or cavities.

Preferably, the gas pump is a micropump. Preferably, the volume of the internal cavity of the gas pump is at most 5 cm^3, more preferably at most 4 cm^3, still more preferably at most 3 cm^3, most preferably at most 2 cm^3, for example at most 1 cm^3. Preferably, the volume of the internal cavity is at least 0.1 cm^3, more preferably at least 0.2 cm^3, still more preferably at least 0.3 cm^3, for example at least 0.4 cm^3. Preferably, the volume of the internal cavity of the gas pump is from 0.1 cm^3 to 2 cm^3, more preferably from 0.2 cm^3 to 1 cm^3, e.g. around 0.3 cm^3.

Preferably, the gas pump is configured to pump up to 1 μL (microlitre) of gas per cycle, more preferably up to 0.8 μL, still more preferably up to 0.6 μL, for example up to 0.4 μL, e.g. up to 0.2 μL. Preferably, the gas pump is configured to pump at least 5 nL (nanolitre) of gas per cycle, more preferably at least 10 nL, still more preferably at least 50 nL, for example at least 0.1 μL.

Preferably, the gas pump is an ultrasonic gas pump. Preferably, the piezoelectric actuator of the gas pump operates at an ultrasonic frequency. Preferably, the gas pump operates at at least 18 kHz, more preferably at least 20 kHz. Preferably, the gas pump operates at at most 26 kHz, more preferably at most 24 kHz, still more preferably at most 22 kHz. For example, the gas pump may operate at from 18 kHz to 25 kHz, preferably at from 20 kHz to 22 kHz. One benefit of operating the gas pump in this frequency range (e.g. operating at an ultrasonic or near-ultrasonic frequency) is that the gas pump is non-audible to most users.

Preferably, the gas pump satisfies one or any combination of two or more of the following conditions:

a) a peak flow of at least 0.1 L/min, more preferably at least 0.5 L/min, still more preferably at least 1 L/min, for example at least 1.5 L/min;

b) a peak flow of at most 5 L/min, more preferably at most 4 L/min, still more preferably at most 3 L/min, for example at most 2 L/min;

c) a peak pressure of at least 100 mbar(g), more preferably at least 200 mbar(g), still more preferably at least 300 mbar(g);

d) a peak pressure of at most 2 bar(g), more preferably at most 1.5 bar(g), still more preferably at most 1 bar(g), for example at most 800 mbar(g);

e) a peak vacuum of at least -100 mbar(g), more preferably at least -150 mbar(g), still more preferably at least -200 mbar(g);

f) a peak vacuum of at most -1.2 bar(g), more preferably at most -1 bar(g), still more preferably at most -800 mbar(g), most preferably at most -600 mbar(g);

g) operates at from 18 kHz to 25 kHz, more preferably at from 20 kHz to 22 kHz, still more preferably at around 21 kHz;

h) weighs at most 10 g, more preferably at most 8 g, still more preferably at most 6 g, for example around 5 g;

i) the gas pump in its largest dimension measures at most 80 mm, preferably at most 60 mm, still more preferably at most 40 mm, e.g. around 30 mm;

j) the gas pump comprises a disc-shaped internal cavity having a cylindrical side wall height of from 0.2 mm to 10 mm, more preferably from 0.4 mm to 6 mm, still more preferably from 0.6 mm to 2 mm, for example around 1 mm; and

k) the gas pump comprises a disc-shaped internal cavity having a radius of from 2 mm to 90 mm, more preferably from 4 mm to 60 mm, still more preferably from 6 mm to 30 mm, most preferably from 8 mm to 15 mm, for example around 10 mm.

For example, suitable pumps include Disc Pump™ products (e.g. the 'BL Series', 'XP Series', 'LT Series', 'HP Series' and 'UltraSlim Series' pumps) obtainable from TTP Ventus Limited of Melbourn Science Park, Melbourn, Hertforshire, SG8 6 EE, UK.

In a further example, suitable pumps include the piezoelectric resonant acoustic gas pumps disclosed in international patent application publications WO-A1-2006/111775, WO-A1-2009/112866, WO-A1-2010/139916, WO-A1-2010139917, WO-A1-2010139918, WO-A1-2011/095795A1 and/or

WO-A1-2015/087086, the entire contents of which are herein incorporated by reference. A more specific (but non limiting) example of suitable pumps include the piezoelectric resonant acoustic gas pumps illustrated in Figures 4 to 9 and described from page 12, line 25 to page 22, line 8 of international patent application publication WO-A1-2015/087086 referenced above.

Preferably, the device comprises at least two gas pumps (more preferably, the device comprises only two gas pumps) in fluid communication with the soft pneumatic actuator, the gas pumps for pressurising and/or depressurising the soft pneumatic actuator. Preferably, the gas pumps are configured in a parallel or in a series arrangement. More preferably, the soft pneumatic actuator is in fluid communication with two piezoelectric resonant acoustic gas pumps, the two pumps configured in a parallel or in a series arrangement. Most preferably, the two gas pumps are configured in a series arrangement.

For example, where the device comprises two gas pumps: by series arrangement, it is meant that a gas pump inlet of a first gas pump is in fluid communication with a general pump inlet, a gas pump outlet of the first gas pump is in fluid communication with a gas pump inlet of a second gas pump, and a gas pump outlet of the second gas pump is in fluid communication with a general pump outlet (e.g. for improved head). By parallel arrangement, it is meant that a gas pump inlet of a first gas pump and a gas pump inlet of a second gas pump are in fluid communication with a shared intake (i.e. with a general pump inlet) and a gas pump outlet of the first gas pump and a gas pump outlet of the second gas pump are in fluid communication with a shared outlet (i.e. with a general pump outlet) (e.g. for improved flow rate).

Herein, the term ‘fluid communication’ means airtight fluid communication, unless fluid communication is said to be with atmosphere. Where the context allows, fluid communication (e.g. between separate components of the device) is preferably provided by a conduit, such a tube or hose or within (or defined by) a manifold (e.g. a manifold block). An example conduit is an air hose, e.g. an air hose consisting of polyurethane, having a conduit wall thickness of around 1.5 mm, having an outer diameter of around 4 mm, having an inner diameter of around 2.5 mm, and/or that is flexible. Therefore, it is preferred that a conduit providing fluid communication between components of the device has an airtight connection with those components. Where three or more components are said to be in fluid communication, the fluid communication is preferably provided by a branched conduit. Where two components of the device are in fluid communication, there is a ‘line’ of fluid communication between them.

Where the device comprises at least two soft pneumatic actuators (see below), the device preferably comprises at least two gas pumps (more preferably, the device comprises two gas pumps). In one option, each soft pneumatic actuator is in fluid communication with a single, dedicated gas pump. Preferably, all the soft pneumatic actuators are in fluid communication with a general pump outlet, e.g. where the at least two gas pumps are configured in a series or parallel arrangement.

The assistive or rehabilitative device comprises a soft pneumatic actuator. Preferably, the soft pneumatic actuator comprises an actuator body. Preferably, the actuator body (or an actuator wall of the actuator body) comprises a resilient (e.g. elastic) and/or ‘soft’ material. Preferably, at least a portion or portions of the actuator body is/are configured to expand and/or contract when the soft pneumatic actuator is pressurised/depressurised. Expansion and/or contraction of the actuator body causes the soft pneumatic actuator to move, preferably in a predefined trajectory. For example, a soft pneumatic actuator may move by lengthening, shortening, straightening, bending, twisting, widening, narrowing or any combination of two or more thereof. For example, a soft pneumatic actuator may move in a predefined bending, twisting, extending, shortening, extend-twisting or bend-twisting trajectory.

Preferably, the actuator body comprises an internal chamber (or chambers). Preferably, the actuator body comprises an actuator wall. Preferably, the actuator wall encloses the internal chamber (or chambers).

Reference above to pressurising or depressurising the soft pneumatic actuator preferably means increasing the pressure or decreasing the pressure, respectively, of the internal chamber (e.g. by operating the gas pump or venting to atmosphere). Reference above to measuring gas pressure of the soft pneumatic actuator preferably means measuring gas pressure of the internal chamber. Reference above to the soft pneumatic actuator being in fluid communication with the gas pump preferably means the internal chamber is in fluid communication with the gas pump.

Preferably, the actuator body comprises an internal chamber access means. Preferably, the access means comprises an access conduit through the actuator wall. The access means is for providing fluid communication with the internal chamber (e.g. between the internal chamber and an exterior of the actuator body). Preferably, the access means comprises a connection means for connecting to a conduit, such as a tube or hose. For example, the connection means is a hose tail. Preferably, the connection means and the conduit, such as a tube or hose, form an airtight seal.

Preferably, as the internal chamber is pressurised by the gas pump at least a portion of the actuator wall expands and when the internal chamber is subsequently depressurised back to atmospheric pressure the at least a portion of the actuator wall contracts and returns to its original shape. Preferably, as the internal chamber is depressurised (e.g. placed under vacuum) by the gas pump at least a portion of the actuator wall contracts and when the internal chamber is subsequently repressurised back to atmospheric pressure the at least a portion of the actuator wall expands and returns to its original shape. The internal chamber may be returned to atmospheric pressure by using the gas pump or venting to atmosphere. Thus, preferably, the degree of movement of the soft pneumatic actuator is dependent on the degree of pressurisation or depressurisation of the internal chamber.

Preferably, the actuator wall comprises wall portions having different thicknesses to each other and/or that are comprised from different materials to each other. Preferably, different wall portions may have a different compliance (or stiffness). More compliant wall portions expand/contract more when the internal chamber is pressurised/depressurised by contrast to less compliant wall portions. By adjusting the relative compliance of portions of the actuator wall the soft pneumatic actuator may be configured to move in a pre-determined way when the internal chamber is pressurised/depressurised.

Preferably, the soft pneumatic actuator is a bending actuator (e.g. is configured to move in a bending trajectory). Preferably, the soft pneumatic actuator bends when it is pressurised and straightens (and optionally bends in an opposite direction) when it is depressurised, or vice versa. Preferably, the soft pneumatic actuator is configured to bend to correspond to flexion and/or extension movement of a digit or digits of a hand. Therefore, preferably, the soft pneumatic actuator is configured to have a range of motion corresponding to the range of motion of a digit or digits of a hand. Preferably, the hand is a human hand.

Preferably, the actuator body comprises a strain-limiting base, more preferably a non-extensible base. Preferably, the base is strain-limited (or non-extensible) at least in the lengthwise direction of the actuator body. Therefore, preferably, the length of the actuator body is substantially constant irrespective of pressurisation and/or depressurisation of the soft pneumatic actuator.

Optionally, the strain-limiting base comprises a relatively non-compliant material by contrast to the material of non-base portion(s) of the actuator body. Optionally, the strain-limiting base is relatively thicker by contrast to the thickness of non-base portions(s) of the actuator body. For example, the strain-limiting base comprises a non-extensible material, e.g. a fabric or textile. A soft pneumatic actuator comprising a strain-limiting base may be configured to bend when the soft pneumatic actuator is pressurised and/or depressurised.

Preferably, the actuator wall comprises (more preferably, consists of) an elastomeric material. For example, the actuator wall is a unitary moulded actuator wall. Preferably, the elastomeric material is a thermoplastic elastomer (TPE), e.g. a thermoplastic polyurethane (TPU), a thermoplastic vulcanisate (TPV) and/or a polypropylene (PP). Optionally, the elastomeric material is silicon or a silicon rubber. As discussed above, at least a portion or portions of the actuator body is/are configured to expand and/or contract when the soft pneumatic actuator is pressurised and/or depressurised respectively. Thus, preferably, at least a portion or portions of the actuator wall consists of an elastomeric material.

Preferably, the actuator body is elongate (i.e. has a generally elongate shape). Preferably, the actuator body is sized for positioning on top (i.e. on the dorsal side) of a digit or digits of a hand.

Preferably, the actuator body has a length of at least 5 cm, more preferably at least 7 cm, for example at least 9 cm. Preferably, the actuator body has a length of at most 20 cm, more preferably at most 18 cm, still more preferably at most 16 cm, for example at most 14 cm. Preferably, the actuator body has a length of from 5 cm to 20 cm, more preferably from 7 cm to 18 cm, still more preferably from 9 cm to 16 cm, for example around 12 cm.

Preferably, the actuator body has a width of at least 0.5 cm, more preferably at least 1 cm, still more preferably at least 1.5 cm, for example at least 2 cm. Preferably, the actuator body has a width of at most 6 cm, more preferably at most 5 cm, still more preferably at most 4 cm, for example at most 3 cm. Preferably, the actuator body has a width of from 0.5 cm to 6 cm, more preferably from 1 cm to 5 cm, still more preferably from 1.5 cm to 4 cm, most preferably from 2 to 3 cm, for example around 2.5 cm.

Preferably, the actuator body has a height of at least 0.5 cm, more preferably at least 1 cm, e.g. at least 1.5 cm. Preferably, the actuator body has a height of at most 5 cm, more preferably at most 4 cm, still more preferably at most 3 cm, for example at most 2 cm. Preferably, the actuator body has a height of from 0.5 cm to 4 cm, more preferably from 1 cm to 3 cm, for example from 1.5 cm to 2 cm, e.g. of 1.7 mm.

Preferably, the actuator body is configured to be straight and/or flexible (e.g. may flex with any degree of freedom) when the internal chamber is at atmospheric pressure.

Preferably, the actuator body comprises at least two (more preferably, a plurality of) cells disposed adjacent to each other and along the actuator body. Preferably, the at least two cells are disposed along an upper side of the actuator body. By ‘along the actuator body’, it is meant along at least a portion of the length of the actuator body. Preferably, each cell extends upwardly from a base of the actuator body. Preferably, the internal chamber of the actuator body comprises at least two (more preferably, a plurality of) fluidly connected sub-chambers, wherein each actuator body cell comprises an internal sub-chamber. Preferably, each pair of adjacent cells comprises a first cell having a first end wall proximal to or in contact with a second end wall of a second cell. Preferably, the first and second end walls comprise a resilient material (e.g. an elastomeric material) and/or are configured to expand and/or contract when the soft pneumatic actuator is pressurised/depressurised. In this embodiment, as the internal chamber (including the sub-chambers) is pressurised the first end wall and second end wall of each pair of adjacent cells expand and therefore push against each other. The pushing force between cells of the actuator body cause the soft pneumatic actuator to bend.

In one option, each actuator body cell is generally cube or cuboid shaped. Preferably, each cell comprises two end walls, two sides walls and a top wall (e.g. these walls forming part of the actuator wall). Preferably, a bottom of each cell is open to the internal chamber. Alternatively, the bottom of each cell may consist of a bottom wall (e.g. forming part of the actuator wall).

The soft pneumatic actuator (preferably, the internal chamber of the actuator body) is in fluid communication with the gas pump. In one option, the soft pneumatic actuator is in fluid communication with a gas pump manifold (see the second aspect of invention below, which incorporates features of the first aspect of invention where the context allows). Herein, where the context allows, ‘gas pump’ may be interchanged with ‘gas pump manifold’. Preferably, a conduit, such as a hose or tube, fluidly connects the soft pneumatic actuator and the gas pump. Preferably, the conduit is flexible. An example conduit is an air hose as described above.

Preferably, the device comprises a pressure sensing means for measuring gas pressure of (e.g. inside) the soft pneumatic actuator. More preferably, the pressure sensing means is for measuring gas pressure of the internal chamber of the actuator body. Preferably, the pressure sensing means is in fluid communication with the soft pneumatic actuator. More preferably, the pressure sensing means is in fluid communication with the internal chamber of the actuator body. For example, the pressure sensing means may be in fluid communication with a conduit fluidly connecting the soft pneumatic actuator and the gas pump (e.g. the conduit is a branched conduit). In one option, a conduit fluidly connecting the soft pneumatic actuator and the gas pump comprises a junction, such as a T-junction, in fluid communication with the pressure sensing means.

Preferably, the pressure sensing means is configured to measure pressures above and/or below ambient atmospheric pressure (e.g. above and/or below 1 atm). Preferably, the pressure sensing means is configured to measure gauge pressure. In one option, the pressure sensing means comprises an absolute pressure sensor. In a further option, the pressure sensing means comprises a differential pressure sensor. In a still further option, the pressure sensing means comprises two absolute pressure sensors or an absolute pressure sensor and a barometric pressure sensor. Where the pressure sensing means comprises two absolute pressure sensors, it is preferred that a first absolute pressure sensor is configured to measure positive gauge pressure and a second absolute pressure sensor is configured to measure negative gauge pressure.

Preferably, the device is configured to selectively vent the soft pneumatic actuator to atmosphere. Therefore, the device preferably comprises a soft pneumatic actuator venting means.

In one option, the venting means is disposed in a line of fluid communication (e.g. at a point along a conduit providing fluid communication) between the soft pneumatic actuator and the gas pump. For example, the venting means is a valve ('venting valve'). Preferably, the venting valve comprises three positions and two states (e.g. the venting valve is a 3/2-way valve).

Preferably, where the device comprises a pressure sensing means, the venting means is disposed upstream to (i.e. closer to the gas pump than) the pressure sensing means along the line of fluid communication between the soft pneumatic actuator and the gas pump. For example, where the pressure sensing means is in fluid communication with a junction in a conduit fluidly connecting the soft pneumatic actuator and the gas pump, the venting means is disposed between the junction and the gas pump.

Preferably, the device is configured to selectively isolate (e.g. to selectively seal or fluidically isolate) the soft pneumatic actuator from the gas pump. Therefore, the device preferably comprises a soft pneumatic actuator isolating means.

Preferably, the isolating means is disposed in a line of fluid communication (e.g. at a point along a conduit providing fluid communication) between the soft pneumatic actuator and the gas pump. For example, the isolating means is a valve ('isolating valve'). Preferably, the isolating valve may comprise 2 positions and 2 states (e.g. the isolating valve is a 2/2-way valve). In one option, the isolating valve may comprise 3 positions and 2 states (e.g. the isolating valve is a 3/2-way valve), wherein one of an inlet or an exhaust of the isolating valve is blocked/sealed.

In one alternative option, embodiments of the pumping direction interchange means (described below) may be configured to selectively isolate the soft pneumatic actuator (or the soft pneumatic actuator and the gas pump) from atmosphere.

An advantage of the isolating means is that the pressure waveform of the soft pneumatic actuator can be used to monitor the resistance of a body movement with greater sensitivity, precision and/or accuracy. This is because, when the isolating means is closed, any potential pressure leakage downstream of the isolating means (e.g. via the gas pump or the gas pump manifold) does not affect the pressure of the soft pneumatic actuator and the volume of gas to be compressed is reduced.

Preferably, where the device comprises a pressure sensing means, the isolating means is disposed upstream to (i.e. closer to the gas pump than) the pressure sensing means along the line of fluid communication between the soft pneumatic actuator and the gas pump. Therefore, preferably, the device is configured such that the pressure sensing means can measure the pressure of the soft pneumatic actuator when the isolating means is isolating the soft pneumatic actuator from the gas pump. For example, where the pressure sensing means is in fluid communication with a junction in a conduit fluidly connecting the soft pneumatic actuator and the gas pump, the isolating means is disposed between the junction and the gas pump.

The device is an assistive and/or rehabilitative device configured to actuate, assist, monitor and/or resist a movement of a body part. An assistive device is configured to actuate a movement of a body part where the user of the device cannot move that body part (e.g. due to paralysation) or to assist a movement of a body part where the user of the device cannot, without assistance, move the body part with full strength, accuracy and/or to its full extent (e.g. due to stroke or traumatic injury). A rehabilitative device is configured to monitor, maintain and/or improve a movement (e.g. the underlying strength, accuracy and/or range of movement) of a body part. For example, the device may be configured for repetitive task practice rehabilitation. For example, the device may be configured to rehabilitate the movement of a hand where a user has a loss of hand motor ability.

Preferably, the movement of a body part is extension and/or flexion of a body part. Preferably, the movement of a body part is movement of a hand (more preferably, a human hand). Preferably, the movement of a hand is movement of one or more digits of a hand (e.g. one or more of the fingers and/or the thumb). Most preferably, the movement of a body part is extension and/or flexion of one or more digits of a hand. For example, the movement of a body part is extension and/or flexion of the carpometacarpal, metacarpophalangeal and/or interphalangeal joints of the hand. In this example, in one option, the movement of a body part further includes extension and/or flexion of the scaphotrapeziotrapezoidal joint (e.g. of the wrist).

Preferably, the device is configured such that the soft pneumatic actuator is engageable with (e.g. attachable to) a digit or digits of a hand. Preferably, the digit or digits engaged by the soft pneumatic actuator is/are caused to bend and straighten when the soft pneumatic actuator bends and straightens, respectively. For example, the soft pneumatic actuator may be attached to a digit(s) of a hand using straps or as part of a glove to be donned. Preferably, the device is configured such that the soft pneumatic actuator is engageable with (e.g. attachable to) a top (i.e. dorsal side) of a digit or digits of a hand. Preferably, the device is configured such that a first end of the soft pneumatic actuator may be positioned at (e.g. anchored in place relative a point on) a top side of the hand in metacarpal region.

In one example, the device is configured such that the soft pneumatic actuator is engageable with (e.g. attachable to) two, three or four adjacent digits of a hand.

Preferably, the device is a wearable device. More preferably, the device is a self-contained wearable device. For example, during operation a self-contained wearable device does not need to be connected to an external power source (e.g. a mains power supply) or an external pressure supply means (e.g. an external gas pump). Preferably, the device is wearable on a hand and, in one option, is wearable across a hand and a forearm of the same arm. Thus, preferably, the device does not extend beyond a hand (or a hand and a forearm) when worn. Preferably, the device is a glove or glove-based device.

Preferably, the device comprises from two to five soft pneumatic actuators, i.e. the device preferably comprises two, three, four or five soft pneumatic actuators. Preferably, where the device comprises four soft pneumatic actuators, each actuator is engageable with (e.g. attachable to) one finger of a hand. i.e. each of four fingers can receive a dedicated soft pneumatic actuator. Preferably, where the device comprises five soft pneumatic actuators, each actuator is engageable with (e.g. attachable to) one finger or the thumb of a hand.

In a preferred option, where the device comprises two or more soft pneumatic actuators, all soft pneumatic actuators are pressurised and/or depressurised by the same gas pump (or group of gas pumps). i.e. all soft pneumatic actuators are in fluid communication with each other downstream of the gas pump (or group of gas pumps). In this preferred option, the device preferably comprises an actuator selection means. Preferably, the actuator selection means is configured such that the gas pump or a group of gas pumps pressurise and/or depressurise, in a first selection state, all the soft pneumatic actuators and, in a second selection state, a subset (e.g. one, two, three or four) of the soft pneumatic actuators. Preferably, in the second state, any one or combination of two or more (excluding all) soft pneumatic actuators may be selected. For example, the actuator selection means may be an actuator selection valve arrangement.

In an alternative option, where the device comprises two or more soft pneumatic actuators, it is preferred that the device comprises at least an equal number of gas pumps. Preferably, each soft pneumatic actuator is in fluid communication with at least one (e.g. with one or two) dedicated gas pump. A dedicated gas pump is a gas pump that is in fluid communication with a single soft pneumatic actuator.

In a preferred embodiment, the assistive or rehabilitative device comprises a soft pneumatic bending actuator and a piezoelectric resonant acoustic gas pump (or a gas pump that is configured to generate and rectify an acoustic standing wave to provide gas flow), the soft pneumatic bending actuator configured to actuate, assist and/or resist extension and/or flexion movement of a digit or digits of a hand (preferably, a human hand), wherein the soft pneumatic bending actuator is in fluid communication with the gas pump, the gas pump for pressurising and/or depressurising the soft pneumatic bending actuator. Preferably, the gas pump is for pressurising and/or depressurising an inside or an internal chamber of the soft pneumatic bending actuator. Preferably, the gas pump comprises a disc-shaped internal chamber. Preferably, the device comprises a pressure sensing means for measuring gas pressure of the soft pneumatic bending actuator. Preferably, the pressure sensing means is in fluid communication with the soft pneumatic bending actuator (e.g. an inside or an internal chamber of the soft pneumatic bending actuator). Where the context allows, further features or sub-features described herein in relation to the first aspect may be incorporated into this preferred embodiment.

Preferably, the device comprises a gas pump manifold for directing and/or controlling gas flow from and/or to the gas pump (or gas pumps), e.g. for directing and/or controlling gas flow through the device.

Furthermore, in a second aspect of the invention there is disclosed a gas pump manifold for directing and/or controlling gas flow from and/or to a gas pump (or gas pumps) of an assistive or rehabilitative device. Preferably, the device comprises a soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part. Preferably, the soft pneumatic actuator is in fluid communication with the gas pump and/or the gas pump is for pressurising the soft pneumatic actuator.

Hereunder, the gas pump manifold will be described as applicable to both the first and second aspects of invention. Where the context allows, features of the first aspect of invention above may be incorporated into the second aspect of invention. Non-limiting examples of such features of the first aspect include the soft pneumatic actuator, the gas pump (in particular, the piezoelectric resonant acoustic gas pump), the pressure sensing means, the soft pneumatic actuator venting means, the soft pneumatic actuator isolating means, their sub-features, and their configuration relative to each other.

In one option, the gas pump manifold may comprise conduits, e.g. hoses (such as the air hose described above) or tubes, and valves configured to direct and/or control gas flow from and/or to the gas pump (or gas pumps). Preferably, the conduits are flexible. In a further option, the gas pump manifold may comprise a manifold body (or manifold block) comprising internal conduits, the manifold body enclosing or housing valves, the internal conduits and valves arranged to direct and/or control gas flow from and/or to the gas pump (or gas pumps).

Preferably, the device (more preferably, the gas pump manifold) is configured to interchange between a first pumping direction state wherein the gas pump may pressurise the soft pneumatic actuator and a second pumping direction state wherein the gas pump may depressurise the soft pneumatic actuator. Therefore, preferably, in the first pumping direction state (when the gas pump is in operation) gas flows in the direction of (i.e. is pumped into) the soft pneumatic actuator and in the second pumping direction state (when the gas pump is in operation) gas flows in a direction away from (i.e. is pumped out of) the soft pneumatic actuator, e.g. to atmosphere.

Preferably, the device (more preferably, the gas pump manifold) comprises a pumping direction interchange means configured such that in the first pumping direction state a general pump inlet is in fluid communication with atmosphere and a general pump outlet is in fluid communication with the soft pneumatic actuator and in the second pumping direction state the general pump inlet is in fluid communication with the soft pneumatic actuator and the general pump outlet is in fluid communication with atmosphere.

The preferred piezoelectric resonant acoustic gas pump of the invention is advantageous for the reasons set out above. However, such pumps are unidirectional (i.e. the direction of gas flow through the pump cannot be reversed). As such, the pumping direction interchange means provides for a particularly advantageous configuration because the soft pneumatic actuator can be pressurised and depressurised improving the range of functionality of the device. Furthermore, it is advantageous to depressurise (where the pressure of the soft pneumatic actuator is above ambient pressure) or repressurise (where the pressure of the soft pneumatic actuator is below ambient pressure) the soft pneumatic actuator via the gas pump (as opposed to by venting directly to atmosphere) because this provides for improved control of the rate of gas flow.

Where the device comprises a single gas pump the general pump inlet is the gas pump inlet and the general pump outlet is the gas pump outlet. Where the device comprises two or more gas pumps, arranged in series or in parallel, the general pump inlet is a general inlet for all the gas pumps and the general pump outlet is a general outlet for all the gas pumps. For example, see the discussion above pertaining to the meaning of series and parallel arrangement of two gas pumps.

Preferably, the pumping direction interchange means comprises (or is) a pumping direction valve arrangement. Preferably, the pumping direction interchange means comprises (or consists of) two 3/2-way valves. A 3/2-way valve comprises an inlet port, an outlet port, and an exhaust port, wherein in a first (or open) position the outlet port is in fluid communication with the inlet port and in a second (or closed) position the outlet port is in fluid communication with the exhaust port.

Preferably, the pumping direction interchange means (more preferably, the pumping direction valve arrangement) comprises: a first two-way valve comprising a first inlet, a first outlet and a first exhaust, and a second two-way valve comprising a second inlet, a second outlet and a second exhaust, wherein the first outlet is in fluid communication with the general pump inlet and the second outlet is in fluid communication with the general pump outlet, wherein one of the first inlet and the first exhaust is in fluid communication with atmosphere and the other of the first inlet and the first exhaust is in fluid communication with the soft pneumatic actuator, wherein one of the second inlet and the second exhaust is in fluid communication with atmosphere and the other of the second inlet and the second exhaust is in fluid communication with the soft pneumatic actuator, and wherein the first and second valves are operable such that in the first pumping direction state the first outlet is in fluid communication (i.e. via/through the first valve) with atmosphere and the second outlet is in fluid communication (i.e. via/through the second valve) with the soft pneumatic actuator and in the second pumping direction state the first outlet is in fluid communication with the soft pneumatic actuator and the second outlet is in fluid communication with atmosphere.

The first valve and the second valve may be normally open or normally closed valves. Preferably, the first valve and second valve are both normally open or both normally closed valves.

The first inlet is in fluid communication with atmosphere and the first exhaust is in fluid communication with the soft pneumatic actuator or the first inlet is in fluid communication with the soft pneumatic actuator and the first exhaust is in fluid communication with atmosphere. The second inlet is in fluid communication with atmosphere and the second exhaust is in fluid communication with the soft pneumatic actuator or the second inlet is in fluid communication with the soft pneumatic actuator and the second exhaust is in fluid communication with atmosphere.

In a first preferred option, the first inlet and the second exhaust are in fluid communication with atmosphere and the first exhaust and the second inlet are in fluid communication with the soft pneumatic actuator. In a second preferred option, the first inlet and the second exhaust are in fluid communication with the soft pneumatic actuator and the first exhaust and the second inlet are in fluid communication with atmosphere. Where the first valve and second valve are both normally open or both normally closed valves, a particular advantage of these two options is that interchange between the first pumping direction state and the second pumping direction state may occur by supplying power to both valves or not suppling power to both valves, which reduces the overall complexity of the device.

In one embodiment, the device (more preferably, the gas pump manifold) is configured to switch between a first pumping direction state wherein the gas pump may pressurise the soft pneumatic actuator, a second pumping direction state wherein the gas pump may depressurise the soft pneumatic actuator, and a soft pneumatic actuator isolation state wherein the soft pneumatic actuator is isolated from the gas pump (or the soft pneumatic actuator and the gas pump are isolated from atmosphere). For example, the first and second valves are operable such that in the gas pump isolation state the first outlet and the second outlet are in fluid communication with the soft pneumatic actuator such that the soft pneumatic actuator and the gas pump are isolated from atmosphere. In a further example, the first and second valves are operable such that in the gas pump isolation state the first outlet and the second outlet are in fluid communication with atmosphere such that the soft pneumatic actuator is isolated from the gas pump. An advantage of the soft pneumatic actuator isolation state is that, when the gas pump is not in operation, pressure leakage via/through the gas pump (or gas pumps) is prohibited or has no effect on the pressure of the soft pneumatic actuator, providing more accurate and precise soft pneumatic actuator pressure measurements.

As discussed above, it is preferred that the soft pneumatic actuator is in fluid communication with two gas pumps, the two gas pumps configured in a parallel or in a series arrangement. Therefore, it is preferred that there are two gas pumps for pressurising the soft pneumatic actuator.

In one embodiment, where the device comprises first and second gas pumps, the device (more preferably, the gas pump manifold) is configured to interchange between a first pumping mode wherein the two gas pumps are configured in a parallel arrangement and a second pumping mode wherein the two gas pumps are configured in a series arrangement. Therefore, preferably, in the first pumping mode gas pump inlets of the two gas pumps are in fluid communication with a shared general pump inlet and gas pump outlets of the two gas pumps are in fluid communication with a shared general pump outlet. And therefore, preferably, in the second pumping mode a gas pump inlet of the first gas pump is in fluid communication with the general pump inlet, a gas pump outlet of the first gas pump and a gas pump inlet of the second gas pump are in fluid communication with each other, and a gas pump outlet of the second gas pump is in fluid communication with the general gas pump outlet.

Preferably, the device (more preferably, the gas pump manifold) comprises a pumping mode interchange means for interchanging between the first and second pumping modes. Preferably, the pumping mode interchange means comprises (or is) a pumping mode valve arrangement. Preferably, the pumping mode interchange means comprises (or consists of) either one 3/2-way valve and one 2/2-way valve, or two 3/2-way valves.

The preferred piezoelectric resonant acoustic gas pump of the invention is advantageous for the reasons set out above. However, such pumps have a limited peak flow, peak pressure and peak vacuum. As such, the pumping mode interchange means provides for a particularly advantageous configuration because the soft pneumatic actuator can be pressurised and/or depressurised with improved flow rate (parallel arrangement) or improved peak pressure (series arrangement). For example, by using a parallel arrangement when beginning to pressurise the soft pneumatic actuator initial response time is improved (e.g. providing a more natural feeling to the user) and by switching to a series arrangement during pressurisation a greater maximum pressure of the soft pneumatic actuator can be achieved (e.g. providing an improved range of motion and/or improved gripping strength).

Preferably, the pumping mode interchange means comprises: a third two-way valve comprising a third inlet, a third outlet and a third exhaust, and a fourth two-way valve comprising a fourth inlet, a fourth outlet, and optionally a fourth exhaust, wherein the fourth exhaust is blocked, wherein a first pump inlet and the fourth outlet are in fluid communication with a general pump inlet, the fourth inlet is in fluid communication with a second pump inlet, a second pump outlet is in fluid communication with a general pump outlet, a first pump outlet is in fluid communication with the third outlet, wherein one of the third inlet and the third exhaust is in fluid communication with the second pump inlet and the other of the third inlet and the third exhaust is in fluid communication with the general pump outlet, and wherein the third and fourth valves are operable such that in the first pumping mode the third outlet is in fluid communication with the general pump outlet and the fourth outlet is in fluid communication with the second pump inlet (e.g. the fourth valve is open) and in the second pumping mode the third outlet is in fluid communication with the second pump inlet and the fourth outlet is sealed (e.g. the fourth valve is closed or blocked).

The third inlet is in fluid communication with the second pump input and the third exhaust is in fluid communication with the general pump outlet or the third inlet is in fluid communication with the general pump outlet and the third exhaust is in fluid communication with the second pump input.

To avoid doubt, in some embodiments the third and fourth valves of the pumping mode interchange means may be present while the first and second valves of the pumping direction interchange means are not present.

The third valve and the fourth valve may be normally open or normally closed valves. Preferably, the third valve and fourth valve are both normally open or both normally closed valves.

In one embodiment, where the device comprises first and second gas pumps, the device (more preferably, the gas pump manifold) is configured to interchange between a first pumping direction state wherein the gas pumps may pressurise the soft pneumatic actuator and a second pumping direction state wherein the gas pumps may depressurise the soft pneumatic actuator, and to interchange between a first pumping mode wherein the two gas pumps are configured in a parallel arrangement and a second pumping mode wherein the two gas pumps are configured in a series arrangement.

Therefore, in this embodiment, the device (more preferably, the gas pump manifold) preferably comprises the pumping direction interchange means and the pumping mode interchange means as described above. As such, in this embodiment the pumping direction interchange means and the pumping mode interchange means (and/or their sub-features) may be combined where the context allows. For example, above it is said the first outlet (of the pumping direction interchange means) and the fourth outlet and the first pump inlet (of the pumping mode interchange means) may be in fluid communication with the general pump inlet. As such, the first outlet, the fourth outlet and the first pump inlet may be in fluid communication with each other. Likewise, above it is said the second outlet (of the pumping direction interchange means) and the second pump outlet and one of the third inlet or third exhaust (of the pumping mode interchange means) may be in fluid communication with the general pump outlet. As such, the second outlet, second pump outlet and one of the third inlet or third exhaust may be in fluid communication with each other.

In one option, the gas pump manifold further comprises (or houses) the pressure sensing means, the soft pneumatic actuator isolating means and/or the soft pneumatic actuator venting means described above in relation to the first aspect of invention.

Preferably, the valves of the gas pump manifold are solenoid valves.

Preferably, the device comprises a power source for powering the device. Preferably, the power source is a battery, more preferably a rechargeable battery.

Preferably, the gas pump or gas pumps (e.g. each gas pump) comprises a gas pump driver for driving the gas pump. The gas pump driver comprises electronics and software for driving the gas pump. For example, the gas pump driver comprises a 'Disc Pump Drive PCB' supplied by TTP Ventus Limited (address above).

Preferably, the device comprises a processing and communication means for controlling the device. For example, the device comprises a computer and/or a control system for controlling the device. Preferably, the processing and communication means (e.g. the computer and control system) comprises a user interface, a Bluetooth® communication means, a memory, and/or a microcontroller. Preferably, the user interface comprises at least one button, e.g. for turning the device on and off. Preferably, the microcontroller is configured to communicate with the gas pump (and/or the gas pump driver), the gas pump manifold (e.g. valves of the gas pump manifold), any further valves and/or the pressure sensing means. For example, the microcontroller is configured to communicate with the gas pump or gas pump driver with universal asynchronous receiver-transmitter (UART) signals. For example, the microcontroller is configured to communicate with the gas pump manifold (e.g. valves of the gas pump manifold) and any further valves with valve control signals. Preferably, the valves are controlled using at least metal oxide semiconductor field-effect transistors (MOSFET).

In a third aspect of the invention, there is provided a method of using an assistive device of the first aspect, the assistive device configured to actuate, assist and/or resist a movement of a body part, the method comprising: optionally, providing the device to a user; donning the device; optionally, priming the soft pneumatic actuator by pressurising or depressurising the soft pneumatic actuator to a pre-determined pressure level using the gas pump; optionally, intermittently or continuously measuring the pressure of the soft pneumatic actuator; optionally, using the pressure measurements to determine (or infer) when to start or stop pressurising or depressurising the soft pneumatic actuator; using the device to actuate, assist or resist the movement of the body part; optionally, doffing the device; and optionally, intermittently charging a power source of the device.

Preferably, the user cannot move the body part or requires assistance to move the body part with full strength, accuracy and/or to its full extent.

The method steps of the third aspect may also be used in a method of actuating, assisting and/or resisting a movement of a body part. Therefore, in the third aspect of the invention there is also provided a method of actuating, assisting and/or resisting a movement of a body part.

In a fourth aspect of the invention, there is provided a method of using a rehabilitative device of the first aspect, wherein the rehabilitative device is configured to actuate, assist, resist and/or monitor a movement of a body part, the method comprising: optionally, providing the device to a user in need of rehabilitation; donning the device; optionally, priming the soft pneumatic actuator by pressurising or depressurising the soft pneumatic actuator to a pre-determined pressure level using the gas pump; optionally, intermittently or continuously measuring the pressure of the soft pneumatic actuator; optionally, providing (i.e. to the user) instructions for moving the body part; optionally, using the pressure measurements to determine (or infer) when to start or stop pressurising or depressurising the soft pneumatic actuator and/or using the pressure measurements to monitor (or infer) the underlying strength, accuracy and/or range of motion of the movement of the body part; using the device to actuate, assist or resist the movement of the body part and/or using the device to monitor the underlying strength, accuracy and/or range of motion of the movement of the body part; optionally, doffing the device; and optionally, intermittently charging a power source of the device.

Preferably, the user is a user in need of rehabilitation.

The method steps of the fourth aspect may also be used in a method of rehabilitating a movement of a body part. Therefore, in the fourth aspect of invention there is also provided in a method of rehabilitating a movement of a body part.

With respect to the third and fourth aspects, donning the device means to put on a least a wearable element or elements of the device such that the wearable elements or worn. Preferably, the method comprises donning the entire device.

Where the context allows, features and configurations of the first aspect of invention may be incorporated into the third and fourth aspects of invention. For example, as described above in relation to the first aspect, pressurising or depressurising the soft pneumatic actuator preferably means pressurising or depressing the inside or an internal chamber of the soft pneumatic actuator.

The invention will now be described in more detail, without limitation, with reference to the accompanying Figures.

Figure 1 is a schematic diagram of an assistive and rehabilitative device 101 for wearing on a hand (not shown). The device 101 comprises five soft pneumatic bending actuators 103, 105, 107, 109, 111 for attaching to the digits of the hand. Each soft pneumatic bending actuator 103, 105, 107, 109, 111 is configured for attaching to a specific digit of the hand (i.e. to one of the thumb, the index finger, the middle finger, the ring finger and the little finger). The soft pneumatic bending actuators 103, 105, 107, 109, 111 are configured for attaching to the dorsal side of the digits of the hand, for example by way of a resilient loop(s), a hook and loop strap(s) or a pocket for receiving the digit therein (not shown).

Each soft pneumatic bending actuator 103, 105, 107, 109, 111 comprises an internal chamber (not shown) in airtight fluid communication with a gas pump manifold 113 via air hose 119. Further, a pair of gas pump modules 115 and 117 are in airtight fluid communication with the gas pump manifold 113 via air hosing 121. The gas pump manifold 113 comprises a valve arrangement (not shown) for directing and controlling gas flow from and to the pair of gas pump modules 115 and 117. The gas pump manifold 113 can direct gas flow from the pair of gas pump modules 115 and 117 to any one or combination of two or more of the soft pneumatic bending actuators 103, 105, 107, 109, 111.

Each gas pump module 115, 117 comprises a 'XP Series' Disc Pump® and a 'Disc Pump Drive PCB', supplied by TTP Ventus Limited of Melbourn Science Park, Melbourn, Hertforshire, SG8 6 EE, UK.

The valve arrangement (not shown) of the gas pump manifold 113 can switch between a first pumping direction state wherein the gas pumps of the pair of gas pump modules 115 and 117 pressurise the soft pneumatic bending actuator(s) and a second pumping direction state wherein the gas pumps of the pair of gas pump modules depressurise the soft pneumatic bending actuator(s). Further, the valve arrangement (not shown) of the gas pump manifold 113 can switch between a first pumping mode wherein the gas pumps of the pair of gas pump modules 115 and 117 operate in parallel and a second pumping mode wherein the gas pumps of the pair of gas pump modules 115 and 117 operate in a series. Therefore, the valve arrangement (not shown) of the gas pump manifold 113 operates in four states.

In some embodiments, the device 101 comprises a pair of gas pump modules (e.g. 115, 117) for each soft pneumatic bending actuator 103, 105, 107, 109, 111. In these embodiments, the gas pump manifold 113 comprises discrete valve arrangements, each operable in the four states, for each pair of gas pump modules.

The device 101 further comprise a differential pressure sensor 123 (manufactured by Honeywell Sensing and Control of 2080 Arlingate Lane, Columbus, Ohio, 43228, USA and having part number TSCDRRN015PDUCV) in airtight fluid communication with one or any combination of two or more of the soft pneumatic bending actuators 103, 105, 107, 109, 111 via air hose 125, the gas pump manifold 113 and air hosing 119. Which soft pneumatic bending actuator(s) the differential pressure sensor is in airtight fluid communication with is dependent on which one or combination of two or more of the soft pneumatic bending actuators 103, 105, 107, 109, 111 are in fluid communication with the pair of gas pump modules 115, 117 via the gas pump manifold 113.

In embodiments where the device 101 comprises a pair of gas pump modules (e.g. 115 and 117) for each soft pneumatic bending actuator 103, 105, 107, 109, 111 (as discussed above), each soft pneumatic bending actuator is preferably in airtight fluid communication with a discrete differential pressure sensor 123.

The gas pump manifold 113, gas pump modules 115, 117 and differential pressure sensor 123 together form a pneumatic control system 127.

The device 101 comprises a microcontroller 131 for receiving pressure measurements from the differential pressure sensor(s) 123 and for controlling the gas pump modules (e.g. 115, 117) and the gas pump manifold 113. The microcontroller 131 communicates with the gas pump modules (e.g. 115, 117) using universal asynchronous receiver-transmitter (UART) signals. The microcontroller 131 controls the gas pump manifold 113 (and in particular valves of the valve arrangement thereof) using metal oxide semiconductor field-effect transistors (MOSFETs). The device comprises a memory 133, a Bluetooth®-based communication means for communication with a peripheral device, and user interface 137 comprising at least one button (e.g. the at least one button is for turning the device on or off).

The microcontroller 131, memory 133, Bluetooth®-based communication means 135 and user interface 137 together form a processing and communications system 129.

The device 101 further comprises a rechargeable battery in electrical communication with and for powering the pneumatic control system 127 and the processing and communications system 129.

In an alternative embodiment to that illustrated in Figure 1, the device 101 comprises a single gas pump module (e.g. 115) or a single gas pump module dedicated to each soft pneumatic bending actuator. In this alternative embodiment, the valve arrangement (not shown) of the gas pump manifold 113 does not switch between a first pumping mode and a second pumping mode. In which case, the valve arrangement (not shown) of the gas pump manifold 113 operates in two states.

In Figure 2, there is illustrated a side view of an assistive and rehabilitative device 201 worn on a hand 202 and comprising five soft pneumatic bending actuators 203, 205 and 207 (two soft pneumatic bending actuators are not shown). Figure 2 is intended to provide an illustrative example of how the device 201 is worn by a user and as such several features discussed above (e.g. the battery, the microcontroller and the user interface) are omitted from view. Soft pneumatic bending actuator 203 is attached to the dorsal side of thumb 209; soft pneumatic bending actuator 205 is attached to the dorsal side of the index finger 211; and soft pneumatic bending actuator 207 is attached to the dorsal side of middle finger 213. A first of the further two soft pneumatic bending actuators (not shown) is attached to the dorsal side of the ring finger (not shown) and a second of the further two soft pneumatic bending actuators (not shown) is attached to the dorsal side of the small finger. The thumb and fingers may be referred to as 'digits' of a hand 202.

The five soft pneumatic bending actuators 203, 205, 207 each comprise a resilient thermoplastic polyurethane (TPU) actuator wall 206 and an internal chamber (not shown). Each soft pneumatic bending actuator 203, 205, 207 comprises, disposed along their length, a plurality of actuator body cells 208 extending upwardly from a lengthwise-inextensible actuator base 210. The structure and function of a soft pneumatic bending actuator is discussed in further detail below in relation to Figure 4. Each of the soft pneumatic bending actuators are attached to their allocated digit by way of straps 215. The straps 215 are resilient and therefore can be stretched when donning and doffing the device 201 (i.e. so a digit can slide through them) but hold their respective soft pneumatic bending actuator firmly in position on the dorsal side of a digit during use of the device 201 by compressing around the digit. Furthermore, the device 201 is securely attached to the hand 202 and wrist 217 by way of compression sleeve 219 and forearm frame 221.

To don the device 201, a user slides their hand 202 through a forearm frame 221 rear opening (not shown) and the compression sleeve rear opening 223 in a single movement. Once the compression sleeve 219 and forearm frame 223 are in place on the hand 202 and wrist 217, the soft pneumatic bending actuators 203, 205, 207 may be attached to the digits of the hand 209, 211, 213 by sliding each digit through the respective straps 215.

First 227 and second 229 gas pump housings, each housing a piezoelectric resonant acoustic gas pump ('XP Series' Disc Pump®, supplied by TTP Ventus Limited of Melbourn Science Park, Melbourn, Hertforshire, SG8 6 EE, UK) (not shown), is attached to the top side 228 of the compression sleeve 219. The gas pumps (not shown) of gas pump housings 227 and 229 are in airtight fluid communication with the internal chambers (not shown) of all five soft pneumatic bending actuators 203, 205 and 207 via air hosing 231, 233.In alternative embodiments, the internal chamber of each of the soft pneumatic bending actuators may be in airtight fluid communication with one or two dedicated piezoelectric resonant acoustic gas pumps arranged in series or parallel.

In Figure 2, the digits of the hand are in a generally extended (e.g. near straight) position. As such, each internal chamber of the soft pneumatic bending actuators 203, 205, 207 has a pressure at or close to atmospheric pressure. During use of the device 201, the piezoelectric resonant acoustic gas pumps (not shown) are used to increase the pressure of the internal chambers of the soft pneumatic bending actuators 203, 205, 207. When the pressure of the internal chambers (not shown) of the soft pneumatic bending actuator 203, 205, 207 is increased this causes the soft pneumatic bending actuators to bend (discussed in further detail below) which in turn causes or assists flexion movement of the digits, each attached to a soft pneumatic bending actuator.

Figures 3A and 3B illustrate cross-sectional side views of exemplary piezoelectric resonant acoustic gas pumps 301 and 303 (not to scale). The gas pumps 301 and 303 comprise a cylindrical side wall 307, a first circular end wall 309 and a second circular end wall 311. The walls 307, 309 and 311 together enclose an internal disc-shaped acoustic resonant cavity 305.

Gas pump 301 comprises a circular piezoelectric actuator 313 attached and parallel to the first circular end wall 309. As such, the first circular end wall 309 is a driven end wall. Gas pump 301 further comprises, through the second circular end wall 311, an un-valved nodal gas inlet 315 and a central gas outlet 317 comprising an ultra-fast valve.

Gas pump 303 comprises a circular piezoelectric actuator 313 anchored centrally with the acoustic resonant cavity 305 by anchors 319. The piezoelectric actuator 313 is anchored in a position parallel to the circular end walls 309 and 311. The piezoelectric actuator 313 is anchored by the anchors 319 such that a perimeter of the piezoelectric actuator 313 does not move from position (but may pivot) when the piezoelectric actuator 313 oscillates. The piezoelectric actuator 313 defines a first cavity portion 321 and a second cavity portion 323. The first and second cavity portions 321, 323 are fluidically connected around the perimeter of piezoelectric actuator 313 to form a single continuous acoustic resonant cavity 305 which wraps around the piezoelectric actuator 313. Through each of the two end walls 309, 311 there is central gas outlet 317 comprising an ultra-fast valve and through the side wall 307 there is an un-valved gas inlet.

In operation, the piezoelectric actuator 313 of gas pumps 301 and 303 flexes at its mechanical resonance and thus oscillates in a direction perpendicular to the end walls 309, 311. The gas pumps 301 and 303 operate at around 21 kHz. Oscillation of the piezoelectric actuator 313 generates an acoustic standing wave (more particular, in the case of gas pump 303, an acoustic wrapped standing wave) within the acoustic resonant cavity 305. The standing wave is rectified by the ultrafast valve(s) of the gas outlet(s) 317 to provide air flow from the gas pump 301, 303.

In Figure 4 there is illustrated a cross-sectional perspective view of an exemplary soft pneumatic actuator 401. The soft pneumatic actuator 401 comprises an actuator body 403 comprising an actuator wall 405. The actuator wall 405 comprises a top portion 407 and an inextensible base (not shown). The top portion 407 and base (not shown) of the actuator wall 405 enclose an airtight internal chamber 409 of the actuator body 403. The internal chamber 409 of the actuator body 403 is accessed via an internal chamber access means (not shown) which is disposed through the actuator wall 405.

The top portion 407 comprises a plurality of generally cuboid-shaped cells 411 disposed at equal intervals along the actuator body 403. Each cell 411 extends upward from the base (not shown). Each cell 411 encloses a sub-chamber 413 of the internal chamber 409.

The top portion 407 of the actuator wall 405 consists of a thermoplastic polyurethane elastomer. The compliance of the top portion 407 is higher where its wall thickness is relatively less. Inner side walls 415, 417 are more compliant than top walls (at 411) and outer side walls (at 405) of the cells 411. Therefore, as the pressure of the internal chamber 409 increases the inner side walls 415, 417 will expand at a faster rate by contrast to areas of the top portion 407 that have a thicker wall.

Each pair of adjacent cells 419 comprise a first cell having a first side wall 415 proximal to a second side wall 417 of a second cell. As discussed above, the inner side walls 415, 417 expand at a faster rate relative other areas of the top portion 407 as the internal chamber 409 is pressurised. Thus, as the internal chamber 109 (including the sub-chambers 413) is pressurised the first end wall 415 and second end wall 417 of each pair of adjacent cells 419 expand and therefore push against each other. The pushing force between each pair of cells 419 of the actuator body 403 in combination with the inextensible characteristics of the base (not shown) causes the soft pneumatic actuator 401 to bend.

Because at least the top portion 407 consists of a thermoplastic polyurethane elastomer once the pressure of the internal chamber 409 is reduced back to its starting pressure the actuator body 403 returns to its original shape. Furthermore, the internal chamber 409 can be placed under vacuum which causes the actuator body 403 to bend in the opposite direction (e.g. to ‘hyper-extend’) by contrast to the direction of bending when the internal chamber 409 is pressurised.

In Figure 5A there is illustrated a schematic diagram of a pumping direction valve arrangement 501. The direction valve arrangement 501 comprises a first 503 and a second 505 type 6164 three-position, two-way pneumatic cartridge solenoid valve (supplied by Burkert UK Limited of Fluid Control Centre, 1 Bridge End, Cirencester, GL7 1QY, UK under article number 292601). The first valve 503 and second valve 505 are normally closed valves and each comprises a first/second inlet port ‘1’, a first/second outlet port ‘2’ and a first/second exhaust port ‘3’. The first outlet port is in airtight fluid communication via a conduit with a general pump inlet 507 and the second outlet port is in airtight fluid communication with a general pump outlet 509. The first inlet port is in fluid communication with atmosphere via a conduit and an air filter 511, and the second inlet port is in airtight fluid communication with an internal chamber of a soft pneumatic actuator(s) (denoted by arrow 513) via a conduit. The first exhaust port is in airtight fluid communication with the internal chamber of the soft pneumatic actuator(s) (denoted by arrow 513) via a conduit, and the second exhaust port is in in fluid communication with atmosphere via a conduit and the air filter 511.

Conduits providing fluid communication between the internal chamber of the soft pneumatic actuator(s) and the second inlet port and the first exhaust port join to form a single conduit 521 at conduit branch 515. Likewise, conduits providing fluid communication between the filter 511 (i.e. with atmosphere) and the first inlet port and the second exhaust port join to form a single conduit 525 at conduit branch 517.

Pressure sensor 519 is in airtight fluid communication with the internal chamber of the soft pneumatic actuator(s) via a conduit that joins, at conduit branch 523, the single conduit 521 downstream of conduit branch 515.

In the schematic diagram illustrated in Figure 5A power is applied to the first and second normally closed valves. As such, the first outlet port is in fluid communication with the first inlet port (i.e. with atmosphere) and the second outlet port is in fluid communication with the second inlet port (i.e. with the internal chamber of the soft pneumatic actuator(s)). Therefore, when power is applied to the first and second valves and when a gas pump or gas pumps (denoted by 'pump circuit') is/are in operation gas is pumped from atmosphere into the internal chamber of the soft pneumatic actuator(s). However, when power is not applied to the first and second normally closed valves the first outlet port is in fluid communication with the first exhaust port (i.e. with the internal chamber of the soft pneumatic actuator(s)) and the second outlet port is in fluid communication with the second exhaust port (i.e. with atmosphere). Therefore, when power is not applied to the first and second valves and when a gas pump or gas pumps (denoted by 'pump circuit') is/are in operation gas is pumped out of the internal chamber of the soft pneumatic actuator(s) to atmosphere. Furthermore, when power is applied only to the first normally closed valve 503 the internal chamber of a soft pneumatic actuator(s) (denoted by arrow 513) and the pressure sensor 519 are isolated from the 'pump circuit' and from atmosphere. And, when power is applied only to the second normally closed valve 505 the internal chamber of a soft pneumatic actuator(s) (denoted by arrow 513), the pressure sensor 519, and the 'pump circuit' are isolated from atmosphere.

In Figure 5B there is illustrated a schematic diagram of a pumping mode valve arrangement 551. The mode valve arrangement 551 comprises a first 553 and a second 555 type 6164 three-position, two-way pneumatic cartridge solenoid valve (supplied by Burkert UK Limited of Fluid Control Centre, 1 Bridge End, Cirencester, GL7 1QY, UK under article number 292601). The first valve 553 and second valve 555 are normally closed valves and each comprises a first/second inlet port '1', a first/second outlet port '2' and a first/second exhaust port '3'.

A first pump inlet 557 of a first pump 'P1' 559 and the second outlet port are in airtight fluid communication with a general pump inlet 559. The second inlet port is in airtight fluid communication with a second pump inlet 561 of a second pump 'P2' 563. The second exhaust port is blocked (i.e. fluidically sealed). A second pump outlet 565 of the second pump 563 is in airtight fluid communication with a general pump outlet 567. A first pump outlet 569 of the first pump 559 is in airtight fluid communication with the first outlet port. The first inlet port is in airtight fluid communication with the general pump outlet 567. The first exhaust port is in fluid communication with the second pump inlet 561.

Conduits 571, denoted by black lines, provide airtight fluid communication between the elements discussed directly above. Conduits 571 merge at conduit branches 573, 575, 577.

The first pump 559 and the second pump 563 are 'XP Series' Disc Pump®s, supplied by TTP Ventus Limited of Melbourn Science Park, Melbourn, Hertforshire, SG8 6 EE, UK.

In the schematic diagram illustrated in Figure 5B power is applied to the first and second normally closed valves. As such, the first outlet port is in fluid communication with the first inlet port (i.e. with general pump outlet 567) and the second outlet port is in fluid communication with the second inlet port (i.e. with the second pump inlet 561). Thus, the first pump outlet 569 is not in fluid communication with the second pump inlet 561, both pump inlets 557, 561 are in direct fluid communication with the general pump inlet 559, and both pump outlets 565, 569 are in direct fluid communication with the general pump outlet 567. Therefore, the first pump 559 and the second pump 563 are arranged in parallel. However, when power is not applied to the first and second normally closed valves the first outlet port is in fluid communication with the first exhaust port (i.e. with the second pump inlet 561) and the second outlet port is in fluid communication with the second exhaust port (i.e. is sealed). Thus, the first pump outlet 569 is in fluid communication with the second pump inlet 561, only first pump inlet 557 is in direct fluid communication with the general pump inlet 559, and only second pump outlet 565 is in direct fluid communication with the general pump outlet 567. Therefore, the first pump 559 and the second pump 563 are arranged in series.

Air hoses used in the embodiments of Figures 1 and 2 described above are preferably soft polyurethane air hosing (or tubing) supplied by SMC Pneumatics (U.K.) Ltd. of Vincent Avenue, Crownhill, Milton Keynes, MK8 0AN, UK and having part number TUS0425B-20. Further, conduits of the valve arrangements of Figures 5A and 5B described above may be said soft polyurethane air hosing (part number TUS0425B-20). However, conduits of the valve arrangements of Figures 5A and 5B described above may also be internal conduits of manifold block 113 (see Figure 1).

Figures 6A and 6B illustrate comparative pressure waveforms of a soft pneumatic bending actuator during gas pump operation. Figure 6A illustrates the pressure (mbar(g)) of an internal chamber of a soft pneumatic bending actuator over time (s) as the internal chamber is being pressurised by a diaphragm pump. The diaphragm pump is a micropump having model number D200-03 702 6894 and was supplied by RS Components Ltd of Birchington Road, Corby, Northants, NN17 9RS, UK. Figure 6B illustrates the pressure (mbar(g)) of the internal chamber of the same soft pneumatic bending actuator over time (s) as the internal chamber is being pressurised by a 'BL Series' Disc Pump®, supplied by TTP Ventus Limited (address above). The pressure waveform of Figure 6B (i.e. when using a piezoelectric resonant acoustic gas pump) is significantly smoother than that of Figure 6A which uses a diaphragm pump. Therefore, as described above, the illustrated reduced 'distortion' pressure waveform of Figure 6B, generated by the inventive configuration of the present application, can be used to accurately and precisely: track the three-dimensional position of the body part, determine when the pump should be turned on and/or off, and/or monitor the strength of the underlying body part.

Figure 7 illustrates a pressure waveform of an internal chamber of a soft pneumatic bending actuator during manual manipulation of the bending actuator. An internal chamber of a soft pneumatic bending actuator was depressurised to approximately -152 mbar(g) and was then fluidically sealed. As can be seen in the first image (from left to right), the bending actuator is hyper-extended when depressurised to approximately -152 mbar(g). The sealed bending actuator was then manually bent by approximately 90° (second image) causing the pressure of the internal chamber to reduce to approximately -172 mbar(g). The sealed bending actuator was then manually further bent to approximately 180° (third image) causing the pressure of the internal chamber to further reduce to approximately -184 mbar(g). The sealed bending actuator was then manually retuned to a bend of approximately 90° (fourth image) causing the pressure of the internal chamber to increase back to approximately -164 mbar(g). Finally, the sealed bending actuator was then allowed to return to its natural hyper-extended shape (fifth image) when a pressure of approximately -148 mbar(g) was measured. During the experiment, a slight ingress of gas into the internal chamber of the bending actuator caused pressure measurements of the second 90° stage and the second no-manipulation stage to be slightly higher than the respective first 90° stage and the first no-manipulation stage.

This experiment demonstrates that bending a soft pneumatic bending actuator decreases the pressure of the actuator internal chamber and straightening the soft pneumatic bending actuator increases the pressure of the actuator internal chamber. As such, this experiment supports that the pressure waveform of an internal chamber of a soft pneumatic bending actuator can be used to track the three-dimensional position of a body part, determine when a pump should be turned on and/or off, and/or monitor the strength of the underlying body part as described above.

The invention has been described with reference to the preferred embodiments. However, it will be appreciated that variations and modifications can be effected by a person of ordinary skill in the art without departing from the scope of the invention.

CLAIMS:

1. An assistive or rehabilitative device comprising a soft pneumatic actuator and a piezoelectric resonant acoustic gas pump, the soft pneumatic actuator configured to actuate, assist and/or resist a movement of a body part, wherein the soft pneumatic actuator is in fluid communication with the gas pump, and wherein the gas pump is for pressurising and/or depressurising the soft pneumatic actuator.

2. A device as claimed in claim 1, wherein the device further comprises a pressure sensing means for measuring gas pressure of the soft pneumatic actuator.

3. A device as claimed in claim 1 or claim 2, wherein the soft pneumatic actuator is a bending actuator.

4. A device as claimed in any one of the preceding claims, wherein the device is wearable.

5. A device as claimed in claim 4, wherein the device is wearable on a hand.

6. A device as claimed in any one of the preceding claims, wherein the movement of a body part is flexion and/or extension of a digit or digits of a hand.

7. A device as claimed in any one of the preceding claims, wherein the device is configured such that the soft pneumatic actuator is engageable with a digit or digits of a hand, such that if the soft pneumatic actuator bends an engaged digit(s) is caused to bend.

8. A device as claimed in any one of the preceding claims, wherein the device is configured to selectively isolate the soft pneumatic actuator from the gas pump and/or to selectively isolate the soft pneumatic actuator and the gas pump from atmosphere.

9. A device as claimed in any one of the preceding claims, wherein the device is configured to selectively vent the soft pneumatic actuator to atmosphere.

10. A device as claimed in any one of the preceding claims, wherein the device is configured to interchange between a first pumping direction state wherein the gas pump may pressurise the soft pneumatic actuator and a second pumping direction state wherein the gas pump may depressurise the soft pneumatic actuator.

11. A device as claimed in claim 10, wherein the device further comprises a pumping direction interchange means configured such that in the first pumping direction state a pump inlet is in fluid communication with atmosphere and a pump outlet is in fluid communication with the soft pneumatic actuator and in the second pumping direction state the pump inlet is in fluid communication with the soft pneumatic actuator and the pump outlet is in fluid communication with atmosphere.

12. A device as claimed in claim 11, wherein the pumping direction interchange means comprises:

a first two-way valve comprising a first inlet, a first outlet and a first exhaust, and

a second two-way valve comprising a second inlet, a second outlet and a second exhaust,

wherein the first outlet is in fluid communication with the pump inlet and the second outlet is in fluid communication with the pump outlet,

wherein one of the first inlet and the first exhaust is in fluid communication with atmosphere and the other of the first inlet and the first exhaust is in fluid communication with the soft pneumatic actuator,

wherein one of the second inlet and the second exhaust is in fluid communication with atmosphere and the other of the second inlet and the second exhaust is in fluid communication with the soft pneumatic actuator, and wherein the first and second valves are operable such that in the first pumping direction state the first outlet is in fluid communication with atmosphere and the second outlet is in fluid communication with the soft pneumatic actuator and in the second pumping direction state the first outlet is in fluid communication with the soft pneumatic actuator and the second outlet is in fluid communication with atmosphere.

13. A device as claimed in any one of the preceding claims, wherein the soft pneumatic actuator is in fluid communication with two gas pumps, the two gas pumps configured in a parallel or in a series arrangement.

14. A device as claimed in claim 13, wherein the device is configured to interchange between a first pumping mode wherein the two gas pumps are configured in a parallel arrangement and a second pumping mode wherein the two gas pumps are configured in a series arrangement.

15. A device as claimed in claim 14, wherein the device further comprises a pumping mode interchange means for interchanging between the first and second pumping modes.

16. A device as claimed in claim 15, wherein the pumping mode interchange means comprises:

a third two-way valve comprising a third inlet, a third outlet and a third exhaust, and

a fourth two-way valve comprising a fourth inlet, a fourth outlet, and optionally a fourth exhaust, wherein the fourth exhaust is blocked,

wherein a first pump inlet and the fourth outlet are in fluid communication with a general pump inlet, the fourth inlet is in fluid communication with a second pump inlet, a second pump outlet is in fluid communication with a general pump outlet, a first pump outlet is in fluid communication with the third outlet, wherein one of the third inlet and the third exhaust is in fluid communication with the second pump inlet and the other of the third inlet and the third exhaust is in fluid communication with the general pump outlet, and

wherein the third and fourth valves are operable such that in the first pumping mode the third outlet is in fluid communication with the general pump outlet and the fourth outlet is in fluid communication with the second pump inlet and in the second pumping mode the third outlet is in fluid communication with the second pump inlet and the fourth outlet is sealed.

17. A device as claimed in any one of claims 1 to 9, wherein the soft pneumatic actuator is in fluid communication with two gas pumps, wherein the device is configured to interchange between a first pumping direction state wherein the gas pumps may pressurise the soft pneumatic actuator and a second pumping direction state wherein the gas pumps may depressurise the soft pneumatic actuator, and wherein the device is configured to interchange between a first pumping mode wherein the two gas pumps are configured in a parallel arrangement and a second pumping mode wherein the two gas pumps are configured in a series arrangement.

18. A device as claimed in claim 17, wherein the device comprises a pumping direction interchange means as defined in claim 11 or claim 12 and a pumping mode interchange means as defined in claim 15 or claim 16.

19. A device as claimed in any one of the preceding claims, wherein the gas pump(s) is a micropump and/or an ultrasonic pump.

20. A device as claimed in any one of the preceding claims, wherein the gas pump satisfies one or any combination of two or more of the following conditions:

a) a peak flow of at least 0.1 L/min;

b) a peak flow of at most 5 L/min;

c) a peak pressure of at least 100 mbar(g);

d) a peak pressure of at most 2 bar(g);

e) a peak vacuum of at least -100 mbar(g);

f) a peak vacuum of at most -1.2 bar(g);

g) operates at from 18 kHz to 25 kHz;

h) weighs at most 10 g;

i) the gas pump in its largest dimension measures at most 80 mm;

j) the gas pump comprises a disc-shaped internal cavity having a cylindrical side wall height of from 0.2 mm to 10 mm; and

k) the gas pump comprises a disc-shaped internal cavity having a radius of from 2 mm to 90 mm.

21. A device as claimed in any one of the preceding claims, wherein the device comprises from two to five soft pneumatic actuators, the gas pump or gas pumps for pressurising the soft pneumatic actuators.

22. A device as claimed in claim 21, wherein each soft pneumatic actuator is engageable with an individual digit of a hand or with two adjacent digits of a hand.

23. A device as claimed in claim 21 or claim 22, wherein the device comprises a soft pneumatic actuator selection means configured such that the gas pump or a group of gas pumps pressurise and/or depressurise, in a first selection state, all the soft pneumatic actuators and, in a second selection state, a subset of the soft pneumatic actuators.

24. A method of using an assistive device as claimed in any one of claims 1 to 23, wherein the assistive device is configured to actuate, assist and/or resist a movement of a body part, the method comprising:

donning the device; and

using the device to actuate or assist the movement of the body part.

25. A method of using a rehabilitative device as claimed in any one of claims 1 to 23, wherein the rehabilitative device is configured to actuate, assist and/or resist a movement of a body part, the method comprising:

donning the device;

using the device to actuate, assist or resist the movement of the body part and/or using the device to monitor the underlying strength, accuracy and/or range of motion of the movement of the body part.

Intellectual Property Office

Application No:	GB2213268.2	**Examiner:**	Mr Tony Judge
Claims searched:	1-23	**Date of search:**	15 February 2023

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	US 2018/0296419 A1 (UNIV HONG KONG CHINESE) Please see figures and paragraphs 26-37.
A	-	CN 110236880 A (UNIV XI AN JIAOTONG) Please see whole document.
A	-	US 2017/0119614 A1 (UNIV SINGAPORE) Please see figures and paragraphs 8 and 35-39.
A	-	WO 2012/148472 A2 (HARVARD COLLEGE) Please see figures and paragraphs 12-14 and 126-128.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

Worldwide search of patent documents classified in the following areas of the IPC

A61F; A61H; B25J; F04B

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC, XPI3E

Intellectual
Property
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International Classification:

Subclass	Subgroup	Valid From
A61H	0001/02	01/01/2006
A61F	0002/50	01/01/2006
A61F	0002/54	01/01/2006
A61F	0002/60	01/01/2006
A61F	0002/68	01/01/2006
A61F	0002/74	01/01/2006
B25J	0015/00	01/01/2006