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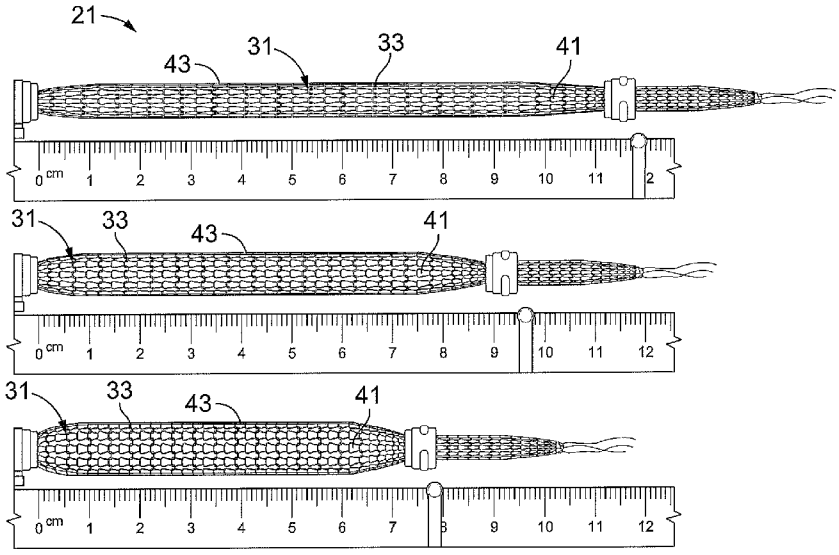


FIG. 1

(57) **Abstract**: Disclosed are a system and methods for actuating an object. The system includes a knitted sleeve within which is disposed a pressurizable bladder.

WO 2015/066286 A1

SYSTEM AND METHODS FOR ACTUATING AN OBJECT

CROSS-REFERENCE TO RELATED PATENTS

This application claims the benefit of U.S. Provisional Application No. 61/899,183 filed November 2, 2013.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

BACKGROUND OF THE INVENTION

Artificial muscle actuators are used in various applications, including robotics, biomimetic systems, medical devices, and aerospace systems. Artificial muscles are designed to approximate biological muscles in shape and motion. They function as tensile actuators, usually with little or no ability to apply compressive force, and, as a result, may be constructed from soft and/or lightweight materials. Among the fluidic artificial muscles, which are controlled by the application of pressurized gas or liquid, force-to-weight and power-to-weight ratios can be quite high, but maximum contraction is usually limited to 40% and often less.

The most common type of fluidic muscle, the "McKibben muscle", is relatively easy to manufacture. The McKibben muscle consists of a tubular bladder, made of a material like rubber, with a pressure inlet at one end, enclosed in a braided, bias-woven fiber sleeve. Each fiber of the braided sleeve winds in a helical path around the bladder. The bladder and sleeve are clamped together at each end. When the bladder is pressurized, it presses outward on the sleeve, causing the sleeve to expand radially, increasing the fiber angle and decreasing the length of the muscle as the internal volume increases. Variations of this design include combining the bladder and sleeve by rubberizing the sleeve, and leaving the bladder ends disconnected from the sleeve. Various end fittings have been devised to transmit tensile force from the sleeve fibers

into the mounting points. Various versions of McKibben muscles are available commercially from companies including Festo and the Shadow Robot Company.

An ideal McKibben muscle is considered to contract theoretically up to 42%, at which point the volume contained inside the shell reaches a maximum. Further contraction reduces the volume of pressurized fluid it holds. However, in practice, McKibben muscles are often found to contract by about 30%. The motion is generally similar to that of a biological muscle on the ascending limb portion of its motion range. This limitation requires significant extra space to be allocated for the actuator, which can be cumbersome and limit the usefulness of the device.

Pleated pneumatic artificial muscles use a bladder material with high stiffness and tensile strength, with no braided sleeve, and numerous axial folds that confer a pleated tube shape when stretched, and a spherical shape when inflated. The maximum theoretical contraction has found to be 54%, and the practical maximum is 45% for this type of muscle.

The Paynter knitted muscle works on the same basic principle as the pleated pneumatic artificial muscle, but is designed with a separate bladder and sleeve, each having tubular ends and a roughly spherical expanded section at the center. The bladder is an elastomer and the sleeve is made by knitting a stiff fiber like Dacron or Kevlar in a tubular pattern, with looser stitches in the middle to make the expanded section. The bladder is disposed within the sleeve and pressurized to fully expand until stopped by the sleeve, then the bladder and sleeve are bonded together with an adhesive. The adhesive bonding prevents sliding of the fiber strand crossings in the sleeve, preserving the wide, square-shaped stitches near the center and tight stitches near the ends. Pleats form irregularly when the actuator is stretched, but can be improved by heating within a pleated mold.

Given the limitations of the various conventional systems, there is a demand for an artificial muscle having an improved ability to contract. The present invention satisfies this demand.

SUMMARY OF THE INVENTION

In certain embodiments, the present invention includes an actuator system for moving an object. The actuator system includes a knitted sleeve within which is disposed a fluidic bladder that can be pressurized with a fluid, i.e., a liquid or gas.

In certain embodiments, the knitted sleeve is made of a substantially inextensible yarn.

In certain embodiments, the knitted sleeve is made of an ultra-high molecular weight polyethylene

In certain embodiments, the knitted sleeve is made of a high-tensile yarn, such as a para-aramid or an aramid.

In certain embodiments, the knitted sleeve is made of a low coefficient-of-friction yarn.

In certain embodiments, the actuator system further includes a lubricant to reduce friction.

In certain embodiments, the knitted sleeve is a tubular knitted sleeve.

One object of the present invention is to provide an actuator system for use in any suitable device or application.

It is an advantage that certain embodiments of the actuator system of the present invention achieve maximum volume at a relatively high degree of contraction.

Another advantage of certain embodiments of the actuator system of the present invention is that it may be used in series with linear springs for actuating constant loads.

An additional advantage of certain embodiments of the present invention is that the actuator system or knit muscle can employ energy more efficiently to pull a weight or spring a greater distance than other artificial muscles.

The present invention and its attributes and advantages will be further understood and appreciated with reference to the detailed description below of presently contemplated embodiments, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments of the invention will be described in conjunction with the appended drawings provided to illustrate and not to the limit the invention.

FIG. 1 is a diagram of one embodiment of the present invention showing it in a stretched state (top), relaxed state (middle), and a pressurized state (bottom).

FIG. 2 is a drawing of a section of one embodiment of the present invention showing the knitted sleeve component identifying number of stitches (m) , number (n) of rows of stitches, stitch width (w), stitch height (h), and sleeve length (L) along the muscle axis.

FIG. 3 is a force curve showing force as a function of normalized length of an embodiment of the present invention and a McKibben muscle.

FIG. 4 illustrates a portion of an embodiment of the present invention.

FIG. 5 shows force curves for various embodiments of the present invention each including a different number of stitches (m) per row.

FIG. 6 is a diagram of one embodiment of the present invention identifying a stitch of strand thickness (t), stitch height (h), and stitch width (w); the length of the shaded section A-B is the length of strand section that forms one stitch, L_{row}/m.

FIG. 7 shows an ideal force curve and a force curve including bladder effects for one embodiment of the present invention.

FIG. 8 shows an ideal force curve and a force curve including bladder effects for a McKibben muscle.

FIG. 9 shows theoretical, extension, and contraction force curves from experimental data for one embodiment of the present invention.

FIG. 10 compares force curves for one embodiment of the present invention, a McKibben artificial muscle, and those for a rat, cat, frog, and a human.

DETAILED DESCRIPTION

In certain embodiments, the present invention provides a system 21 for actuating an object comprising a knitted sleeve 31 fitted about a pressurizable bladder 41. One embodiment of a system 21 according to the present invention is shown in FIG. 1, which

shows a knitted-sleeve fluidic artificial muscle comprising a knitted sleeve 31 including eight stitches per row of Spectra thread. To demonstrate the utility of the system 21, the embodiment illustrated in FIG. 1 is shown fully stretched (top), in a relaxed state (middle), and pressurized with a fluid (bottom).

In certain embodiments, the system 21 is a knitted-sleeve muscle including a separate bladder component 41 and sleeve component 31. In certain embodiments, the knitted sleeve 31 is a tubular-knit sleeve made from a thin strand of flexible but inextensible yarn. In certain embodiments, the inextensible yarn or fiber is an ultra-high molecular weight polyethylene (UHMWPE). When the bladder 41 is pressurized, the loops of fiber slide past each other, the dimensions of the rectangular cells in the stitch pattern of the knitted sleeves change, and the knitted sleeve expands. In certain preferred embodiments, the internal volume of the sleeve 31 reaches a maximum when its length has contracted at least 50% from its maximum extension. In certain embodiments, the internal volume of the sleeve 31 reaches maximum volume when its length is contracted by a percentage in the range of from about 50% to about 66% from its maximum extension. In certain embodiments, the sleeve is made from a fiber having a relatively low coefficient of friction in order to reduce hysteresis to an acceptable level.

In certain embodiments, the sleeve 31 is knitted with a thin strand of substantially inextensible yarn or cord made from high-modulus fiber. In certain embodiments, the knitted sleeve 31 is made using a tubular-knitting machine similar in design to those used for sock knitting. However, in a small-diameter actuator, the number of needles must be reduced, e.g., to 8 or 16 needles, in order to obtain sufficiently wide spacing in the mesh. Hobby knitting machines, designed for making "I-cord", may be adapted for this purpose. In larger-diameter actuators, the number of needles used and thus, the number of stitches per row, may be increased. In certain embodiments, when the actuator is contracted, the rectangular cells in the sleeve may have side lengths of about 2mm, depending on the bladder wall thickness and the fluid pressure. A thinner strand may permit greater contraction and extension. In certain embodiments, the knitted sleeve 31 is made from the thinnest strand that can reliably sustain the necessary tensile forces and sliding friction. In certain embodiments, the knitted sleeve 31 is made from high-tensile synthetics like para-aramids or aramids. In certain

embodiments, the knitted sleeve is made from fiber having a low coefficient-of-friction, for example, is polytetrafluoroethylene (PTFE). UHMWPE is a good compromise between high-tensile strength fibers and low coefficient-of-friction fibers. In certain embodiments, the fibers may be made from high-tensile synthetics such as aramids, low coefficient-of-friction fibers such as PTFE, or UHMWPE.

In certain embodiments, the bladder 41 may be cut to an appropriate length and slid inside the sleeve 31. Alternatively, the bladder 41 may be placed into the sleeve 31 during the knitting process. A pressure fitting may be pressed into one end of the bladder 41 and connected to a hose through one of the openings in the sleeve 31. Clamping bands may be placed over both ends of the sleeve 31, stretching the bladder 41 if bladder pre-strain is desired, and clamped down tightly.

The knitted-sleeve muscle may be connected to and form a component of a larger system by directly wrapping or tying the ends of the sleeve strand 31 to mounting points on the structure to be actuated - no additional connectors are necessary. In applications in which the actuator is used to control motion of a joint, as in many robotic applications, one end of the sleeve strand may be fed directly into a cam track to provide a desired torque curve. The force may then be transmitted directly through the strong and stiff fibers and does not rely on clamp friction. The bladder 41 may be pressurized with any working fluid, including any suitable liquid or gas, including, but not limited to, air, water, steam, or if the bladder 41 is made from an oil-resistant elastomer, hydraulic fluid. The maximum working pressure will depend on the size of the cells in the sleeve and the thickness of the bladder wall 43. In certain embodiments, the sleeve 31 is tightly knitted and the pressure is 150 psi or greater.

The sleeve 31 may be constructed with a simple tubular knit 3.3, such as a stockinette stitch, with any number of stitches in a row. Reducing the number of stitches below eight has a significant effect on the force curve and maximum contraction. In certain embodiments, the sleeve 31 may be constructed using a garter stitch, rib knit, or another variety of tubular knit. The sleeve 31 could also be constructed from distinct loops of fiber, one per row, with every loop in the row stitched simultaneously. This variation may require designing a custom knitting machine, as well

as finding a supplier of appropriate fiber loops. The same effect may be achieved with one fiber loop per cell (like chain maille) if the loops could be interconnected.

The bladder 41 may be made from any highly flexible material, including various kinds of synthetic or natural rubber. Any wall thickness, diameter, and bladder pre-strain may be used. In certain embodiments, the bladder 41 is not clamped to the sleeve at both ends. Greater contraction might be achieved by constraining the bladder length separately from the sleeve length, e.g., as done with the drag-in pneumatic artificial muscle (d-PAM). The pressure fitting can be placed at any point along the bladder 41, not just at an end, and multiple pressure fittings may be used. In place of clamps to hold the ends of the sleeve, wrappings of thread or tape may be used to apply the necessary constriction.

In contrast to the traditional McKibben muscle design, bonding the bladder 41 to the sleeve 31 or using a rubberized sleeve is not preferred, as this would prevent the sliding motion necessary for contraction of the actuator.

The actuator system 21 of the present invention knitted may be used in any of the devices of the type in which McKibben muscles are traditionally used. The actuator system 21 according to the present invention is especially useful in devices or applications in which space is constrained, because a shorter knitted-sleeve muscle can generate the same stroke length as a longer braided-sleeve muscle. Applications include prosthetics and other medical devices, industrial automation, aerospace vehicle actuators, and robotics.

As shown in the examples below, the force curve of the actuator system 21 of the present invention is flatter than that of a McKibben muscle, which has very high blocked force that drops off quickly when the muscle contracts slightly. Further, the actuator force of the actuator system 21 of the present invention rises somewhat during the initial portion of the stroke. Therefore, knitted-sleeve muscles may be more appropriate for placement in series with linear springs and may be simpler to control by position feedback.

Derivation of an Ideal Force Curve

Derivation of an ideal force curve for a knitted muscle requires specifying the geometric relationship between its length and its circumference, which together

determine the volume as a function of contraction. In this case, instead of the sinusoidal relationship created by helical strands, the length and circumference are related linearly because each section of the strand is aligned either parallel or perpendicular to the muscle axis. FIG. 2 shows the variables used to describe the geometry of the knitted sleeve 31. In a simplest model of a knitted sleeve, the sleeve 31 includes *n* rows, each made from a single strand that forms *m* stitches about the circumference of the muscle, with its ends connected to form a loop. The height of a stitch, which is the distance between rows, is *h* and the width of a stitch is *w*. The muscle length $L = nh$, and the circumference $C = mw$. Because each strand is substantially inextensible, the length of strand in one row is a constant L_{row}. The lengths of each stitch in a row can be added as follows:

$$L_{row} = m(2h + w)$$

$$w = \frac{L_{row}}{m} - 2h$$

This equation for *w* in terms of *h* forms the basis for calculating muscle volume as a function of length. The radius *r* can be calculated using the formula $r = \frac{mw}{2\pi} = \frac{1}{2\pi}(L_{row} - 2mh)$, which in turn can be used to calculate the volume *V*.

$$V = \pi r^2 L = \frac{L}{4\pi}(L_{row} - 2mh)^2$$

Expanding and substituting $L = nh$,

$$V = \frac{m^2 n}{\pi}h^3 - \frac{mnL_{row}}{\pi}h^2 + \frac{nL_{row}^2}{4\pi}h = \frac{m^2}{\pi n^2}L^3 - \frac{mL_{row}}{\pi n}L^2 + \frac{L_{row}^2}{4\pi}L$$

$$\frac{dV}{dL} = \frac{3m^2}{\pi n^2}L^2 - \frac{2mL_{row}}{\pi n}L + \frac{L_{row}^2}{4\pi}$$

Force *F* is taken to be the derivative of work done by the fluid source:

$$F = -P\frac{dV}{dL} = -\frac{P}{4\pi n^2}(12m^2L^2 - 8mnL_{row}L + n^2L_{row}^2)$$

Thus, the force output is quadratic in *L*, but instead of using one leg of an upward parabola, the knitted muscle force curve is a downward parabola with its peak in the center of the stroke range, as illustrated in FIG. 3.

To determine the free contraction, we calculate the length of the muscle at which its volume is maximized:

$$\frac{dV}{dL} = 0 = \frac{3m^2}{\pi n^2}L^2 - \frac{2mL_{row}}{\pi n}L + \frac{L_{row}^2}{4\pi} \qquad L_{free} = \frac{1}{3}\frac{nL_{row}}{m} \pm \frac{nL_{row}}{m}\sqrt{\frac{1}{9} - \frac{1}{12}}$$

$$= \frac{nL_{row}}{m}\left(\frac{1}{3} \pm \frac{1}{6}\right)$$

Since the maximum height of a row when the muscle is fully stretched is $h_{max} = \frac{L_{row}}{2m}$, the stretched muscle length is

$$L_{max} = nh_{max} = \frac{nL_{row}}{2m}$$

Combining those and choosing the solution at which volume is maximized, we find that $L_{free} = L_{max}/3$, one third of the stretched length. Therefore, the ideal knitted muscle could contract by up to 67%, compared with 42% for an ideal McKibben muscle.

Tubular-Knit Model

The model above assumes that each row of the knitted sleeve 31 consists of a separate yarn loop. In practice, there is no easy way to assemble such loops into a knitted tube. Instead, in certain embodiments, the knitted sleeve 31 is made using a technique known as tubular knitting or "knitting in the round," which is commonly used for making socks and other cylindrical fabric items. Instead of each row connecting to itself, the end of one row becomes the beginning of the next row, so that the entire piece is actually made from a single strand of yarn, making this design easy to produce on a common knitting machine. However, it also invalidates the assumption that each row runs circumferentially, perpendicular to the muscle axis. Instead, the stitches go around in a gradual spiral, with each section at a slight angle compared to the circumference (FIG. 4).

Making the appropriate changes to the sleeve geometry, the above equations are modified as follows:

$$L_{max} = nh_{max} = \frac{nL_{row}}{2m+1}$$

$$L_{row} = m(2h) + \sqrt{m^2w^2 + h^2} \qquad w^2 = \frac{1}{m^2}(L_{row}^2 - 4hmL_{row} + 4h^2m^2 - h^2)$$

$$r = \frac{mw}{2\pi} \qquad V = \pi r^2 L = \frac{L}{4\pi}\left(L_{row}^2 - 2hmL_{row} + h^2(4m^2-1)\right)$$

$$= \frac{1}{4\pi n^2}\left((4m^2-1)L^3 - 2mnL_{row}L^2 + L_{row}^2 n^2 L\right)$$

$$\frac{dV}{dL} = \frac{3}{4\pi n^2}(4m^2-1)L^2 - \frac{2m}{\pi n}L_{row}L + \frac{L_{row}^2}{4\pi}$$

$$F = -P\frac{dV}{dL} = -\frac{P}{4\pi n^2}(3(4m^2-1)L^2 - 8mnL_{row}L + L_{row}^2 n^2)$$

The change in the force curve (FIG. 5) is especially noticeable when the number of stitches per row is small, and may be safely neglected when $m > 16$.

Thick Strand Model

A second correction that can substantially improve the accuracy of the force model above is the assumption that the thread making up the sleeve has significant thickness *t*, which constrains both the maximum length and the maximum sleeve diameter, reducing the range of motion. FIG. 6 shows how the length of strand in one stitch, L_{row}/m, is no longer equal to $2h+w$ as before, but must include a correction for the thickness. Indicated paramaters are strand thickness *t*, stitch height *h*, and stitch width *w*. The length of the shaded section A-B is the length of strand section that forms one stitch, L_{row}/m.

$$\frac{L_{row}}{m} \approx 2(2t+h) + w$$

Given this assumption about strand length, the corrected force equation is:

$$F = -\frac{P}{4\pi n^2}\left(12L^2 + \left(32nt - 8\frac{L_{row}n}{m}\right)L + n^2\left(\frac{L_{row}^2}{m^2} - \frac{8tL_{row}}{m} + 16t^2\right)\right)$$

Inclusion of Bladder Effects

The inclusion of a rubber bladder with non-negligible thickness, along with its effects on the force output of the actuator, has been thoroughly studied for McKibben muscles. These results apply to a knit muscle. A force curve (FIG. 7) was generated by applying the methods described in Ball, E. and Garcia, E., "Effects of Geometric Variations on McKibben Pneumatic Artificial Muscles," Proc. SPIE, 2013 to the knit muscle model. FIG. 7 shows the predicted force-displacement curves for an 11 cm knitted-sleeve fluidic artificial muscle, maximum diameter during stroke 14.6 mm, at 80 psi. The ideal force curve is the ideal geometric case in which the bladder and strand thicknesses are insignificant, and reaches 67% displacement. The force including bladder effects curve includes the effects of a thick-walled rubber bladder with no pre-strain, with .2 mm strand thickness. Both curves neglect the tubular-knit correction described above. The predicted work done in one contraction stroke is 2.6 J. The force curve that takes into account bladder effect s lower overall than ideal, with reduced free contraction, but has a higher initial force near maximum length. (FIG. 7). Pre-straining the bladder could potentially increase actuator force and stroke.

FIG. 8 shows a force curve for equivalent a traditional McKibben muscle with the same length, diameter, and pressure as the knitted muscle system of FIG. 7. Including bladder effects, the work of one stroke is 2.3 J, less than the contraction work of the knitted muscle, even though an ideal McKibben muscle performs more work than an ideal knitted muscle.

Muscle Testing

A prototype knitted muscle was constructed for quasi-static testing, using the tubular-knitting technique described above. In this embodiment, the knitting machine used to make the knitted sleeve was an Addi Express Professional with 22 needles. The "yarn" must be thin and made from an inextensible high-modulus fiber, to best approximate the ideal model; Spectra (UHMWPE) fishing line rated to 50 lbf was used. UHMWPE is advantageous because of its combination of high stiffness and strength (allowing it to be thin) and its low coefficient of friction to reduce hysteresis.

The bladder was made of a thin polyethylene bag membrane, in order to reduce passive force effects from stretching of the bladder. In contrast to the construction of a

McKibben muscle, bonding the bladder to the sleeve or using a rubberized sleeve is not an option, as this would prevent the sliding motion of the sleeve threads necessary for contraction of the actuator.

The bladder was placed inside the sleeve and connected at the ends by circular clamps. A simple barbed hose fitting was clamped into one end to allow the application of pressurized air. The bladder was cut slightly shorter than the sleeve so that extra material was available at the ends (outside the clamps) for tying into mounting points on the object to be actuated. This attachment method allows tensile force to be transmitted through the stiff fibers directly, and does not rely on clamp friction to prevent stretching of the actuator. The prototype had a stretched length of 51.4 cm, m = 22, n = 49, maximum sleeve diameter 15.3 cm, and maximum bladder diameter roughly 8.5 cm.

Experimental Setup

The prototype knitted muscle was tied into an Instron tensile testing machine and quasi-static tensile tests were performed over the stroke length of the actuator on both the contraction and extension strokes in order to validate the theoretical force curves and estimate hysteresis. All tests were performed with the muscle pressurized to approximately 4 psi with air. Crosshead speed was 40 mm/minute for both extension and contraction.

FIG. 9 shows the result of tensile testing and the corresponding theoretical prediction. Maximum contraction observed in this test was 45%. Free contraction at 15 psi was measured at 51%. The increased contraction at higher pressure is likely due to stretching of the polyethylene bladder.

With reference to FIG. 9, the force curve of the prototype diverges from the theoretical prediction in several ways. First, extension force is about three times as high as contraction force at the same pressure, which suggests that friction has a more significant effect in this prototype than in a typical McKibben muscle. Second, maximum contraction is significantly lower than predicted; this is due partly to strand thickness effects, and may be caused partly by the maximum bladder diameter being less than the maximum sleeve diameter. Lastly, the data does not show the distinct "descending limb" portion of the curve when the muscle is near its maximum length. Instead, the

force appears to stay nearly constant over the first 25% contraction. This discrepancy is related to the progressive inflation of the muscle down its length.

A McKibben muscle has very high blocked force because at full length, its circumference varies as $\sin\theta$ and rises quickly with a slight increase in braid angle, but its length varies as $1 - cos\theta$ and so changes hardly at all with the initial increase in angle—thus, an initial small decrease in length comes with a large volume increase. However, the force drops off quickly once the muscle contracts slightly, so when the McKibben muscle is employed to lift a constant load, or to tension a spring, the initial high force is wasted. Once the force falls below the load, the rest of the stroke is unuseable. Because the knit muscle force curve is flatter than that of a McKibben muscle, and in fact the actuator force may rise somewhat during the initial portion of the stroke, knitted-sleeve muscles are more appropriate for use in series with linear springs and for actuating constant loads. Despite its lower maximum force and lower energy output per stroke, under the right circumstances, the knit muscle can employ that energy more efficiently to pull a weight or spring a greater distance. When any artificial muscle is used to actuate a joint, the torque can be made constant by changing the lever arm of the attachment point to balance the change in actuator force. But for a McKibben muscle, the necessary changes in lever arm or cam radius are much more extreme than for the relatively constant force output of a knit muscle.

Finally, knit muscles have greater similarity to the behavior of animals' skeletal muscle than other types of fluidic artificial muscle. FIG. 10 compares quasi-static force curves for animal muscles and fluidic artificial muscles.

Not only is the stroke length of a knit muscle closer to that of animal muscle than that of a McKibben muscle, the knit muscle also has an extended plateau region in which force output is nearly constant. This plateau area is used extensively in skeletal motion. Other fluidic artificial muscles have only an ascending limb, the leftmost portion of the force curve, in which force increases steadily with length, leaving other fluidic artificial muscles unable to mimic some functions of animal muscle.

While the disclosure is susceptible to various modifications and alternative forms, specific exemplary embodiments of the present invention have been shown by way of example in the drawings and have been described in detail. It should be understood,

however, that there is no intent to limit the disclosure to the particular embodiments disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the scope of the disclosure as defined by the appended claims.

5

CLAIMS

What is claimed is:

1. A system for actuating an object, comprising:
a fluid-pressurizable bladder; and
a knitted sleeve positioned generally around the bladder.

2. The system of claim 1, wherein the bladder and the knitted sleeve are configured to allow a sliding motion of stitches that form the knitted sleeve.

3. The system of claim 1, wherein the knitted sleeve is made from a thread made from an ultra-high molecular weight polyethylene (UHMWPE).

4. The system of claim 1, wherein the knitted sleeve is made from a thread made from a high-tensile synthetic.

5. The system of claim 4, wherein the high-tensile synthetic is a para aramid.

6. The system of claim 4, wherein the high-tensile synthetic is an aramid.

7. The system of claim 1, wherein the knitted sleeve is made from a thread made from a low coefficient-of-friction fiber.

8. The system of claim 7, wherein the low coefficient-of-friction fiber is polytetrafluoroethylene (PTFE).

9. The system of claim 1, wherein the knitted sleeve is made from a thread woven in a stockinette stitch.

10. The system of claim 1, wherein the knitted sleeve is made from a thread woven in a garter knit.

11. The system of claim 1, wherein the knitted sleeve is made from a thread woven in a rib knit.

12. The system of claim 1, wherein the knitted sleeve is made from a thread, using one distinct loop per row.

13. The system of claim 1, wherein the knitted sleeve is made from small loops of thread, using one loop for each unit cell.

14. The system of claim 1, wherein the knitted sleeve is made with a tubular knit.

15. The system of claim 1, wherein the knitted sleeve is made with a flat knit.

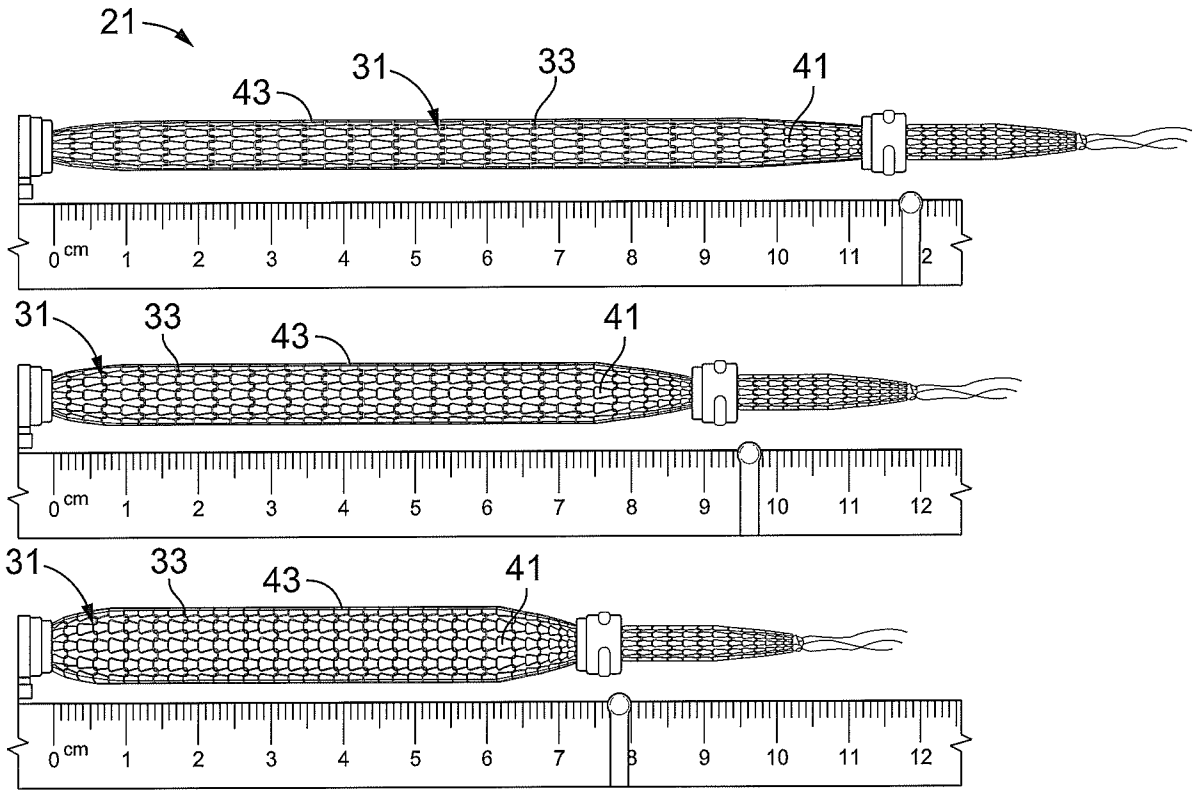

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0 cm 1 2 3 4 5 6 7 8 9 10 11 12
31
33
43
41
0 cm 1 2 3 4 5 6 7 8 9 10 11 12

FIG. 1

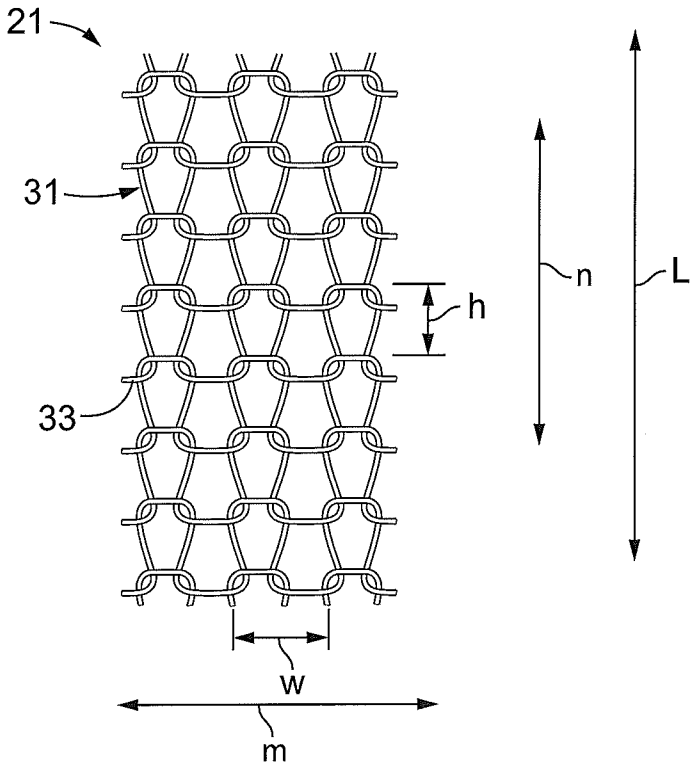

21
31
33
h
n
L
w
m

FIG. 2

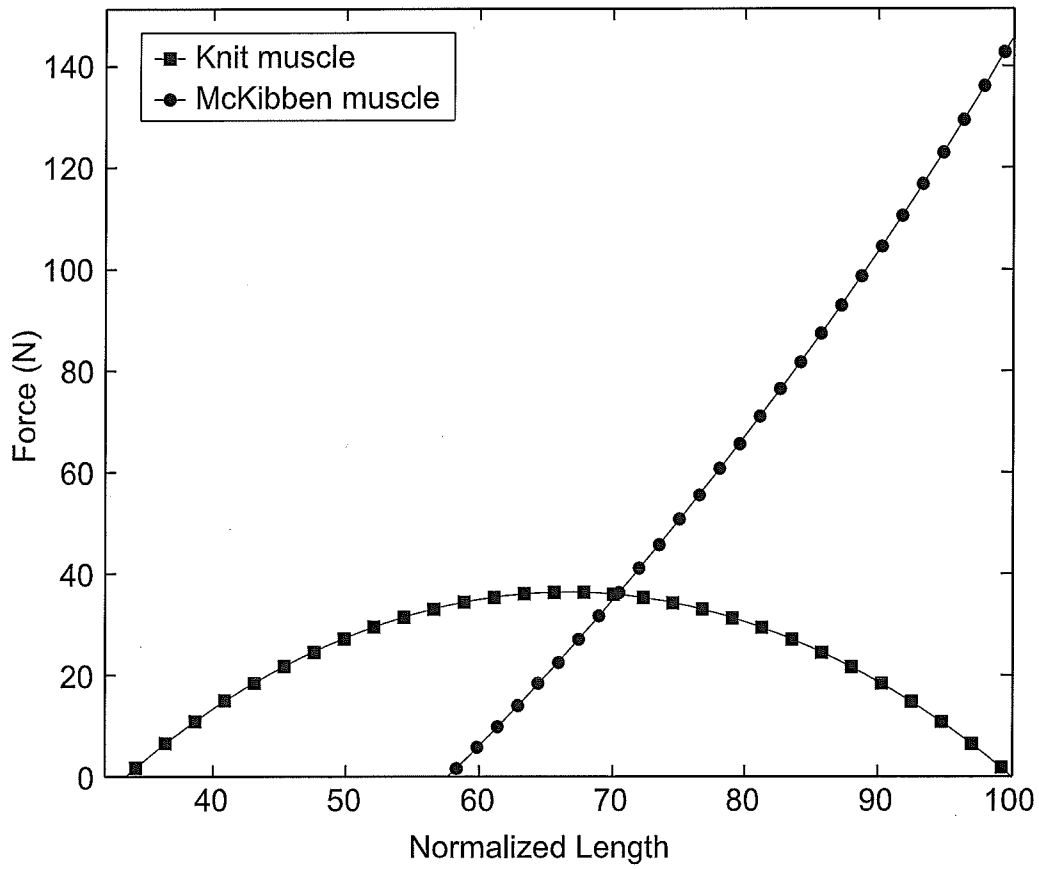

Knit muscle
McKibben muscle
Force (N)
Normalized Length
0
20
40
60
80
100
120
140
40
50
60
70
80
90
100

FIG. 3

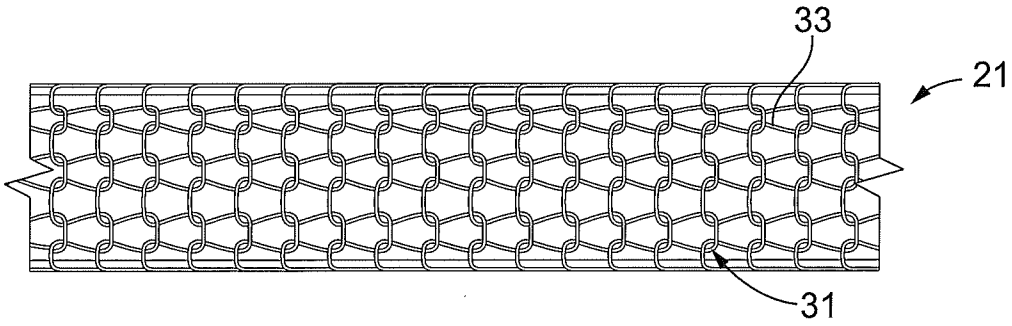

33
21
31

FIG. 4

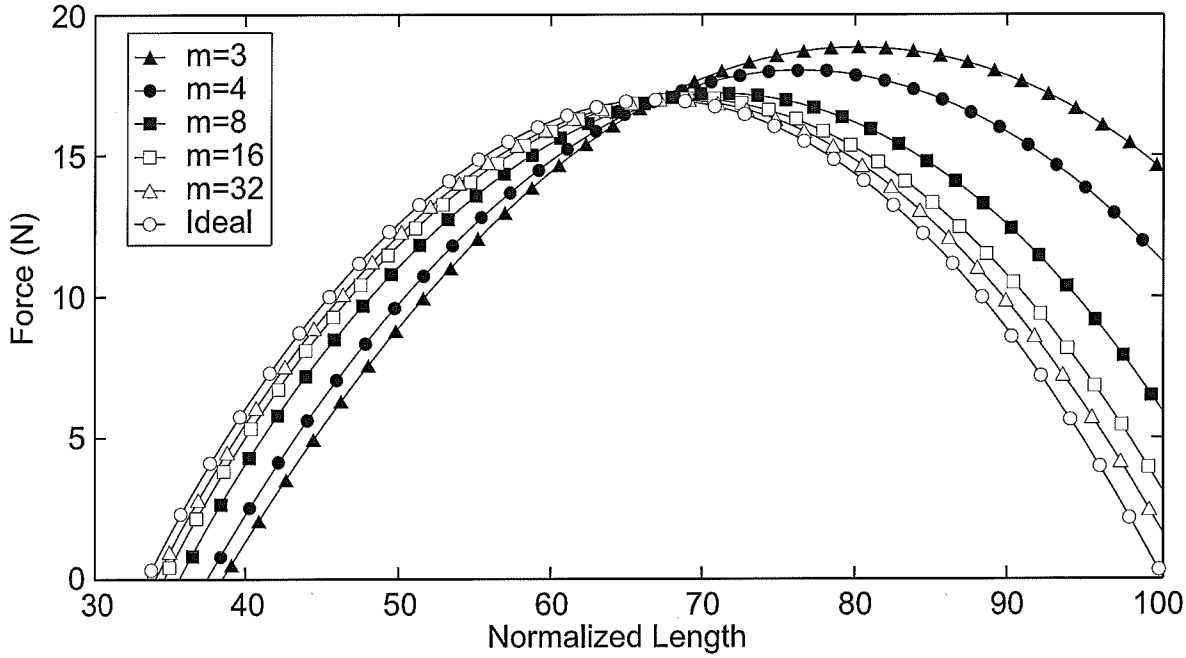

m=3
m=4
m=8
m=16
m=32
Ideal
Force (N)
Normalized Length
0
5
10
15
20
30
40
50
60
70
80
90
100

FIG. 5

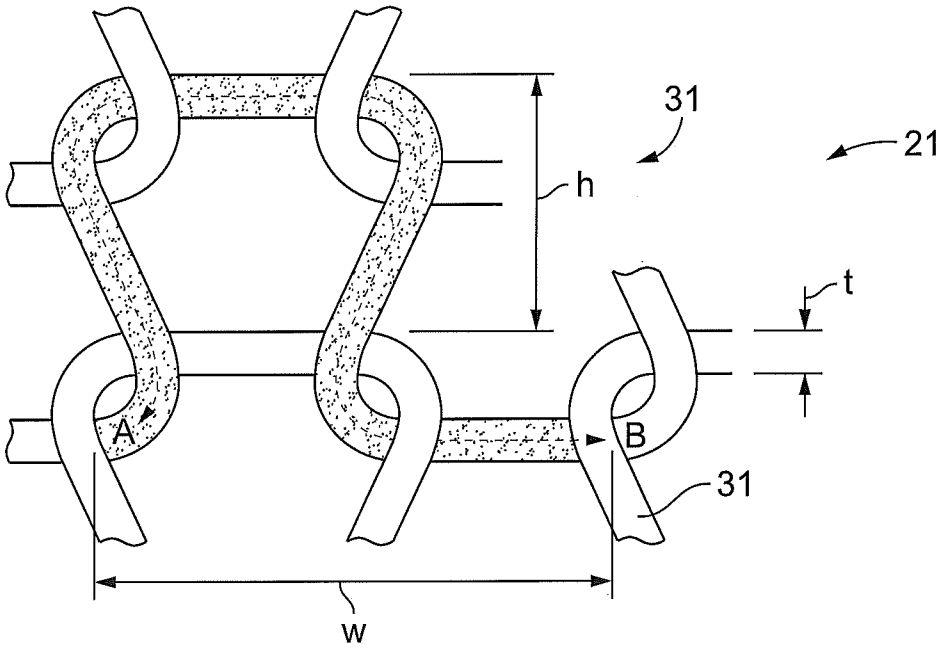

31
21
h
t
A
B
31
w

FIG. 6

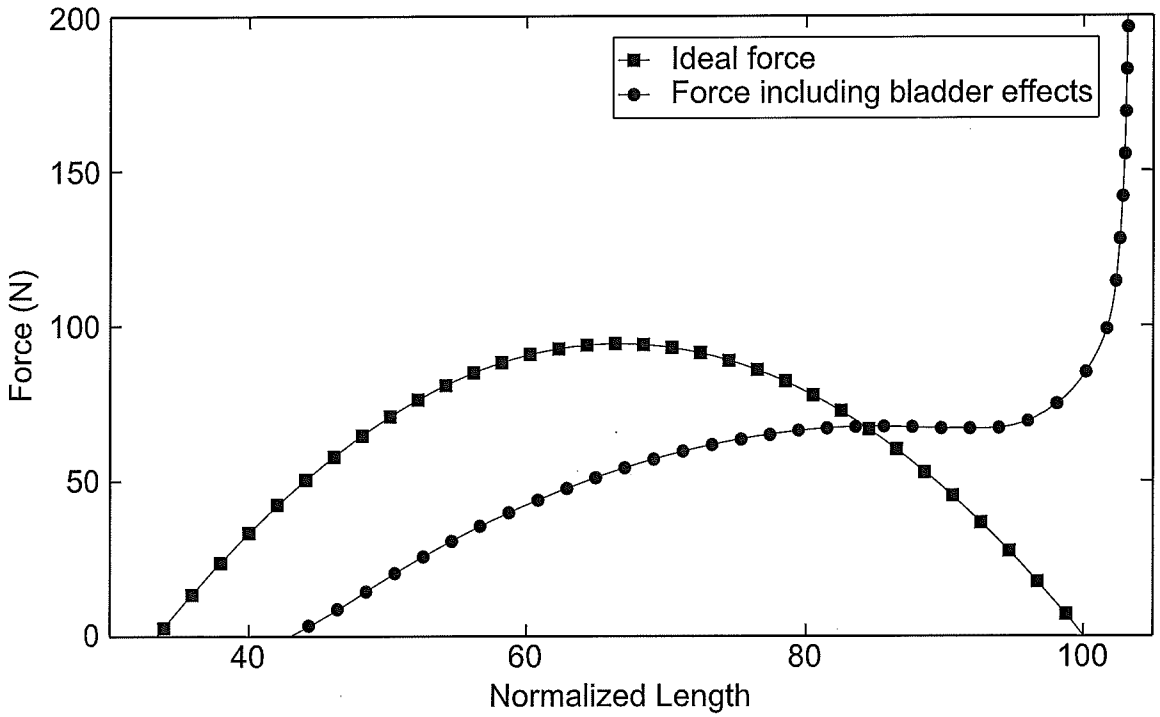

Ideal force
Force including bladder effects
Force (N)
Normalized Length
0
50
100
150
200
40
60
80
100

FIG. 7

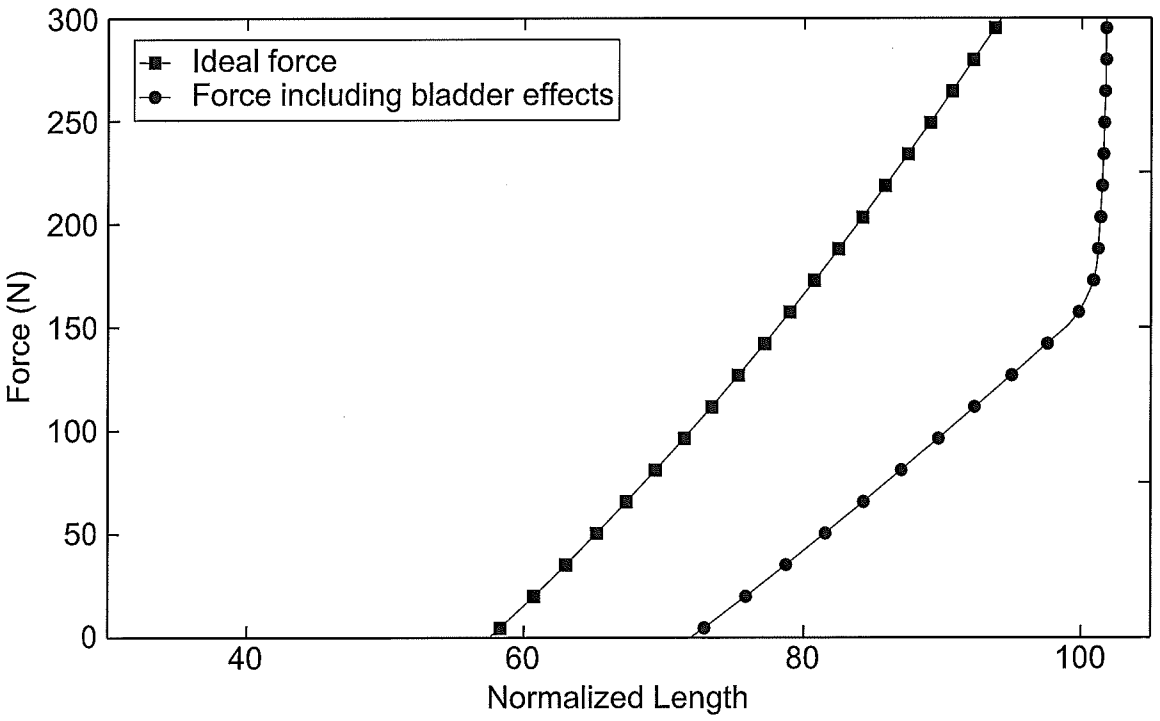

Ideal force
Force including bladder effects
Force (N)
Normalized Length
0
50
100
150
200
250
300
40
60
80
100

FIG. 8

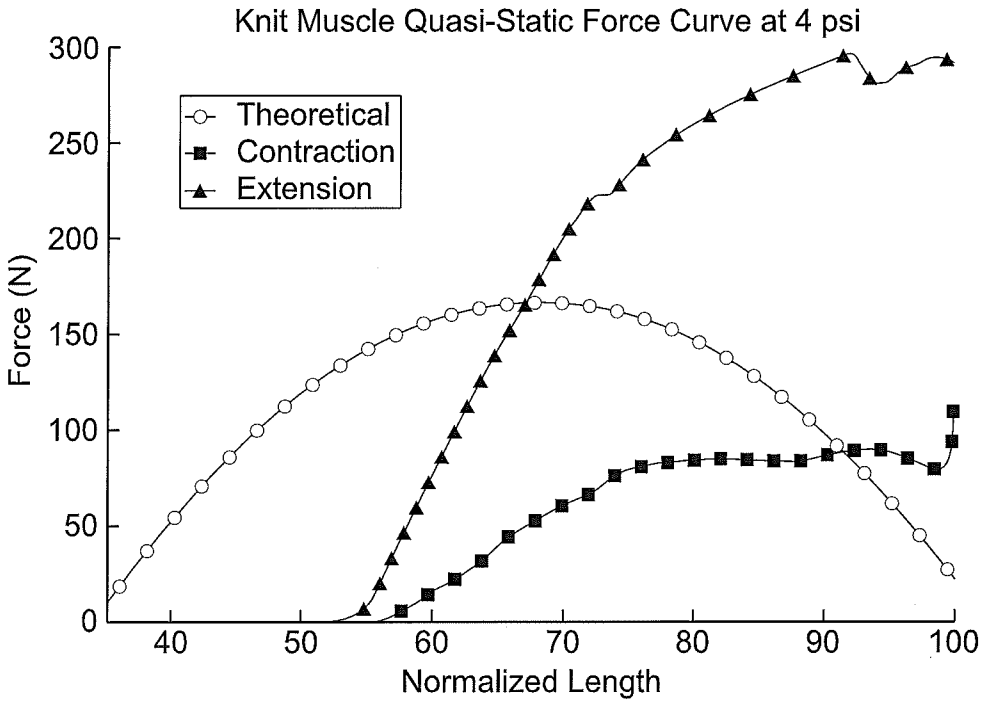

Knit Muscle Quasi-Static Force Curve at 4 psi
Theoretical
Contraction
Extension
Force (N)
Normalized Length
300
250
200
150
100
50
0
40
50
60
70
80
90
100

FIG. 9

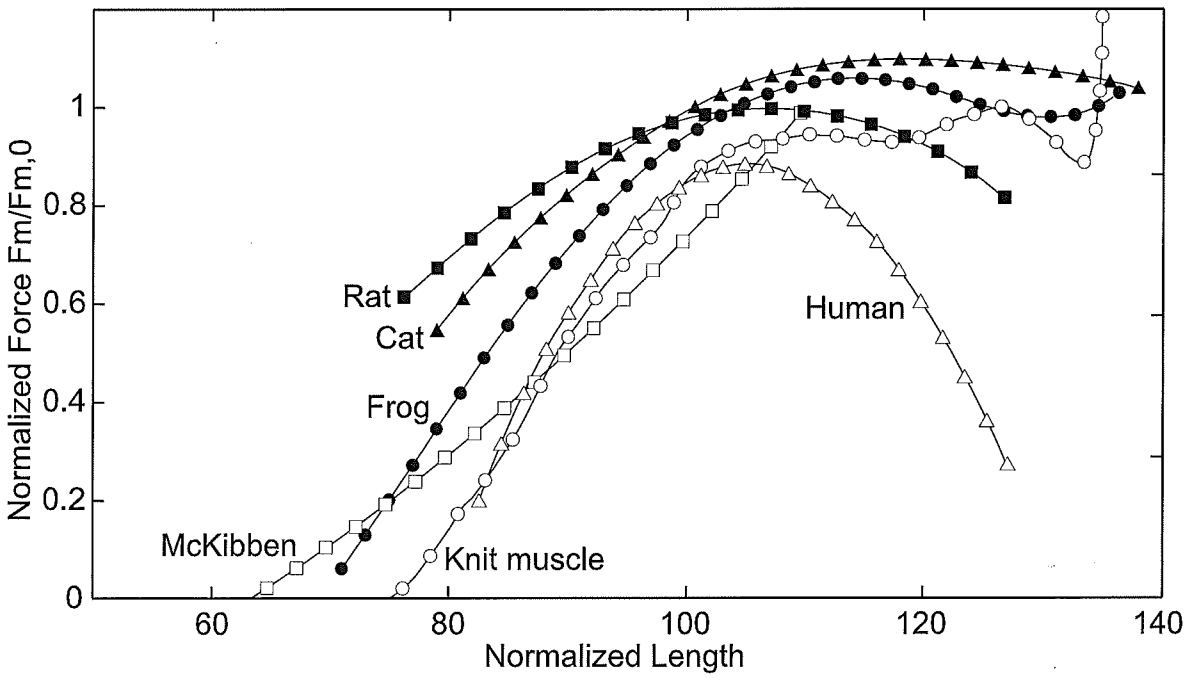

Normalized Force Fm/Fm,0
Normalized Length
Rat
Cat
Frog
McKibben
Knit muscle
Human
1
0.8
0.6
0.4
0.2
0
60
80
100
120
140

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US14/63090

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - F15B 15/10, 15/14 (2014.01)
CPC - F15B 15/10, 15/103
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) Classification(s): F15B 15/10, 15/14 (2014.01)
CPC Classification(s): F15B 15/10, 15/103: USPC Classification(s): 92/92

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data): actuator, robot, inflatable, bladder, sleeve, knit, thread, stitch, slide, low friction, fiber, synthetic, aramid, Kevlar, stockinette, garter, rib, loop, flat, round, circular

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,751,869 A (PAYNTER H. M.) June 21, 1988; abstract; column 6, lines 40-45	1, 4-6, 12-14
X	US 2006/0249017 A1 (HIRAMATSU K. et al.) November 09, 2006; abstract; paragraph [0053]	1-3, 7-11, 15
A	US 6,223,648 B1 (ERICKSON J. R.) May 01, 2001; entire document	1-15
A	US 2002/0108491 A1 (STAHN K. S.) August 15, 2002; entire document	1-15
A	US 2007/0197943 A1 (HAKONSON G. et al.) August 23, 2007; entire document	1-15
A	US 2009/0301292 A1 (KOTHERA C. et al.) December 10, 2009; entire document	1-15

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

* Special categories of cited documents:
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 December 2014 (27.12.2014)	29 JAN 2015
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774