

# **TITLE OF THE INVENTION: A CONDUCTIVE COMPOSITE MATERIAL AND SYNTHETIC FIBRE UNIT**

## **FIELD OF THE INVENTION**

5 [0001] The invention relates to a composite material and synthetic fibre unit that may be used in the field of robotics and mechanical motion.

## **BACKGROUND OF THE INVENTION**

[0002] Currently, most robots and artificial muscles use a rotary motion as the  
10 main driver of the joint motion. However, such rotary joint motion is limited and not human-like. Further, the rotary joint motion is susceptible to friction and wear and tear.

[0003] WO2022/213976 describes an artificial muscle having two flexible  
electrodes wrapped by a flexible insulating material. The wrapped electrodes are  
15 arranged in a double helix structure and are immersed in a dielectric fluid (which can be a liquid or gas).

## **SUMMARY OF THE INVENTION**

[0004] In a first aspect, there is provided a composite material comprising a  
20 plurality of conductive layers, each conductive layer comprises a substrate layer and an electrical conducting element attached to the substrate layer, wherein the electrical conducting element on each conductive layer is arranged in a spiral configuration to allow flow of an electrical current from a perimeter region of the substrate layer to a centre region of the substrate layer and back to the perimeter  
25 region, wherein the spiral configurations of adjacent electrical conducting elements are arranged such that the electrical current in adjacent spirals in adjacent electrical conducting elements flow in a direction; at least one elastic layer attached between two adjacent conductive layers of the plurality of conductive layers to form a stack of layers; an electrical connection inlet; an  
30 electrical connection outlet; and a plurality of intermediate electrical connectors arranged to allow the electrical connection inlet and the electrical connection outlet to be electrically connected to each of the electrical conducting element of the

plurality of conductive layers in a parallel circuit arrangement. The direction of the current in the adjacent spirals in adjacent electrical conducting elements may be clockwise or anticlockwise. Advantageously, the configuration of the electrical conducting element in the conductive layers allow the composite material to contract axially and expand laterally when an electrical current flows through the electrical conducting elements. When the current is reduced or stopped, the respective contraction and expansion is reversed and thus allows the composite material to serve as an electrical actuator controlled by the flow of the current. It should be noted that the electrical connection inlet and electrical connection outlet may be connected to the electrical conducting element at any region of the substrate layer. In an embodiment, the electrical connection inlet and electrical connection outlet are connected to the electrical conducting element at the perimeter region of the substrate.

[0005] Preferably, there is an equal number of conductive layers and elastic layers.

[0006] Preferably, the electrical conducting element, the electrical connection inlet, the electrical connection outlet, and the plurality of intermediate electrical connectors is each independently selected from the group consisting of a carbon-based electrical conductor and a metal-based electrical conductor. The metal-based electrical conductor may be enclosed in an insulator, for example an electrical wire. In an embodiment, the electrical conducting element is a carbon-based electrical conductor like graphene and the electrical connection inlet, the electrical connection outlet, and the at least one intermediate electrical connection are metal-based electrical conductors.

[0007] Preferably, the substrate layer is an elastomer or an elastic organic polymer. More preferably, the substrate layer has a (first) Shore A hardness value from 0 to 30. Even more preferably the substrate layer is an electrical insulator. In an embodiment, the substrate layer comprises silica gel or silicone gel.

[0008] Preferably, the at least one elastic layer is an insulator and is an elastomer or an elastic organic polymer, wherein the elastic layer has a (second) Shore A hardness value that is lower than the Shore A hardness value of the substrate layer. More preferably, the Shore A hardness value of the elastic layer is

from 0 to 30. In an embodiment, the elastic layer comprises silica gel or silicone gel. The silica gel or silicone gel for the elastic layer is softer (i.e. a lower Shore A hardness value) than the substrate layer in particular when the substrate layer uses silica gel or silicone gel.

5 [0009] In an embodiment, the plurality of conductive layers and the at least one elastic layer have a generally cylindrical shape. In an embodiment, the first spiral pattern and the second spiral pattern are generally circular spirals. Circular spirals are generally preferred as the distance from the centre is generally equidistant, however other patterns like triangular, square, and rectangular patterns may be  
10 feasible.

[0010] In an embodiment, each of the electrical conducting element comprises a first terminal end and a second terminal end located proximal to each other at the perimeter region of the substrate layer, each of the first terminal end is electrically connected in parallel to the electrical connection inlet via at least one of  
15 the plurality of intermediate electrical connectors and each of the second terminal end is electrically connected in parallel to the electrical connection outlet via at least one of the plurality of intermediate electrical connectors. Preferably, the first terminal ends of the electrical conducting elements are aligned with each other and the second terminal ends of the electrical conducting elements are aligned  
20 with each other, and the plurality of intermediate electrical connectors are parallel to each other.

[0011] In an embodiment, the spiral configuration is identical and aligned on each electrical conducting element such that the electrical current in adjacent spirals in adjacent electrical conducting elements flow in the direction.  
25 Advantageously, the conductive layers may be prepared in bulk and provides ease of manufacturing, and may still provide flexibility to adjust the thickness of the substrate layer if desired.

[0012] Preferably, the electrical current is a direct current.

[0013] In a second aspect, there is provided a synthetic fibre unit comprising the  
30 composite material according to the first aspect; an outer elastic cover to wrap around the composite material; and a support structure to attach the outer elastic cover to the stack of layers, the outer elastic cover comprising a fabric sheet and

an outer elastic layer, the outer elastic layer is an elastomer or an elastic organic polymer, the outer elastic layer having a Shore A hardness value from 0 to 30. The outer elastic layer is attached to the fabric sheet.

[0014] Preferably, the support structure comprises a plurality of axial filaments and a plurality of lateral fibre filaments, wherein the plurality of axial filaments and the plurality of lateral fibre filaments are generally in orthogonal planes with respect to each other. More preferably, the plurality of axial filaments ends at opposite faces of the synthetic fibre unit and attaches the outer elastic cover to the stack of layers. Advantageously, the axial filaments are able to provide structural strength and tension to the synthetic fibre unit. The axial filaments may be able to bend to allow for the compression in the axial (or vertical) direction of the synthetic fibre unit when the elastic layer is compressed when a current passes through.

[0015] Preferably, the plurality of lateral fibre elements is distributed in a plurality of sets in spaced intervals. Advantageously, the spaced apart lateral fibre elements restrict the lateral expansion of the composite material especially the elastic layer resulting in alternating expandable segments and non-expandable segments along the axial (or vertical direction) of the synthetic fibre unit. The alternating segments allow waves to be formed when a current is passed through the synthetic fibre unit increasing the contraction (or shrinkage) per unit length.

[0016] In an embodiment, the plurality of axial filaments and the plurality of lateral fibre filaments are high strength fibres, preferably carbon fibres.

[0017] In a third aspect, there is provided a synthetic fibre body comprising a plurality of synthetic fibre units according to the second aspect, and a cooling system. Preferably, the plurality of synthetic fibre units is arranged in a planar arrangement, a circular arrangement, a cylindrical arrangement, other regular arrangement, in any combinations thereof.

[0018] Preferably, each synthetic fibre unit in the plurality of synthetic fibre units are identical, different, or a mixture. Thus, the synthetic fibre units may all be identical or different or have a mixture of identical and different fibre units.

[0019] In an embodiment, the plurality of synthetic fibre units comprises a first synthetic fibre unit and a second synthetic fibre unit, the first synthetic fibre unit and the second synthetic fibre unit are arranged on opposite sides, wherein the

first synthetic fibre unit and the second synthetic fibre unit are configured such that the first synthetic fibre unit contracts (or shrink) and/or expands less than the second synthetic fibre unit. Advantageously, this allows the synthetic fibre body to mimic a human joint or animal joint more closely.

5 [0020] In a fourth aspect, a joint or an artificial muscle comprises a plurality of synthetic fibre bodies according to the third aspect.

[0021] In a fifth aspect, there is provided a method of operating the synthetic fibre unit according to the second aspect, the synthetic fibre body according to the third aspect or the artificial muscle according to the fourth aspect, the method  
10 comprising passing an electrical current into the synthetic fibre unit according to the second aspect, the synthetic fibre body according to the third aspect or the artificial muscle according to the fourth aspect, via the electrical connection inlet and out of the synthetic fibre unit via the electrical connection outlet; compressing the at least one elastic layer attached between two conductive layers due to the  
15 passing of the electrical current; and expanding the substrate layer due to the passing of the electrical current.

[0022] Preferably, the method further comprises reducing the electrical current, preferably the electrical current is a direct current; and expanding the at least one elastic layer and compressing the substrate layer. When the electrical current is  
20 reduced to zero, the elastic layer and the substrate layer should return to their original state.

[0023] Advantageously, the various aspects and embodiments described herein allows for a joint or a soft artificial muscle to be created with a wide range of human-like and animal-like motion. The various aspects and embodiments may be  
25 manufactured to as small as micrometre or nanometre dimensions and may be suitable to be used to manufacture medical equipment, for example minimally invasive surgical equipment. The small size may also make it feasible to manufacture microrobots and in bionics.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

30 [0024] Figure (FIG.) 1 shows a schematic perspective view on an electrically actuated fibre unit.

[0025] FIG. 2 shows a schematic perspective exploded view of the electrically actuated fibre unit with the layers spaced apart.

[0026] FIG. 3 shows a schematic of the flow of the electrical current in the electrically actuated fibre unit.

5 [0027] FIG. 4 shows the electrically actuated fibre unit at its resting state or when no electrical current is passed through.

[0028] FIG. 5 shows the electrically actuated fibre unit when the electrical current is passing through the unit.

10 [0029] FIG. 6 shows a synthetic fibre body with multiple electrically actuated fibre units.

### **DETAILED DESCRIPTION OF THE INVENTION**

[0030] In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative embodiments of the invention. It will be understood, however, to one skilled in the art, that  
15 embodiments of the invention may be practiced without some or all of these specific details. Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

20 [0031] Unless defined otherwise, all technical and scientific terms used herein have the meaning commonly understood by a person skilled in the art to which this invention belongs. Unless otherwise specifically noted, articles depicted in the drawings are not necessarily drawn to scale.

[0032] As used herein, the articles “a”, “an” and “the” as used with regard to a  
25 feature or element include a reference to one or more of the features or elements. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items. As used herein, the terms “first,” “second,” and “third,” etc. are used merely as labels, and are not intended to impose numerical requirements on their objects. As used herein, the terms “top”, “bottom”,  
30 “left”, “right”, “side”, “vertical”, “lateral” and “horizontal” are used to describe relative arrangements of the elements and features. As used herein, the term

“each other” denotes a reciprocal relation between two or more objects, depending on the number of objects involved.

[0033] Terms such as “connected”, “attached”, “conjugated and “linked” are used interchangeably herein and encompass direct as well as indirect connection,  
5 attachment, linkage or conjugation unless the context clearly dictates otherwise.

[0034] Where a combination is disclosed, each subcombination of the elements of that combination is also specifically disclosed and is within the scope of the invention. Conversely, where different elements or groups of elements are disclosed, combinations thereof are also disclosed. Where any element of an  
10 invention is disclosed as having a plurality of alternatives, examples of that invention in which each alternative is excluded singly or in any combination with the other alternatives are also hereby disclosed; more than one element of an invention can have such exclusions, and all combinations of elements having such exclusions are hereby disclosed.

[0035] Where a range of values is recited, it is to be understood that each intervening integer value, and each fraction thereof, between the recited upper and lower limits of that range is also specifically disclosed, along with each subrange between such values. The upper and lower limits of any range can independently be included in or excluded from the range, and each range where  
20 either, neither or both limits are included is also encompassed within the invention. Where a value being discussed has inherent limits, those inherent limits are specifically disclosed. Where a value is explicitly recited, it is to be understood that values which are about the same quantity or amount as the recited value are also within the scope of the invention, as are ranges based thereon.

[0036] Although each of these terms has a distinct meaning, the terms “comprising”, “consisting of” and “consisting essentially of” may be interchanged for one another throughout the instant application. The term “having” has the same meaning as “comprising” and may be replaced with either the term “consisting of” or “consisting essentially of”.

[0037] The term “axial” and related terms as used herein refers to an axis or a line in one direction of the composite material, in particular the length of the composite material as the context requires. The term “lateral” and associated

terms as used herein refers to a direction perpendicular to the axial axis or line, when the composite material is cylindrical shaped the lateral direction may also be termed the radial direction. The two lateral axes thus form a plane which is orthogonal to the axial axis.

5 [0038] It will be appreciated that the description of possible materials for the different components of the embodiments described herein are a non-exhaustive and non-limiting list of possible options that may be used, and other suitable alternatives may be used without deviating from the inventive concept.

[0039] With the development of robot technology, especially bionic robot  
10 technology, there are limitations with using motor rotation as a robotic joint. Instead, it may be more advantageous to simulate muscle contraction by a mechanism that changes the shape of a device by the passing of current or voltage through the device thereby providing motion.

[0040] Described herein is a composite material that can change the shape by  
15 passing a current through the composite material or adjusting the voltage across the composite material. The composite material can be used to make a synthetic fibre unit which can be applied in the field of simulated robots to imitate muscle movements and replace rotary motors. The synthetic fibre units 100, synthetic fibre bodies 200, and artificial muscle described herein have a greater degree of  
20 motion and is more human-like.

[0041] The synthetic fibre units 100 may be made to a micron level (for example having dimensions in micrometres like 1 micrometre to 1000 micrometres) and may be used to manufacture medical equipment and replace traditional minimally invasive surgical equipment. It may be possible that the synthetic fibre units are  
25 made to a nanometre level (like from 1 nanometre to 1000 nanometres). The fibre units 100 may be combined and arranged in any way to achieve the desired objective, and replace existing electro-pneumatic mechanism to build more advanced micro robots, and bionics, etc.

[0042] FIG. 1 shows a schematic of a synthetic fibre unit 100 containing a  
30 composite material (or composite body) and a support structure. FIG. 2 shows a schematic of the composite material (or composite body) with the layers 5, 10 spaced apart to view the components more clearly.

[0043] The composite material (or composite body) contains alternating layers of an elastic layer 5 and a conductive layer 10 stacked together to form a stack of layers as shown in the sectional cutout in FIG. 1 and exploded view in FIG. 2. Each conductive layer 10 has a substrate layer 20 with an electrical conducting element 15 or conductive body attached on the substrate layer 20. At a minimum, the composite material should have two conductive layers 10 and one elastic layer 5 between two adjacent conductive layers, but should preferably have more layers 5, 10. In an embodiment, there may be an equal number of elastic layers 5 and conductive layers 10. Hence, an elastic layer 5 and a conductive layer 10 may form an elastic-insulating conductive layer. The number of conductive layers 10 and elastic layers 5 required depends on the purpose and use of the composite material and the synthetic fibre body 200 and artificial muscle as described herein. For example, if the synthetic fibre body 200 is of a shorter length, it will require less layers 5, 10 than a longer synthetic fibre body 200. The synthetic fibre bodies 200 of different lengths may be used for different purposes and different positions for a robot. The conductive layers 10 and elastic layer/s 5 may be joined by any suitable means, for example adhesives. Certain materials may also have weak adhesive properties that allow the layers 5, 10 to be attached without an external adhesive.

[0044] Each conducting layer 10 may be made by placing (for example by printing or spraying) an electrical conducting element 15 onto the surface of a substrate layer 20. 3D printing may also be used for any of the layers 5, 10. The electrical conducting element 15 may be any carbon-based, metal-based or other suitable conductive material. Carbon-based conductive material includes graphene. Metal-based conductive material includes copper, aluminium, zinc, nickel, iron, lead, silver, gold, steel, and alloys of these metals like brass and bronze. The electrical conducting element 15 may be attached by any suitable means like adhesives, or the conducting element 15 may have adhesive properties itself. The substrate layer 20 may be any suitable material, for example an elastomer or an elastic organic polymer. which are preferably an electrical insulator. The material for the substrate layer 20 is also preferably elastic, non-limiting examples of materials suitable for the substrate layer 20 includes silica gel,

silicone gel or other elastic and insulating film structures. In an embodiment, the material for the substrate layer 20 may have a Shore A hardness value of 0 to 30. The thickness of the substrate layer 20 may be from millimetres to micrometres (microns). The width of the printed conductive lines can also be in the range of millimetres to micrometres (microns).

[0045] The electrical conducting element 15 may be arranged or attached on the substrate layer 20 in a spiral configuration to allow flow of an electrical current from a perimeter region of the substrate layer 20 to a centre region of the substrate layer 20 and back to the perimeter region. This may be specifically termed a double spiral configuration as it contains a first spiral 15A from the perimeter region to the centre region, a spiral turn 15C, and a second spiral 15B from the centre region to the perimeter region. It should be noted that the double spiral may or may not start and end at the same perimeter region. In other words, the terminal ends of the double spiral may be proximal to each other or may be away from each other like opposite, or between 30 to 150 degrees away when measured from the centre region. The spiral pattern is preferably a regular and symmetrical pattern and will be advantageous as explained in greater detail herein, and may have the following shapes: circular, oval, square, rectangular, rhombus, parallelogram. However, other spiral patterns are also possible. A circular spiral pattern is preferred as it has several advantages including simple and straightforward manufacture process and is concentric or near concentric which will be particularly advantageous in how the composite material and the synthetic fibre unit 100 operates. The spiral configurations of adjacent electrical conducting elements 15 should be arranged such that the electrical current in adjacent spirals in adjacent electrical conducting elements flow in the same direction which may be clockwise or anti-clockwise. The electrical current should be a direct current.

[0046] An elastic layer 5 is placed between two adjacent conductive layers 10, and the elastic layer may be an elastomer or elastic organic polymer. Examples of a suitable elastomer or elastic organic polymer includes silica gel or silicone gel. The silica gel or silicone gel used for the elastic layer may have a Shore A hardness value in the range of 0 to 30 and should be lower than the Shore A

hardness value of the material used for the substrate layer 20. A plurality of conductive layers 10 and elastic layers 5 are elastically stacked to form the composite material. The elastic layer 5 may have a thickness in the micrometre to millimetre range, for example from 10 micrometres to 2 millimetres.

5 [0047] In an embodiment, both the substrate layer 20 and the elastic layer 5 are formed with silica gel or silicone gel of differing hardness. The silica gel or silicone gel for both should have a Shore A hardness value from 0 to 30, but the silica gel or silicone gel for the elastic layer 5 should have a lower Shore A hardness value than that of the substrate layer 20. Advantageously, as silica gel or silicone gel has  
10 weak adhesive properties on its own, the formed conductive layers 10 and elastic layer 5 may simply be stacked together to form the stack of layers without needing additional adhesive. However, in certain embodiments additional adhesive or attachment means may be used to provide greater strength.

[0048] The composite material has an electrical connection inlet 45 to allow the  
15 current to flow into the composite material, an electrical connection outlet 50, and a plurality of intermediate electrical connectors 60. The plurality of intermediate electrical connectors 60 is arranged to allow the electrical connection inlet 45 and the electrical connection outlet 50 to be electrically connected to each of the electrical conducting element 15 of the plurality of conductive layers 10 in a  
20 parallel circuit arrangement.

[0049] Each of the electrical conducting element 15 has a first terminal end and a second terminal end at the perimeter region of the substrate layer 20. The first terminal end and the second terminal end thus form the two ends (or start and end) of the double spiral electrical conducting element 15. Each of the first  
25 terminal end is electrically connected in parallel to the electrical connection inlet 45 via an intermediate electrical connector 60 and each of the second terminal end is electrically connected in parallel to the electrical connection outlet 50 via at least another intermediate electrical connector 60. In an embodiment, one intermediate electrical connector 60A is used to connect all of the first terminal ends of all the  
30 electrical conducting elements 15 and another intermediate electrical connector 60B is used to connect all of the second terminal ends of all the electrical conducting elements 15. Each of the first terminal end and second terminal end

may be located proximal or away from each other. In an embodiment, the first terminal ends of the electrical conducting elements are aligned with each other and the second terminal ends of the electrical conducting elements are aligned with each other, and the plurality of intermediate electrical connectors are aligned (for example parallel) to each other. In an embodiment, the electrical current may be a direct current and the electrical conducting elements 15, electrical connection inlet 45, electrical connection outlet 50, and intermediate electrical connectors 60 are configured to be suitable for a direct current.

[0050] Without being limited by theory, as may be seen in FIG. 2 and FIG. 3, the direction of the current of each electrical conducting element 15 in each (and adjacent) conductive layer 15 are arranged in the same direction and may be considered regular vortex lines ( $r = a\theta$ ) while the adjacent currents in each electrical conducting element 15 are in opposite directions. As the direction of the current in the double spiral arrangement is opposite in the same electrical conducting element 15 and conductive layer 10, there is a repelling force when a current flows through the electrical conducting element 15 and it stretches the conductive layer 10 and attached elastic layer 5. For electrical conducting elements 15 on adjacent conductive layers 10, the direction of the current is the same hence when a current flows through the electrical conducting elements 15, there is an attractive force between adjacent electrical conducting elements 15 and compresses the elastic layer 5 between the adjacent conductive layers 10.

[0051] The electrical connection inlet 45 and electrical connection outlet 50 may be an electrical contact, electrical wire, or any other suitable means that allow for a current to enter and exit the composite material, and may be carbon-based, metal-based or any other suitable electrical conductor. The intermediate electrical connectors 60 may be an electrical wire or any other suitable means that allows for the current to flow between the conductive layers 10, may be carbon-based, metal-based or any other suitable electrical conductor. The electrical connection inlet 45, electrical connection outlet 50, and intermediate electrical connectors 60 may use carbon-based conductive material including graphene or metal-based conductive material including copper, aluminium, zinc, nickel, iron, lead, silver, gold, steel, and alloys of these metals like brass and bronze.

[0052] The arrangement of the electrical elements and the convention flow of the current may be exemplified in an example shown in FIG. 2 and FIG. 3. In FIG. 2 and FIG. 3, the positive terminal is labelled as the electrical connection inlet 45 and the negative terminal is labelled as the electrical connection outlet 50 and may be switched. FIG. 2 and FIG. 3 show an exploded view of an embodiment of the composite material having three elastic layers 5 and three conductive layers 10 which alternate with each other. This forms three elastic-insulating conductive layers. FIG. 3 shows only the electrical conducting elements 15. FIG. 2 and FIG. 3 shows the conventional current flow with arrows to aid in the understanding of the embodiments described herein. It will be appreciated that the number of layers 5, 10 can differ, and the flow of the current can be in either direction.

[0053] The electrical conducting elements 15, the electrical connection inlet 45, electrical connection outlet 50, and intermediate electrical connectors 60 are arranged in a parallel circuit. Each electrical conducting element 15 is arranged in a double spiral configuration pattern within each conductive layer 10 from a perimeter region of the substrate layer to a centre region of the substrate layer and back to the perimeter region. The double spiral configuration is termed as such because there is a first spiral 15A from the perimeter region to the centre region of the substrate layer 20, a spiral turn 15C, and a second spiral from the centre region to the perimeter region of the substrate layer 20. As may be seen in FIG. 2 and FIG. 3 the double spiral pattern in each electrical conducting element 15 alternates between the first spiral 15A and the second spiral 15B as the spiral is viewed from the perimeter to the centre and vice versa. When the current flows through the electrical conducting elements 15, the direction of the current in adjacent horizontal spirals of the double spiral configuration in each electrical conducting element 15 is in the opposite direction (i.e. one spiral is in a clockwise direction and the adjacent spiral is the anti-clockwise direction). As a result, there is a repulsion force between the adjacent spirals in the same electrical conducting element 15 and stretches the attached elastic layer 5 and the substrate layer 10 in a radial direction 75 as indicated in FIG. 2.

[0054] In the example shown in FIG. 2 and FIG. 3, the double spiral arrangement of the electrical conducting element 15 starts and ends proximal to

each other at the perimeter region, however this is not necessary, and the two ends of the double spiral arrangement may be located apart from each other. FIG. 2 and FIG. 3 shows the simplest placement where all the ends of the electrical conducting elements 15 are stacked above each other and two intermediate electrical connectors 60A, 60B are used to connect the ends of the electrical conducting elements 15. Hence, all of the electrical conducting elements 15 are electrically connected with the electrical connection inlet 45, electrical connection outlet 50 in a parallel circuit.

[0055] The spiral configurations of adjacent electrical conducting elements 15 are arranged such that the electrical current in adjacent spirals in adjacent electrical conducting elements flow in the same direction which may be clockwise or anti-clockwise. FIG. 2 and FIG. 3 shows an embodiment where the spiral configurations of the electrical conducting elements 15 are identical and stacked directly on top of each other (i.e. the spiral configurations are aligned). As a result, the direction of the current flow in the adjacent (top and/or bottom) vertical spirals in adjacent electrical conducting elements 15 are in the same direction which may be clockwise and anti-clockwise. Hence, there is an attractive force between the adjacent spirals of the adjacent electrical conducting elements 15 and compresses the elastic layer 5 between the adjacent conductive layers 10. It will be appreciated that the spiral configurations of adjacent electrical conducting elements 15 need not be identical as long as the adjacent spirals of adjacent electrical conducting elements 15 have the current flowing in the same direction. Advantageously, in embodiments where the spiral configurations of adjacent electrical conducting elements 15 are identical and aligned together, this facilitates ease of manufacturing and joining the electrical connections with the electrical connection inlet 45, electrical connection outlet, and intermediate electrical connectors 60, and the mass production of the composite material and synthetic fibre unit 100.

[0056] In an embodiment, the conductive layers 10 and elastic layer/s 5 have a generally cylindrical shape. When the layers 5, 10 are stacked together, the stack of layers or composite material would also be generally cylindrical in shape. A generally cylindrical shape refers to the object having at least 70% of the object

having a cylindrical shape, preferably at least 80% of the object having a cylindrical shape, more preferably at least 90% of the object having a cylindrical shape, even more preferably at least 95% of the object having a cylindrical shape, and also includes the object having a cylindrical shape. Since the cylindrical shape has a circular cross-section, it will be preferred to have a circular spiral pattern.

[0057] The composite material may be considered an elastic conductive actuator as the composite material will change its shape and move with the passage of current into the composite material as shown in FIG. 4 and FIG. 5. As the strength of elastic materials like silica gel is limited, it may be necessary to reinforce the outer surface of the stack of layers in order to provide sufficient tension to hold the deformed material and to restore the material to its original state.

[0058] An outer elastic cover (or layer) 25 and a strength supporting structure 30 are disposed outside the composite material (or elastic conductive actuator) to form a synthetic fibre unit 100 (or an electric actuator fibre unit). The support structure 30 may be made up of a plurality of axial filaments 35 and a plurality of lateral fibre filaments 40.

[0059] Without being limited by theory, it is believed that for each conductive layer due to the double spiral arrangement of the electrical conducting elements 15, after a voltage is applied to the circuit, a current flows through the composite material via the electrical connection inlet 45, electrical connection outlet 50, electrical conducting elements 15 and the intermediate electrical connectors 60 as illustrated in the simplified embodiment in FIG. 2 and FIG. 3. This produces a repulsive force between the current flow in the spiral pattern and translates to a lateral stretching force on the substrate layer 20 and conductive layer 10. Thus, the substrate layer 20 (and conductive layer 10) is stretched sideways as indicated by the arrow 75 in FIG. 2. When the current is reduced (including stopped which is equivalent to reducing to zero), the lateral stretching force on the substrate layer 20 decreases and the substrate layer 20 returns towards its original shape.

[0060] For adjacent conductive layers 10, this generates an electromagnetic attraction between the adjacent conductive layers 10 and generates a contraction force between the conductive layers 10 to overcome the elasticity of the elastic layer 5 and preferably the elastic substrate layer 20. Thus, the elastic layer 5, and

preferably elastic substrate layer, are compressed and the stack of layers are compressed as indicated by the arrow 80 in FIG. 2. When the current is reduced (including stopped which is equivalent to reducing to zero), the compression force on the elastic layer 5, and preferably substrate layer 20, decreases and returns to their original shape.

[0061] From a macroscopic point of view, assuming the stack of layers forms a cylindrical structure, the cylinder will receive an axial contraction force as indicated by arrow 80 in FIG. 2 and a lateral expansion force (or radial expansion force for a cylindrical structure) as indicated by arrow 75 in FIG. 2 after the current is applied.

The deformed cylinder will thus have a smaller axial dimension and a larger lateral (or radial) dimension (i.e. the cylinder contracts axially and expands radially). After the current has been cut off, the cylinder will return to its original shape and size due to the elasticity of the elastic layer 5 and preferably substrate layer 20. FIG. 4 shows the cylindrical shaped synthetic fibre unit 100 and FIG. 5 shows the deformed cylindrical shaped synthetic fibre unit 100 when a current passes through the synthetic fibre unit 100. In FIG. 5, it may be seen that the synthetic fibre unit 100 is compressed axially and expanded radially. When the current is stopped, the synthetic fibre unit 100 is restored to the original state in FIG. 4. The current may also be reduced or increased that will weaken or strengthen respectively the attractive and repulsive forces acting within the synthetic fibre unit 100.

[0062] The outer elastic cover 25 may be used to enclose the inner soft elastic composite material and allows it to expand laterally when a current is passed through the composite material and restore to the original state after the current is stopped. The outer elastic cover 25 helps the composite material maintain its stacking during the electrically actuated deformation.

[0063] In an example, the axial filaments 35 are high-strength fibres arranged along the axial direction and may be applied to the outer surface of the outer elastic cover 25. The axial filaments 35 may be carbon fibres or any other suitable material that has the required strength and flexibility. These axial filaments 35 extend along the longitudinal side and joins at the opposite ends (top and bottom) of the cylindrical shaped stack of layers shown in FIG. 1. It will be appreciated that

the arrangement of axial filaments 35 are applicable to other shapes as well. The axial filaments 35 provide strength and tension to support the composite material and should have a certain degree of flexibility to bend. The axial filaments 35 limit the length of the synthetic fibre unit 100 when it is not energised (i.e. no current is passed through) as in FIG. 4. When the synthetic fibre unit 100 is energised, the axial filaments 35 bend to allow the composite material and synthetic fibre unit 100 to be compressed in an axial direction (arrow 80 in FIG. 2 and FIG. 5). When the electric current is stopped, the composite material and synthetic fibre unit 100 uncompresses itself axially (arrow direction 80) to restore the composite material and synthetic fibre unit 100 to its original shape in FIG. 4.

[0064] A plurality of lateral fibre filaments 40 may be distributed spaced apart along the longitudinal length of the synthetic fibre unit 100 as shown in FIG. 2 and FIG. 4. The lateral fibre elements 40 may be high strength fibres. For example, carbon fibre filaments or any other suitable material with the required strength.

The lateral fibre elements 40 limit the lateral expansion of the composite material including the elastic layer 5 and substrate layer 20. The lateral fibre elements 40 may be used to create expandable segments 41 and non-expandable segments 42 and is most clearly seen in FIG. 4 and FIG. 5. The expandable segments 41 refer to the lateral expansion of the composite material or synthetic fibre unit 100 as exemplified in FIG. 4. For example, each non-expandable segment may be considered to have a set of lateral fibre filament 40 as shown in FIG. 4 and FIG. 5. In an embodiment, each set may contain one lateral fibre filament 40 coiled a few times around the cylindrical shaped synthetic fibre unit 100. In another embodiment, each set may contain two or more lateral fibre filaments 40 coiled around the cylindrical shaped synthetic fibre unit 100.

[0065] The sets of lateral fibre filaments 40 may be spaced apart at equal intervals, with an increasing spacing interval from one end to the opposite end, or with an increasing spacing interval followed by a decreasing spacing interval from one end to the opposite end around the outer circumference (or perimeter more generally for other shapes) of the cylindrical shaped synthetic fibre unit 100. The spacing intervals of the lateral fibre filaments 40 largely depend on the end usage requirement of the synthetic fibre unit 100 and synthetic fibre body 200.

[0066] The lateral fibre elements 40 provide some resistance to the lateral expansion by the composite material. Hence, when the current is passed through the composite material, the part of the synthetic fibre unit 100 with the lateral fibre filaments 40 is less likely to expand laterally due to the lateral fibre filaments 40 compared to the part of the synthetic fibre unit 100 without the lateral fibre filaments which are able to expand without resistance. As the composite material (in particular the elastic layer 5) is elastic, the composite material can deform and expand laterally where there are no lateral fibre filaments 40 which is the point of least resistance compared to where there are lateral fibre filaments 40. Hence, the placement of the lateral fibre filaments 40 will form the non-expandable segments, and the sections without the lateral fibre filaments 40 forms the expandable segments of the synthetic fibre unit 100. It would be appreciated that these segments overlap partially and may not be completely distinct. After a current is passed through, the lateral fibre filaments 40, which are distributed in sets along the axial direction, form waves under the action of the electromagnetic force, advantageously increasing the contraction or shrinkage per unit length. The lateral expansion of the composite material may also cause the lateral fibre filaments 40 to move in the axial direction (i.e. up and down along the axial length of the cylindrical shaped synthetic fibre unit 100).

[0067] In the cylindrical shaped synthetic fibre unit 100, the axial filaments 35 and lateral (or radial more specifically with a circular cross-section) fibre filaments 40 are in orthogonal planes with the lateral fibre filaments 40 being in a circular ring whilst the axial filaments 35 are orthogonal to the circular ring. It will be appreciated that the synthetic fibre unit 100 may take other shapes but the orthogonal relationship of the axial filaments 35 and lateral fibre filaments 40 may be retained in the support structure for synthetic fibre units 100 of other shapes. The lateral fibre filaments 40 are thus considered to be arranged at intervals in the axial direction and the synthetic fibre unit 100 is segmented in the lateral direction.

[0068] In an embodiment, the expandable segments 41 contain the conductive layer 10 and the non-expandable segment 42 contains the elastic layer 5. This is not a strict requirement as without it the synthetic fibre unit 100 may still function

as intended and may be varied according to the requirements and use of the synthetic fibre unit 100.

[0069] To prevent the soft silica gel from extruding from the gap between the axial filaments 35 after tensioning, an outer elastic cover 25 is placed between the composite material and the axial filaments 35. The outer elastic layer 25 includes a fabric sheet and an outer elastic layer. The outer elastic layer is attached to the fabric sheet. The outer elastic layer may be an elastomer or an elastic organic polymer and have a Shore A hardness in the range from 0 to 30. In an example, the fabric sheet is a twill woven fabric and the outer elastic layer is a silica gel film layer, and thus the outer elastic cover 25 is made of a twill woven fabric and a silica gel film layer. The silica gel film layer in the outer elastic cover 25 may have a Shore A hardness in the range of 0 to 30. Other elastomers or elastic organic polymers like silicone gel may be used in the outer elastic layer as long as it has the required Shore A hardness value as described. Depending on the requirements and intended use of the synthetic fibre unit 100, the outer elastic layer may have a higher, lower or same Shore A hardness value as (i.e. harder, softer, or same strength) than the elastic layer 5.

[0070] In an embodiment, each of the elastic layer 5, substrate layer 20, and outer elastic layer independently comprises an elastomer or an elastic organic polymer.

In an embodiment, each of the elastic layer 5, substrate layer 20, and outer elastic layer independently comprises silica gel or silicone gel. The elastic layer 5, substrate layer 20, and outer elastic layer should each have a Shore A hardness value from 0 to 30. The elastic layer 5 should have a lower Shore A hardness value than that of the substrate layer 20. The relative softness of the outer elastic layer to the elastic layer 5 depends on the intended use of the composite material and synthetic fibre unit 100, and may have a higher, lower, or equal Shore A hardness value. It would be appreciated that the materials listed herein for the elastic layer 5, substrate layer 20, and outer elastic layer is to provide guidance on a suitable material and is a non-exhaustive list but should have a Shore A hardness value of 0 to 30.

[0071] FIG. 4 shows a view of the synthetic fibre unit 100 when no electrical current is passed through. FIG. 5 shows a view when electrical current is passing

through the synthetic fibre unit 100 and shows the compression of the synthetic fibre unit 100 axially and expansion laterally.

[0072] A plurality of synthetic fibre units 100 (or electric actuator fibre units) forms a synthetic fibre body 200 (or an electric actuator fibre body) as shown in FIG. 6. Multiple electric actuator fibre body units can be used in different configurations and combinations according to different action requirements to form an artificial muscle for a robot or other machine.

[0073] In an embodiment, the synthetic fibre units 100 may be arranged to form a fibre body 200 such that the laterally expandable segments 41 and the non-expandable segments 42 are arranged in parallel, hence the adjacent expandable segments are staggered.

[0074] The electrically actuated (synthetic) fibre units 100 may be arranged in a planar arrangement, an annular arrangement, a cylindrical arrangement, other regular and specific arrangements, and in any combinations thereof according to the intended use as required. The synthetic fibre units 100 in the arrangement may be identical, different or a mixture of identical and different synthetic fibre units 100 to cater to the intended use. FIG. 6 shows three sets of synthetic fibre units 100 arranged in a planar arrangement. The synthetic fibre units 100 may also be arranged in a circular or cylindrical arrangement.

[0075] In an embodiment, if the synthetic fibre units 100 and fibre body 200 are applied to a joint, the synthetic fibre units 100 may be arranged in a cylindrical layout. The synthetic fibre units 100 on opposite sides of the cylindrical layout may be different for a joint. The synthetic fibre unit 100 on one side may contract and/or expand more and the synthetic fibre unit 100 on the opposite side may contract and/or expand less. Advantageously, the use of synthetic fibre units 100 with different ability to contract and expand more accurately mimics the motion structure of a human or animal joint, and is thus a more suitable replacement.

[0076] A cooling system may be provided with the synthetic fibre body 200 to cool or dissipate the heat generated by the electrical actuation of the synthetic fibre body 200 and synthetic fibre units 100. For example, the cooling system may be placed within the annularly arranged synthetic fibre units 100 or on its exterior

depending on the end use requirements. The cooling system may be a closed loop cooling system or other suitable cooling system.

[0077] The embodiments described herein may form an artificial cylindrical material that is able to be telescopically deformed by an electric drive thereby functioning like a muscle movement function which can be used in robots.

[0078] In the process of constructing bionic muscles, a large number of the synthetic fibre units 100 can be used as "Muscle Fibres". It should be noted that the laterally expandable segments of these fibres and the non-expandable annular fibre segments of adjacent fibres are arranged in parallel, i.e. the adjacent expandable segments are staggered.

## CLAIMS

[Claim 1] A composite material comprising:

a plurality of conductive layers, each conductive layer comprises a substrate layer and an electrical conducting element attached to the substrate layer,

5 wherein the electrical conducting element on each conductive layer is arranged in a spiral configuration to allow flow of an electrical current from a perimeter region of the substrate layer to a centre region of the substrate layer and back to the perimeter region, wherein the spiral configurations of adjacent electrical conducting elements are arranged such that the electrical current in adjacent spirals in adjacent electrical conducting elements flow in a direction;

10 at least one elastic layer attached between two adjacent conductive layers of the plurality of conductive layers to form a stack of layers;

an electrical connection inlet;

an electrical connection outlet; and

15 a plurality of intermediate electrical connectors, arranged to allow the electrical connection inlet and the electrical connection outlet to be electrically connected to each of the electrical conducting element of the plurality of conductive layers in a parallel circuit arrangement.

20 [Claim 2] The composite material according to claim 1, wherein there is an equal number of conductive layers and elastic layers.

[Claim 3] The composite material according to claim 1 or claim 2, wherein the electrical conducting element, the electrical connection inlet, the electrical connection outlet, and the plurality of intermediate electrical connectors is each  
25 independently selected from the group consisting of a carbon-based electrical conductor and a metal-based electrical conductor.

[Claim 4] The composite material according to any one of claims 1 to 3,  
30 wherein the substrate layer is an elastomer or an elastic organic polymer, preferably the substrate layer has a Shore A hardness value from 0 to 30, and more preferably the substrate layer is an electrical insulator.

[Claim 5] The composite material according to claim 4, wherein the substrate layer comprises silica gel or silicone gel.

5 [Claim 6] The composite material according to any one of claims 1 to 5, wherein the at least one elastic layer is an insulator and is an elastomer or an elastic organic polymer, wherein the elastic layer has a Shore A hardness value that is lower than the Shore A hardness value of the substrate layer, preferably the Shore A hardness value of the elastic layer is from 0 to 30.

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[Claim 7] The composite material according to claim 6, wherein the elastic layer comprises silica gel or silicone gel.

15 [Claim 8] The composite material according to any one of claims 1 to 7, wherein the plurality of conductive layers and the at least one elastic layer have a generally cylindrical shape.

[Claim 9] The composite material according to any one of claims 1 to 8,  
20 wherein each of the electrical conducting element comprises a first terminal end and a second terminal end located proximal to each other at the perimeter region of the substrate layer, each of the first terminal end is electrically connected in parallel to the electrical connection inlet via at least one of the plurality of intermediate electrical connectors and each of the second terminal end is  
25 electrically connected in parallel to the electrical connection outlet via at least one of the plurality of intermediate electrical connectors, preferably the first terminal ends of the electrical conducting elements are aligned with each other and the second terminal ends of the electrical conducting elements are aligned with each other, and the plurality of intermediate electrical connectors are parallel to each  
30 other.

[Claim 10] The composite material according to any one of claims 1 to 9, wherein the spiral configuration is identical and aligned on each electrical

conducting element such that the electrical current in adjacent spirals in adjacent electrical conducting elements flow in the direction.

[Claim 11] The composite material according to any one of claims 1 to 10,  
5 wherein the electrical current is a direct current.

[Claim 12] A synthetic fibre unit comprising the composite material according to any one of claims 1 to 11; an outer elastic cover to wrap around the composite material; and a support structure to attach the outer elastic cover to the stack of  
10 layers, the outer elastic cover comprising a fabric sheet and an outer elastic layer, the outer elastic layer is an elastomer or an elastic organic polymer, the outer elastic layer having a Shore A hardness value from 0 to 30.

[Claim 13] The synthetic fibre unit according to claim 12, wherein the support  
15 structure comprises a plurality of axial filaments and a plurality of lateral fibre filaments, wherein the plurality of axial filaments and the plurality of lateral fibre filaments are generally in orthogonal planes with respect to each other.

[Claim 14] The synthetic fibre unit according to claim 13, wherein the plurality of  
20 axial filaments ends at opposite faces of the synthetic fibre unit and attaches the outer elastic cover to the stack of layers and/or the plurality of lateral fibre elements is distributed in a plurality of sets in spaced intervals.

[Claim 15] The synthetic fibre unit according to any one of claims 13 or 14,  
25 wherein the plurality of axial filaments and the plurality of lateral fibre filaments are high strength fibres, preferably carbon fibres.

[Claim 16] A synthetic fibre body comprising a plurality of synthetic fibre units according to any one of claims 12 to 15, and a cooling system.

30 [Claim 17] The synthetic fibre body according to claim 16, wherein the plurality of synthetic fibre units is arranged in a planar arrangement, a circular arrangement, a cylindrical arrangement, other regular arrangement, in any combinations thereof.

[Claim 18] The synthetic fibre body according to claim 16 or claim 17, wherein each synthetic fibre unit in the plurality of synthetic fibre units are identical, different, or a mixture.

5 [Claim 19] The synthetic fibre body according to claim 18, wherein the plurality of synthetic fibre units comprises a first synthetic fibre unit and a second synthetic fibre unit, the first synthetic fibre unit and the second synthetic fibre unit are arranged on opposite sides, wherein the first synthetic fibre unit and the second  
10 synthetic fibre unit are configured such that the first synthetic fibre unit shrinks and/or expand less than the second synthetic fibre unit.

[Claim 20] A method of operating the synthetic fibre unit according to any one of claims 12 to 15 or the synthetic fibre body according to any one of claims 16 to 19,  
15 the method comprising:

passing an electrical current into the synthetic fibre unit according to any one of claims 12 to 15 or the synthetic fibre body according to any one of claims 16 to 19, via the electrical connection inlet and out of the synthetic fibre unit via the electrical connection outlet, preferably the electrical current is a direct current;

20 compressing the at least one elastic layer attached between two conductive layers due to the passing of the electrical current;

expanding the substrate layer due to the passing of the electrical current; and optionally reducing the electrical current; and expanding the at least one elastic layer and compressing the substrate layer.