



(51) International Patent Classification:

B25J 9/14 (2006.01) F15B 15/00 (2006.01)
B25J 11/00 (2006.01)

(21) International Application Number:

PCT/SG2024/050372

(22) International Filing Date:

07 June 2024 (07.06.2024)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

10202301636U 09 June 2023 (09.06.2023) SG

(71) Applicant: NATIONAL UNIVERSITY OF SINGAPORE [SG/SG]; 21 Lower Kent Ridge Road, Singapore 119077 (SG).

(72) Inventors: BUXANI, Shaun Mahesh; c/o National University of Singapore, College of Design and Engineering, Department of Biomedical Engineering, 21 Lower Kent Ridge Road, Singapore 119077 (SG). YEOW, Chen Hua; c/o National University of Singapore, College of Design and Engineering, Department of Biomedical Engineering, 21 Lower Kent Ridge Road, Singapore 119077 (SG).

(74) Agent: VIERING, JENTSCHURA & PARTNER LLP;

P.O. Box 1088, Rochor Post Office, Rochor Road, Singapore 911833 (SG).

(81) Designated States (unless otherwise indicated, for every kind of national protection available):

AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available):

ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

(54) Title: JAMMING BRAKE DEVICE

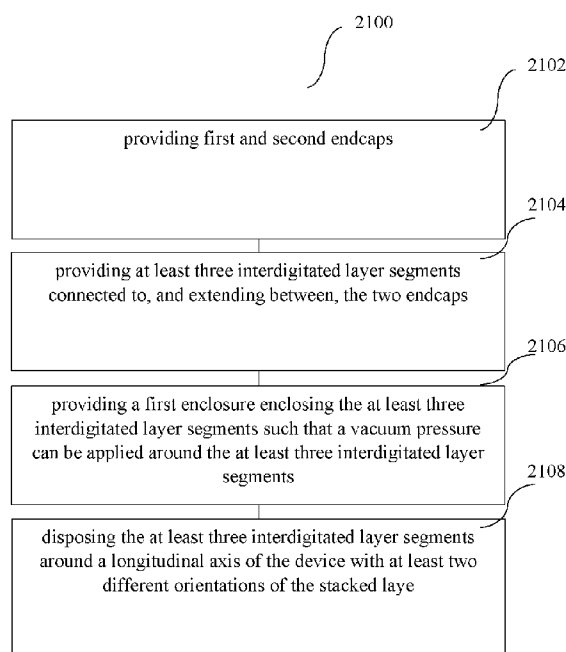


FIG. 21

(57) Abstract: A tunable jamming brake device and a method of fabricating tunable jamming brake device. The method comprises the steps of providing first and second endcaps; providing at least three interdigitated layer segments connected to, and extending between, the two endcaps, wherein each interdigitated layer segment comprises a plurality of stacked layers with interfaces between respective portions of pairs of adjacent layers for friction jamming of the layers, and wherein a first layer of each pair of adjacent layers is connected to the first endcap and a second layer of each pair of adjacent layers is connected to the second endcap; providing a first enclosure enclosing the at least three interdigitated layer segments such that a vacuum pressure can be applied around the at least three interdigitated layer segments; and disposing the at least three interdigitated layer segments around a longitudinal axis of the device with at least two different orientations of the stacked layers.

Published:

— *with international search report (Art. 21(3))*

JAMMING BRAKE DEVICE

FIELD OF INVENTION

5 The present invention relates broadly to a jamming brake device, in particular to a multi-segments, high density stretchable layer jamming brake for wearable and soft robotic applications.

BACKGROUND

10 Tunable stiffness is a crucial property in soft robotic devices, enabling their diverse applications in, for example, grippers, wearable exoskeletons, and deployed structures. This characteristic allows these devices to switch between a soft, compliant state, facilitating shape deformation, and a rigid, load-bearing state, resisting such deformation. In controlling the dynamics of robotic systems, researchers typically explore two main categories of tunable stiffness devices: actuators and brakes or dampers. Actuators can generate and modulate forces, adding energy to the system. Examples include pneumatic artificial muscles (PAM), which offer multi-directional motion and high force density, providing an alternative to traditional robots. In contrast, brakes and dampers remove and modulate energy from the system. Various techniques exist, such as electrorheological (ER) and magnetorheological (MR) mechanisms, electrostatic adhesion (EA), and jamming-based structures. While much research has focused on soft, tunable stiffness actuators, relatively less has delved into brakes and dampers in the context of soft robotics.

Most tunable stiffness brakes utilize active phase-change materials, often subject to external stimuli like temperature, electric or magnetic fields, and pressure. Electrorheological and magnetorheological fluids, for example, adjust their viscosity in response to changes in electric or magnetic fields. These fluids have seen multiple applications in prosthetics, haptics, and grippers. However, these materials are predominantly shear-dependent and cannot withstand tension. Temperature-based tunable stiffness systems employ thermally active materials like wax and solder that transition between solid and liquid states, hence demonstrating significant changes in stiffness. Nevertheless, these materials may exhibit latency, rendering them unsuitable for applications like wearable haptics. Consequently, vacuum pressure-based phase change mechanisms, employing a "jamming" approach, are gaining interest for achieving tunable stiffness.

Vacuum-jamming brakes generally function by applying vacuum pressure within an elastic, enclosed space filled with inextensible materials like particles, fibers, or layers. Particle jamming is valued for its conformability and has been examined for applications in universal grippers, haptic interfaces, and shape-changing displays. However, it requires a substantial volume to generate adequate stiffness, and adding granules to the enclosed space may increase the system's weight. Fiber jamming, another prevalent vacuum-based technique, involves

5 tightly packing light, thin fiber sheets when a vacuum is applied. This method can generate high bending forces and torques, making it suitable for bending-based mechanisms such as wearable haptic gloves and deployable structures. Square fiber jamming rods have been designed to distribute stress evenly, but despite ongoing research into fiber-based jamming for tensile-based applications, fiber jamming might not be the best choice for tasks requiring a high axial payload.

10 Vacuum layer jamming mechanisms have been extensively studied for various applications such as continuum robots, haptic gloves, and rehabilitation. One mechanism used is single stacked of non-extendable/non-stretchable layer jamming. However, they cannot produce high tensile forces and their inextensible structure limits their deformation range.

15 Other researchers have developed vacuum sliding layer jamming (SLJ) mechanisms, offering more degrees of freedom. Vacuum SLJ mechanisms use an elastic enclosure around a single stack of sliding layers, providing tunable stiffness and enabling bending-based [2,3] or tensile-based motion resistance. Various researchers have developed bending based vacuum SLJ mechanisms for robotic exoskeletons, demonstrating higher linear stiffness than vacuum particle jamming mechanisms.

20 Additionally, positive, and negative pressure (PNP) layer jamming systems have been developed, in which negative pressures can be applied to inner enclosure around the single stack of sliding layers and a/or a positive pressure can be applied to an outer enclosure around the inner enclosure, capable of generating braking forces nearing 500N.

Also, existing single stack sliding SLJ brake mechanisms are designed for tensile-based brakes, bending-based brakes, and linear tensile dampers.

Embodiments of the present invention seek to address at least one of the above problems by, inter alia, proposing an alternative SLJ based brake.

25

SUMMARY

In accordance with a first aspect of the present invention, there is provided a tunable jamming brake device comprising:

- first and second endcaps;
- 30 at least three interdigitated layer segments connected to, and extending between, the two endcaps; and
- a first enclosure enclosing the at least three interdigitated layer segments such that a vacuum pressure can be applied around the at least three interdigitated layer segments;
- wherein each interdigitated layer segment comprises a plurality of stacked layers with
- 35 interfaces between respective portions of pairs of adjacent layers for friction jamming of the

layers, wherein a first layer of each pair of adjacent layers is connected to the first endcap and a second layer of each pair of adjacent layers is connected to the second endcap; and

wherein the at least three interdigitated layer segments are disposed around a longitudinal axis of the device with at least two different orientations of the stacked layers.

- 5 In accordance with a second aspect of the present invention, there is provided a method of fabricating tunable jamming brake device, comprising the steps of:

providing first and second endcaps;

providing at least three interdigitated layer segments connected to, and extending between, the two endcaps; and

- 10 providing a first enclosure enclosing the at least three interdigitated layer segments such that a vacuum pressure can be applied around the at least three interdigitated layer segments;

wherein each interdigitated layer segment comprises a plurality of stacked layers with interfaces between respective portions of pairs of adjacent layers for friction jamming of the

- 15 layers, wherein a first layer of each pair of adjacent layers is connected to the first endcap and a second layer of each pair of adjacent layers is connected to the second endcap; and

disposing the at least three interdigitated layer segments around a longitudinal axis of the device with at least two different orientations of the stacked layers.

20 BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1A shows a schematic drawing illustrating a conventional sliding layer jamming break.

- 25 FIG. 1B shows a schematic drawing illustrating a sliding layer jamming break according to an example embodiment.

FIG. 1C shows a schematic drawing illustrating a sliding layer jamming break according to an example embodiment.

- 30 FIG. 2A shows technical drawings illustrating an endcap of a sliding layer jamming break according to an example embodiment.

FIG. 2B shows technical drawings illustrating an endcap of a sliding layer jamming break according to an example embodiment.

FIG. 3A shows schematic drawing illustrating mold arrangement for fabricating a jamming layer for a sliding layer jamming break according to an example embodiment.

FIG. 3B shows schematic drawing illustrating molding apparatus for fabricating a jamming layer for a sliding layer jamming break according to an example embodiment.

- 5 FIG. 3C shows schematic drawing illustrating a jamming layer for a sliding layer jamming break according to an example embodiment.

FIG. 3D shows schematic drawing illustrating a sliding layer jamming break according to an example embodiment.

- 10 FIG. 4A shows schematic drawing illustrating a sliding layer jamming break with positive pressure system according to an example embodiment.

FIG. 4B shows schematic drawing illustrating a sliding layer jamming break positive pressure system according to an example embodiment.

FIG. 4C shows technical drawings illustrating an endcap of a sliding layer jamming break according to an example embodiment.

- 15 FIG. 5 shows technical drawings illustrating an endcap of a sliding layer jamming break according to an example embodiment.

FIG. 6A shows a schematic drawing illustrating a sliding layer jamming break according to an example embodiment in a linear force test set-up.

- 20 FIG. 6B shows a schematic drawing illustrating a conventional sliding layer jamming break in a linear force test set-up.

FIG. 7A shows a graph illustrating linear force test results of a sliding layer jamming break according to an example embodiment.

FIG. 7B shows a graph illustrating linear force test results of a conventional sliding layer jamming break.

- 25 FIG. 8A shows a graph illustrating a comparison of tensile force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

- 30 FIG. 8B shows a graph illustrating a comparison of tensile force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

FIG. 8C shows a graph illustrating a comparison of tensile force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

FIG. 9 shows a schematic drawing illustrating a sliding layer jamming break according to an example embodiment in a torque force test set-up.

FIG. 10 shows a graph illustrating a comparison of torque force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

FIG. 11 shows a graph illustrating a comparison of torque force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

FIG. 12 shows a graph illustrating a comparison of torque force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

FIG. 13 shows a graph illustrating a comparison of torque force test results of a sliding layer jamming break according to an example embodiment and a conventional sliding layer jamming break.

FIG. 14 shows a graph illustrating linear damping test results of a sliding layer jamming break according to an example embodiment.

FIG. 15 shows a photograph of a sliding layer jamming break according to an example embodiment in a rotational damping test set-up.

FIG. 16 shows a graph illustrating rotational damping test results of a sliding layer jamming break according to an example embodiment.

FIG. 17A shows a graph illustrating contractile breaking test results of a sliding layer jamming break according to an example embodiment.

FIG. 17B shows a graph illustrating contractile breaking test results of a sliding layer jamming break according to an example embodiment.

FIG. 18 shows a graph illustrating a lift test results of a sliding layer jamming break according to an example embodiment.

FIG. 19 shows a schematic diagram illustrating application of a sliding layer jamming break according to an example embodiment in a haptic glove.

FIG. 20 shows a schematic diagram illustrating application of a sliding layer jamming break according to an example embodiment in a haptic elbow device.

FIG. 21 shows a flowchart illustrating a method of fabricating tunable jamming brake device, according to an example embodiment.

DETAILED DESCRIPTION

- In an example embodiment of the present invention, a multi-stack, sliding layer jamming (SLJ) brake is provided, capable of generating tensile forces, and rotational bending torques. In the following, the brake's design and fabrication methods according to example embodiments will be described, as well as a model for tensile and contractile forces and torques, facilitating simulation of the brake motion. Also, force, torque, and rotational damping tests are presented, and examples of potential applications of the SLJ brake according to example embodiments in deployable structures, controllers, and wearable haptics are described, paving the way for advanced applications in the field of soft robotics.
- 5 The SLJ mechanism according to another example embodiment comprises a multi-segments SLJ mechanism embedded inside of a positive pressure system (PPS), also referred to as PPS-SLJ brake herein. In addition to generating tensile forces and rotational bending torques, the PPS-SLJ according to an example embodiment can advantageously also provide contractile braking.
- 10 The PPS-SLJ brake implementation according to an example embodiment can address the limitation that in the SLJ according to an example embodiment without the use of a PPS the external pressure is limited to 1 atm. This can be of significance for certain applications, because the maximum force of the system is limited. Furthermore, while existing SLJ brakes demonstrated to have high damping at low velocities [7], even though underdamped PPS by itself cannot function as a damper, according to an example embodiment, a PPS such as a PAM integrated as a PPS-SLJ brake can act as a damper. In the PPS-SLJ brake according to an example embodiment, because the SLJ occupies a central space inside the PPS, rate of inflation/deflation is preferably reduced and the PPS's dynamic response is preferably improved.
- 15 It is noted that even though the SLJ-brake embedded into the PPS actuator according to an example embodiment restricts motion due to the restriction of volume, the PPS (e.g. implemented using a PAM) force output slightly increases due to the reduced volume. Furthermore, the PPS-SLJ brake according to an example embodiment can generate a greater pressure differential across the brake, significantly increasing the braking output force.
- 20 General Structure of SLJ brake according to an example embodiment
- For the SLJ brakes according to an example embodiment, there are three main components: the endcaps, the (first) enclosure, and the sliding layers. The layers are mounted onto the endcap or to each other attached to different endcaps either by push through locks, screws, or threads. The enclosure is typically made from an elastic enclosure material, in non-limiting example
- 25 embodiments either ecoflex-50 or Dragonskin 10 medium (Smooth On, Inc., TX, USA) were used, and sealed with a silicone sealant onto the endcaps. In a non-limiting example embodiment, Silpoxy adhesive (Smooth On, Inc., TX, USA) was used as the sealant. It is noted that as used herein, "enclosure" is intended to refer to an elastic, stretchable cover that prevents

leakages and allows air (pressure can be either positive or negative pressure) to flow within the defined working space.

The jamming brake according to example embodiment comprises multiple stacks of sliding jamming layers, also referred to as segments herein, each providing n interfaces, i.e. $n+1$ (n , $n=1, 2, 3, \dots$) interdigitated layers of stacked materials in each stack, where the number of layers is roughly divided equally between the two endcaps. That is, for modelling purposes, as described below, the number of interfaces between the interdigitated layers is n . There are three different lengths when the layers from different endcaps are interacting with each other in each stack or segment. There is $L1$, the length of the layer attached to the left/first endcap which is not interacting with layers attached to the right endcap. Conversely, $L3$ is the length of the layer attached to the right/second endcap which is not interacting with the layers attached to the left/first endcap. Finally, there is the overlapping layers length $L2$ between the left(first) and the right(second) endcap. Therefore, the areas would have a corresponding cross-sectional area of $A1$, $A2$ and $A3$. The layers in the model used below would have an elastic modulus EL . In a non-limiting example embodiment, the material used is Nylon-coated thermoplastic polyurethane (TPU) with an elastic modulus of 101.5MPa. The friction between the layers μ_L made from Nylon-coated TPU is 0.55, whilst the friction between the layers and the enclosure μ_E is 0.2. This has been tested using a custom test rig based on ASTM D1894-14.

Structure of multiple-stack SLJ brake according to an example embodiment

The three different lengths $L1$ - $L3$ described above form one layer segment of a particular orientation. For the model described below, there are three different types of SLJ brake configurations with layer segments of different orientations that are considered, by way of example, not limitation: a conventional one-segment configuration 100, a three-segments configuration 102 according to an example embodiment, and a five-segments configuration 104 (see FIG. 1(A-C)) according to another example embodiments. It is noted that experimental data is presented herein for the three-segments configuration 102 according to an example embodiment only, but it will be understood by a person skilled in the art that similar trends as those shown discussed below can be expected for other configuration, such as the 5-segments configuration 104 and higher number of segments in different example embodiments.

To encompass different layer segments of different orientations along a longitudinal axis of the device, the endcap and enclosure design differs between the various configurations. The endcap according to a non-limiting example embodiment is made from an off the shelf polylactic acid (PLA) and is designed using Solidworks (Dassault, Systemes, France) and 3D-printed using the Ultimaker 3 (Ultimaker, Utrecht, Netherlands). The infill is best printed at 100% to preferably prevent possible leakages within the material and prevent the vacuum pressure from escaping. In addition, the material is preferably printed in the highest resolution (e.g. 0.06mm) to ensure that no/minimal errors in the design can occur that would lead to leakages. FIG. 2A) shows dimensions of the endcap 200 and the structure 202 of the one-segment configuration and the three-segments configuration, and FIG. 2B) shows the dimensions of the five-segments configuration endcap 204. It is noted that without PPS, one of the endcaps 203 can be closed

since only the vacuum pressure is being used in the multiple-stack SLJ brake according to an example embodiment.

With reference to FIG. 3A), to manufacture the SLJ enclosure according to an example embodiment, a two-part mould 300a, b is made from polylactic acid (PLA) and designed using
 5 Solidworks (Dassault Systemes, France) and 3D-printing using the Ultimaker 3 (Ultimaker, Utrecht, Netherlands) with a 20% infill. The Ecoflex 0050 or Dragon-skin 10 medium is degassed for 15 minutes to prevent air bubbles. Furthermore, the Ecoflex 0050 or Dragon-skin 10 is poured into the mould 300a, and the cavity mould 300b is mounted with M2 screws, and placed in the oven for 1 hour.

10 With reference to FIGs. 3B) and C), for the layer 302-304 design in SLJ, any layer design can be used. Each layer 302-304 is cut using the Silhouette Cameo. There are multiple ways to cut the layer. To preferably reduce the torsion experienced by the layers and to preferably ensure that the layers are aligned, there are two types of layers: a static layer 302 and a sliding layer 303, 304. The layers 302-304 can be of any length depending on the purpose and the application
 15 of the brake. In non-limiting example embodiments, both the static and sliding layers are 45mm in length, 6.5mm in width and 0.35mm thick. The overall starting length of the brake is 80mm and can extend to 100mm based on the slot 306, 307 design. FIG. 3(D) shows the basic structure of the brake 308 according to an example embodiment.

To assemble the SLJ brake according to example embodiments a three step method is used in
 20 one example method: a layer-to-layer attachment, a layer-to-endcap attachment, and an enclosure-to-endcap attachment. It is noted that when using countersunk screws for fastening layer-to-endcap, due to possible wear-and-tear of the endcap and layers over time, the layers may get loose and slip off. Some layers can be sewn onto the endcap, however, while this can provide extra security for the layers, dismantling the layers can be cumbersome and assembling
 25 the system can take longer than inserting a countersunk screw. Thus, to reduce the errors of dismantling and reassembling the product, the use of 2-part push-on fasteners was implemented according to an example embodiment, where one end connects to the layers and one end of the endcap, and the second part has a hole where the first part of the fastener can slot into. Preferably, this can prevent damage, and can also ensure that the layers do not move outside
 30 that fixed length. This also can provide a prismatic and rotational joint between the endcaps and the layers.

Structure of multiple-segments PPS-SLJ brake according to example embodiments

For a multiple segments PPS-SLJ brake according to an example embodiment, there will be two different types of enclosures applied: the first enclosure applied to the SLJ for vacuum
 35 pressure, and the second enclosure applied on top of the first enclosure for positive pressure delivery. However, instead of only using PPS, as is e.g. done in [7], the PPS-SLJ brake according to an example embodiment incorporates highly dense layers inside the first enclosure. In an example embodiment, the enclosures have different shapes as the first enclosure is preferably designed to house all of the multiple layer stacks (e.g., the three-

segments SLJ in one example embodiment), whilst the second enclosure is for example designed to be cylindrical so that the PPS-SLJ brake can also be modelled as a PAM.

- FIG. 4A-C show diagrams of the small/miniature PPS-SLJ 400 according to an example embodiment. However, it is noted that the PPS-SLJ 400 can be of any length, width or height depending on the desired requirements. In one example embodiment, two smaller endcaps 402, 404 are used in the small/miniature PPS-SLJ 400, where one of the endcaps 402 (which is the same the endcap 203 shown in FIG. 2A) is configured to deliver the vacuum pressure for the (inner) SLJ enclosure 406 and the other endcap 404 is configured to deliver positive pressure for the (outer) PPS enclosure 408.
- With reference to FIG. 5, in another embodiment, a miniature endcap without any conduits for delivery of vacuum or positive pressure can be provided at one end and a large endcap 502 at the other end, according to another example embodiment. In such an embodiment, the larger endcap 502 has conduits for delivery of vacuum and positive pressure, and the tubes for the vacuum pressure and positive pressure delivery are attached to the one endcap 502, whereas the miniature enclosure does not have any tubing, which advantageously prevents possible entanglement of the tubes and possible bending of the brake. The duct for applying the positive pressure around the first enclosure may comprise two pneumatic airflow ports e.g. 504.

As described above, advantageously the PPS-SLJ can apply positive and vacuum pressure at various different incorporated SLJ sizes, as may be required for different applications.

20

Overall Force model of the system according to an example embodiment

Because the SLJ brake is constructed inside of a PPS, if PPS is used, according to an example embodiment, and in parallel, their respective forces can be independently modelled. So, the total force for the system according to an example embodiment with PPS is:

25
$$F_{total} = F_{SLJ} + F_{PPS} \quad (1)$$

It is noted that for an embodiment without PPS, $F_{PPS}=0$, as will be appreciated by a person skilled in the art.

- For the outside ambient pressure, the brakes external pressure is atmospheric pressure whilst when a PPS is added to the system, the external pressure will be controlled by the positive pressure applied to the brake.

Force and Stiffness Modelling the brake without the PPS, according to an example embodiment

Tensile force model

To model the resistive tensile force provided by the brake, the multi-segments SLJ brake has two modes: the before sliding phase and the after sliding phase.

Before sliding model

In the domain of layer jamming systems, particularly concerning linear braking mechanisms, a dichotomous categorization is imperative for elucidating force interactions: the before-sliding (BS) and after-sliding (AS) phases. The layer jamming brake is subjected to a differential tensile load within the BS domain, invoking a mechanical response analogous to three helical springs in series. Independent of the specific arrangement of layers, the resulting stacked area is comparable, if not identical, to that of a single-layer jamming configuration. Consequently, the tensile force required for elongational deformation can be described as follows.

$$F_{BS} = K_{eff}x = \left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} \right)^{-1} x \quad (2)$$

wherein denotes the effective spring stiffness K_{eff} conglomerate of the layered assembly. The stiffness parameter for each stratified segment is given by:

$$K_{eff} = \frac{EA_i}{L_i} \quad (i = 1, 2, 3) \quad (3)$$

Where E is the Young's modulus of the layer material, A_i is the total stacked area of the layers in each given section, and L_i is the length of the layers in the given section.

After sliding model

Once the applied tensile force exceeds the frictional force F_f generated by the layer-to-layer contact and the elastic force generated by the layer-to-enclosure contact F_e , the layers will start sliding. The layers will then absorb mechanical energy in the process. For this event, the braking force will be the sum of the frictional and elastic forces, given by:

$$F_{AS} = F_f + F_e \quad (4)$$

Where F_f is given by:

$$F_f = \mu_L n w (L_2 - x) \Delta P_v \quad (5)$$

Where n is the total number of interfaces between layers across all of the multiple stacks of layers, ΔP_v is the absolute pressure (or vacuum pressure) applied to the system, and μ_L is the coefficient of friction between the layers. F_e is given by:

$$F_e = n_e (\sqrt{\mu_e P_v A_e E w L_e}) \quad (6)$$

Where n_e is the maximum number of sliding and static layers combined in contact with the enclosure (i.e. if an enclosure is considered to have four sides (i.e. top, bottom left and right side) and there are four static layers and four sliding layers in contact with the enclosure, i.e. a three stack example embodiment (compare FIG. 1B), the maximum number n_e can be is 4, whereas for a five stack embodiment (compare FIG. 1C), the maximum number n_e can be is

- 6), μ_c is the friction coefficient between the layers and the environment, and L_c and A_c are the length and area of contact between the enclosure and the layers. It was accordingly found by the present inventor that, according to this force model, the elastic forces are more dominant in terms of layer jamming performance than previously assumed and should not be neglected in the assessment of jamming performance, as has been done in previous works.

Force Modelling the brake with PPS

- It is noted that the force modelling does not dependent on the number of jamming layer stacks used inside the inner enclosure of the PPS-SLJ brakes according to example embodiments. For any PPS [7], a generalized model for an ideal cylindrical PPS can be used. Thus, the force model can be determined as:

$$F_{PPS} = -\Delta P' \frac{\Delta V}{\Delta x} \quad (7)$$

- Where $\Delta P'$ is the change in the pressure difference between the positive pressure applied to the system and the ambient environment, ΔV is changes in volume and Δx is the changes in the displacement caused when a tensile load has been added. In this model, two volumes exist: volume occupied by the brake V_b and the volume occupied by the PPS V_p . Thus, the total force generated by the actuator F_a is the total forces generated by the brake and the PPS F_b and F_p from the given volumes V_b and V_p respectively, as:

$$F_a = F_b + F_p = -\Delta P \frac{\Delta V}{\Delta x} = -\left(\Delta P'_b \frac{dV_b}{dx} + \Delta P'_p \frac{dV_p}{dx}\right) = -(P_b - P_{atm}) \frac{dV_b}{dx} - (P_p - P_{atm}) \frac{dV_p}{dx} \quad (8)$$

- Where P_b and P_p are the pressures generated by the actuator from the brakes and the PPS respectively, P'_b and P'_p are the pressure differences between the positive pressure applied to the brake and the PPS, and P_{atm} is the atmospheric pressure.

- The working principle behind how the actuator produces a force output and shortens in length is described next. When the PPS system contracts, $F_b < 0$, $\frac{dV_b}{dx}$ would be greater than 0 as the width and the height of the endcaps remain to be constant and do not change in size. Conversely, $F_p > 0$ when $\frac{dV_p}{dx} < 0$ is the ideal PPS. Thus, by inference, F_a would be less than F_p . This can be proven by:

$$F_a = F_b + F_p = -wh(P_b - P_{atm}) \frac{dL_b}{dx} - \pi r_p^2 (P_p - P_{atm}) \frac{dL_p}{dx} \quad (9)$$

where $\frac{dL_b}{dx} > 0$, and $\frac{dL_p}{dx} < 0$, and r_p is the radius of the PPS.

- When the brake is stretched when the PPS is active, the resulting $\frac{dV_b}{dx}$ would have a miniscule movement as the volume of the brake is occupied by solid layers. Thus, the corresponding volume of the system would be $\frac{dV_p}{dx}$. [7] identified that to operate the multiple-plane brake with a PPS outer layer as a PAM, in particular the McKibben muscle, the system is pressurized such

that $P_b = P_p > P_{atm}$, such that there would be no changes in pressure. Thus, $F_{AS} = 0$. Thus, the hypothesis is that the force generated by the PPS ($F_{pps+brake}$) is higher than the typical PPS of a similar volume. Therefore, the force generated by the multiple-plane SLJ with a PPS would be the force of the PPS and the additional force F_{offset} resulting from the losses of F_b . This can be written as:

$$F_{pps+brake} = F_{pps} + F_{offset} = F_{pps} + P_v wh \quad (10)$$

Stiffness Modelling the brake with the PPS

To model this system as a stiffness-based system, it is realized that both the systems are set in a parallel format. So, the stiffness of the total system is considered as:

$$k_{pps+brake} = k_{pps} + k_{brake} \quad (11)$$

Where k_{pps} is the stiffness generated by the PPS and k_{brake} is the stiffness generated by the SLJ brake. Using the derivation of the $F_{pps+brake}$, $k_{pps+brake}$ can also be rewritten as:

$$k_{pps+brake} = \frac{dF_{pps+brake}}{dx} = \frac{dF_{pps}}{dx} + wh \frac{dP_v}{dx} \quad (12)$$

15

Torque Modelling the brake without the PPS

With the force model (see above), the torque model can be further developed. The bending torque produced by a layer is dependent on the orientation of the layer and the distance between the layer and the rotational point of the brake. Based on previous research [2,3] it may be determined that the side-layer segments according to an example embodiment are designed for rotational motion whilst the front-layer segment according to an example embodiment is designed for tensile-based motion. As it is difficult to determine the exact position at which the brake bends due to constant movement when no vacuum is applied, it will be assumed the bending occurs at the centre of the brake. Furthermore, it will be assumed that each layer-segment can be modelled as one thick layer when a vacuum pressure has been applied. Thus, this would increase the thickness and would increase the bending torque τ of the brake when a torque has been applied to the brake. So, the original torque equation would remain as:

25

$$\tau(\theta) = P_v \mu_L w \int_0^{\frac{L}{2}} \sqrt{(L \cos(\theta))^2 + (2r \sin(\theta))^2} + \frac{r \sin(\theta)^2}{\cos(\theta)} \times \ln \left(\frac{L}{2r} |\cot(\theta)| + \sqrt{\left(\frac{L}{2r} \cot(\theta) \right)^2 + 1} \right) \quad (13)$$

30

Methodology, results and discussion, according to example embodiments:

Force test without the PPS

The objective of the linear force test is to show that the brake according to an example embodiment can maintain a similar linear force output to existing SLJs (in this case, [4]), and in some cases, a significantly greater braking force. To investigate how different vacuum pressures affect the tensile, frictional, and elastic force caused by the brake, five vacuum pressures 0kPa, -20kPa, -40kPa, -60kPa and -80kPa are used. 0kPa is as a reference to demonstrate the braking force produced by the materials without vacuum pressure. The total force created by the brake is measured using the JSV H1000 handy test stand (JISC, Sakurai City, Japan) along with the software SOP-EG1 (JISC, Sakurai City, Japan). FIG. 6(A). shows the setup of the force test for the multi-segments SLJ 1000 according to an example embodiment. The Busch R5 RA 0040 F rotary vane pump 600 generates the required vacuum pressures. A constant 2mm/s pulling speed along a vertical linear extension of 20mm. The length, width, and height of the layers in the multi-segments SLJ 1000 according to an example embodiment are the same as in the single-plane conventional SLJ 1002 layers (FIG. 6(B)). In the experiment, a three jamming layer stacks embodiment was used as the multi-segments SLJ 1000, i.e. there were 12 interfaces in the middle segment 602, and there were 2 x 6 interfaces in the side segments 604, 606 in the SLJ 1000 according to an example embodiment. In the conventional, single stack SLJ 1002, there are 12 interfaces. Hence, the friction braking force of the SLJ 1000 according to an example embodiment is expected to be about double that of the conventional SLJ 1002.

FIG.7A illustrates the total tensile force generated by the SLJ-brake 1000 according to an example embodiment, with three segments of different orientations. The peak forces for the brakes are 49.7N, 59.5N, 70.4N and 90.4N. The results indicate that an increase in vacuum pressure leads to a rise in the total tensile force generated by the brake.

FIG.7(B) shows the force generated by the conventional SLJ 1002 [4]. The peak forces for the brakes are 32.9N, 39.4N, 44.6N and 50.8N. From a comparison of FIGs. 7A and B, while the force generated by the SLJ 1000 according to an example embodiment is not twice that of the conventional SLJ 1002, as would be expected from the number of interfaces as mentioned above, the SLF 1000 according to an example embodiment does generate a significant higher force.

To further verify the force test, a force test was conducted with another layer material: paper. This is to see if warp and weft in fabric play a part in braking. A force test where the layers are made of thick paper for -40kPa, -60kPa and -80kPa was also conducted. -20kPa [and 0kPa were not performed as the layers ripped and would not generate any braking force. The arrangement of the layer configuration is different to the nylon-coated TPU layers for the conventional SLJ. Instead of measuring 12 interfaces as in SLJ 1002, 24 interfaces were used for the conventional SLJ for comparison.

FIGs.8A-C show the comparison of the tensile force generated by the SLJ-brake according to an example embodiment using paper as layer material but otherwise in the same configuration as SLJ 1000, and the conventional single stack SLJ with 24 interfaces. The observation is that the peak forces in the SLJ-brake according to an example embodiment using paper as the layer material yielded greater braking forces than the conventional SLJ. Furthermore, the stiffness, i.e. the force over the displacement, yielded no significant difference when a change in pressure occurred as the stiffness produced an approximate 15kN/m. As frictional forces are expected to be similar based on previous literature [1], the results are consistent with the model described above, i.e. the elastic forces in the SLJ-brake according to an example embodiment play a greater role in the braking force, thus emphasizing the importance of elastic forces in example embodiments.

Torque test without the PPS

Fig.9A shows the setup of the torque experiment, with one end 900 of the SLJ break 902 according to an example embodiment fixed to a JSV H1000 handy test stand 904 with vacuum pump connection. Pressures of -20kPa, -40kPa, -60kPa and -80kPa were performed.

FIGs.10-13 show the experimental torque results for an three jamming layer stacks SLJ according to an example embodiment, simulation data, and a conventional single jamming layer stack SLJ. The peak torques based on the single-stack conventional SLJ from 0kPa to 80kPa are 0.145Nm, 0.152Nm, 0.165Nm, 0.177Nm and 0.196Nm. For the three-stack SLJ brake according to an example embodiment, the peak torques are 0.2060Nm, 0.258Nm, 0.320Nm, 0.356Nm and 0.383Nm. The conventional brake and the brake according to an example embodiment both showed that an increase in vacuum pressure would increase the bending torque exerted by the brake. Furthermore, an increase in the vacuum pressure leads to an increase in bending stiffness, i.e. torque over bending angle. A significant portion of the bending torque generated by the single-stack conventional SLJ is generated by the materials without any vacuum pressure.

Linear damping test without the PPS

Having evaluated the linear braking force and the braking bending torque model, the multi-segments SLJ according to an example embodiment can be evaluated for damping. There are two types of damping: linear and rotational damping. Previous research [1,7] has shown that a single-layer segment can behave as a linear damper. As the multi-segments SLJ according to an example embodiment contains a front layer segment, it is shown that the front-layer segment can make the multiple-segments SLJ brake act as a linear damper, which evaluates how the mechanism dampens the weight during a free-fall drop.

The linear damping is measured in three conditions: with the mechanism but no pressure, a tuneable pressure (-40kPa) a maximum pressure -80kPa. The reason linear damping is divided

into three experiments is because previous work [1] stated that in some instances it is possible to determine the total kinetic energy of the system in real time, but at points, it is not possible to determine the kinetic because of the absence of a sensor within the brake. The vertical height (or y axis) movement will be tracked during the drop-test. The brake and the weight (1.6kg) were attached using a nylon rope.

FIG.14 shows the findings of the linear damping experiment with a three-segment layer jamming mechanism according to an example embodiment. The finding is that without pressure, there was still damping, but not as effective as with vacuum pressure. The maximum pressure slowed down the weight faster than the tuneable pressure but deformed the length by absorbing the kinetic energy. However, the tuneable pressure reduced overshoot by not deforming the length. But the mechanism did take longer to dampen. Thus, even though the mechanism can behave as a linear damper, the damping requirements need to be considered and understood before selecting a pressure.

The next damping performance evaluation is rotational damping. The model presented aims to show that the side-layer segments/planes with different orientations can make the multi-segment SLJ brake according to an example embodiment act as a rotational damper, and evaluates how the mechanism dampens the weight during a rotational motion (e.g. pendulum motion). For rotational damping, the energy dissipated is calculated for the multi-segment/plane SLJ according to an example embodiment during a 30-degree swing from the vertical axis with a weight of 0.5kg attached to the brake in the x-y plane. Like linear damping [1], the dissipated energy is a function of vacuum pressure and can be calculated as:

$$E_{dissipated}(\Delta P) = \int L_0 \left[\left(1 - \frac{a_z}{a_{peak,p}} \right) F_{BS} + \frac{a_x}{a_{peak,p}} F_{AS} \right] d\theta \quad (14)$$

Rotational damping test without the PPS

FIG.15 shows a photo of the setup of the rotational damping experiment. Rotational damping is measured in four conditions: without the brake, i.e only a string attached to the wight, with the SLF brake 1500 according to an example embodiment, but no vacuum pressure, a tunable vacuum pressure (as an example set to -40kPa), and a maximum pressure -80kPa.

FIG. 16 shows the damping results concerning angular displacement. Without the brake, the weight is still moving after 10s. With the multi-stack SLJ brake 1500 (FIG. 15) according to an example embodiment, the 0.5kg stopped moving (no vacuum, stopped moving at 7s). Furthermore, using the highest vacuum pressure will absorb mechanical energy and slow down the weight faster (4s). With the multi-stacks SLJ brake 1500 (FIG. 15) according to an example embodiment controlled to a tuneable pressure, here -40kPa, although the time to slow down the weight is slower (5.9s), not only is the overshoot reduced in contrast to no vacuum or with a

maximum vacuum, but the end position of the brake ended up closest to the vertical axis starting point. Thus, there is a trade-off in overshoot and time taken to brake at higher pressures. Thus, even though the mechanism can behave as a rotational damper, the damping requirements need to be considered and understood before selecting a pressure.

5 *Contractile braking with the PPS*

Another aspect of the brake according to an example embodiment is to show that it can perform contractile braking. To show how the contractile braking works, a setup similar to that shown in FIGs. 6A and B for the force test was used, but with the brake 1000 according to the example embodiment subjected to a (downward) compression force. The vacuum pressures applied
10 were no vacuum pressure (0kPa), and maximum vacuum pressure (-80kPa) with a pressure in the outer (PPS) enclosure of 0kPa and 100kPa respectively. Higher pressures could be tested but were not due to possible ruptures.

FIG.17A-B shows the results of the experiment. Each experiment was repeated three times and an average of the three experiments was taken. With reference to FIG. 17A, what was found
15 was that as vacuum pressure was added to the system with the same PPS pressure (here 100kPa), the layers interacting with each other act as a block. Thus, vacuum pressure increases contractile forces from 25N to 32N with 100kPa PPS.

With reference to FIG. 17B, for the changes in positive pressure with maximum vacuum pressure, there was an increase in force from 25N to 32N. What was also found with maximum
20 vacuum pressure applied, the brake is harder to compress further.

Thus, the PPS-SLJ according to an example embodiment can function as a tool for contractile braking.

Applications of example embodiments

25 *Logistics*

As one of the applications we aim to fulfil is logistics, the aim of the brake if using small mechanisms is to lift, for example, a 5kg plate and return the plate back on the floor using 3-stack jamming mechanism according to an example embodiment. The displacement during the lifting for the conventional 1-stack jamming mechanism is greater in comparison to the 3-stack
30 mechanism according to an example embodiment, as shown in FIG.18. Therefore, the three stack SLJ, here without PPS, according to an example embodiment can advantageously provide for a more compact lift mechanism design.

Haptic Glove

One main application to apply the brake as a damper for smaller-scale applications is a
35 kinesthetic brake in wearable haptics [8] and can be modelled for different groundings [5]. As the brake can generate torques greater than 0.0149Nm and 0.0225Nm. The brake can withstand

bending torques of the finger and the wrist [9] FIG.19 shows how the three stacks SLJ brake 1900, without PPS in this example, can be used as a kinesthetic feedback brake-cable 1902 driven mechanism when attached to a human finger 1904. As haptics improves the immersive experience of virtual reality, future work can for example include performing a haptic study with an actual game.[5, 8].

Physiotherapy for resistive movements and the development of a haptic elbow

As the brake according to example embodiments can be converted to different sizes, another application is for physiotherapy and the use of the system as a haptic elbow device. Currently, there are no systems that can perform haptic feedback on an elbow. FIG. 20 shows a schematic drawing illustrating a brake 2000 according to an example embodiment, tested to jam the elbow 2002 when performing an elbow extension.

In one embodiment, a tunable jamming brake device is provided comprising first and second endcaps; at least three interdigitated layer segments connected to, and extending between, the two endcaps; and a first enclosure enclosing the at least three interdigitated layer segments such that a vacuum pressure can be applied around the at least three interdigitated layer segments; wherein each interdigitated layer segment comprises a plurality of stacked layers with interfaces between respective portions of pairs of adjacent layers for friction jamming of the layers, wherein a first layer of each pair of adjacent layers is connected to the first endcap and a second layer of each pair of adjacent layers is connected to the second endcap; and wherein the at least three interdigitated layer segments are disposed around a longitudinal axis of the device with at least two different orientations of the stacked layers.

The device may comprise a second enclosure enclosing the first enclosure such that a positive pressure equal to or greater than atmospheric pressure can be applied around the first enclosure, whereby the tunable stiffness device can function as a contractile braker.

The first endcap may comprise a first duct formed therein for applying the vacuum pressure around the at least three interdigitated layer segments, and the second endcap may comprise a second duct formed therein for applying the positive pressure around the first enclosure.

The first endcap may be a closed endcap and the second endcap may comprise a first duct formed therein for applying the vacuum pressure around the at least three interdigitated layer segments and a second duct formed therein for applying the positive pressure around the first enclosure. The second duct may comprise two pneumatic airflow ports.

Each of the first and second endcaps may comprise at least three mounting surfaces for mounting respective ones of the at least three interdigitated layer segments, wherein the at least three mounting surfaces may be disposed in respective orientations of the stacked layers of the respective at least three interdigitated layer segments around the longitudinal axis of the tunable stiffness device.

The device may be configured for use in a system for rotational damping, wherein an overshoot of the under-damped system may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for linear force generation, wherein a magnitude of the generated linear force may be tunable by varying the vacuum pressure.

- 5 The device may be configured for use in a system for torque force generation, wherein a magnitude of the generated torque force may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for linear damping, wherein damping properties of the linear damping system may be tunable by varying the vacuum pressure.

- 10 The device may be configured for use in a system for rotational damping, wherein damping properties of the rotational damping system may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for contractile breaking force generation, wherein a magnitude of the generated contractile breaking force may be tunable by varying the vacuum pressure and/or the positive pressure.

- 15 FIG. 21 shows a flowchart 2100 illustrating a method of fabricating tunable jamming brake device, according to an example embodiment. At step 2102, first and second endcaps are provided. At step 2104, at least three interdigitated layer segments connected to, and extended between, the two endcaps are provided, wherein each interdigitated layer segment comprises a plurality of stacked layers with interfaces between respective portions of pairs of adjacent layers for friction jamming of the layers, and wherein a first layer of each pair of adjacent layers
20 is connected to the first endcap and a second layer of each pair of adjacent layers is connected to the second endcap. At step 2106, a first enclosure enclosing the at least three interdigitated layer segments is provided such that a vacuum pressure can be applied around the at least three interdigitated layer segments. At step 2108, the at least three interdigitated layer segments are disposed around a longitudinal axis of the device with at least two different orientations of the
25 stacked layers.

The method may comprise providing a second enclosure enclosing the first enclosure such that a positive pressure equal to or greater than atmospheric pressure can be applied around the first enclosure, whereby the tunable stiffness device can function as a contractile braker.

- 30 The first endcap may comprise a first duct formed therein for applying the vacuum pressure around the at least three interdigitated layer segments, and the second endcap may comprise a second duct formed therein for applying the positive pressure around the first enclosure.

- 35 The first endcap may be a closed endcap and the second endcap may comprise a first duct formed therein for applying the vacuum pressure around the at least three interdigitated layer segments and a second duct formed therein for applying the positive pressure around the first enclosure. The second duct may comprise two pneumatic airflow ports.

Each of the first and second endcaps may comprise at least three mounting surfaces for mounting respective ones of the at least three interdigitated layer segments, wherein the at least three mounting surfaces may be disposed in respective orientations of the stacked layers of the respective at least three interdigitated layer segments around the longitudinal axis of the tunable stiffness device.

The device may be configured for use in a system for rotational damping, wherein an overshoot of the under-damped system may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for linear force generation, wherein a magnitude of the generated linear force may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for torque force generation, wherein a magnitude of the generated torque force may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for linear damping, wherein damping properties of the linear damping system may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for rotational damping, wherein damping properties of the rotational damping system may be tunable by varying the vacuum pressure.

The device may be configured for use in a system for contractile braking force generation, wherein a magnitude of the generated contractile braking force may be tunable by varying the vacuum pressure and/or the positive pressure.

As described herein, an approach that uses a lightweight, portable multi-segments SLJ is provided according to example embodiments, and a PPS-SLJ to be operating as a tensile braker, contractile braker and a bending-torque braker can also be provided in example embodiments. The significance of size and how the endcap design according to example embodiments can allow the PPS-SLJ to perform contractile braking, tensile braking and rotational braking has also been described. The design, modelling, analysis and the results of the multi-segments SLJ mechanism according to example embodiments has been presented. The results have shown that for force modelling, the brake can maintain a similar, and in some cases, a significantly higher linear stiffness than the conventional SLJ [4]. For the bending rotational torque, adding additional side-layer segments with a high layer density according to an example embodiment has shown to produce greater bending rotational torque compared to the single-layer segment demonstrated in [4]. In addition, the brake according to an example embodiment can behave as an under-damped system for rotational damping and tunable vacuum pressures can reduce the overshoot of the system.

The multi-segments SLJ and PPS-SLJ brakes according to an example embodiment serves as an alternate solution for variable stiffness brakes and dampers. The theoretical model described can be a stepping stone in designing multiple applications by determining the number and size of layers, the enclosure and endcap material, and the vacuum pressure applied to the brake.

Furthermore, the functionality of the brake according to an example embodiment having bending-based characteristics and tensile-based characteristics allows the brake to be implemented in a range of applications.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive. Also, the invention includes any combination of features described for different embodiments, including in the summary section, even if the feature or combination of features is not explicitly specified in the summary section or the detailed description of the present embodiments.

References

- [1] Choi, I., Corson, N., Peiros, L., Hawkes, E. W., Keller, S., and Follmer, S., "A Soft, Controllable, High Force Density Linear Brake Utilizing Layer Jamming", IEEE Robotics and Automation Letters, 2017
- [2] Kim, Y. J., Cheng, S., Kim, S., and Iagnemma, K., "A novel layer jamming mechanism with tunable stiffness capability for minimallyinvasive surgery", IEEE Transactions on Robotics, 29(4), 1031-1042,2013
- [3] Shen, M, Clark, A, Rojas, N. A Scalable Variable Stiffness Revolute Joint Based on Layer Jamming for Robotic Exoskeletons. TAROS 2020, LNAI 12228, pp3-14, 2020
- [4] Choi, W., Kim, S., Lee, D. and Shin, D.. Soft, Multi-DoF, Variable Stiffness Mechanism Using Layer Jamming for Wearable Robots. IEEE Robotics and Automation Letters, 4(3), pp.2539-2546, 2019
- [5] Nisar S, Martinez MO, Endo T, Matsuno F, Okamura AM. Effects of Different Hand-Grounding Locations on Haptic Perfor-mance With a Wearable Kinesthetic HapticDevice;4(2):351-8. Available from: <http://arxiv.org/abs/1906.00430>.
- [6] Jang JH, Sales Coutinho Junior A, Park YJ, Rodrigue H. A Positive and Negative PressureSoft Linear Brake for Wearable Applications:1-1. Available from: <https://ieeexplore.ieee.org/document/9709194/>

- [7] Do BH, Choi I, Follmer S. An All-Soft Variable Impedance Actuator Enabled by Embedded Layer Jamming;1-12. Available from:<https://ieeexplore.ieee.org/document/9813557/>.
- 5 [8] Zhang Y, Wang D, Wang Z, Zhang Y, XiaoJ. Passive Force-Feedback Gloves With Joint-Based Variable Impedance Using Layer Jamming;12(3):269-80. Available from:<https://ieeexplore.ieee.org/document/8678855/>
- 10 [9] Serbest K, Cilli M, Eldogan O. A DYNAMIC VIRTUAL HAND MODEL FORESTIMATING JOINT TORQUES DURING THE WRIST AND FINGERS MOVEMENTS;13:12.
- 15 [10] Ching-Ping Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Transactions on Robotics and Automation*, vol. 12, no. 1, pp. 90–102, 1996. doi:10.1109/70.4817

CLAIMS

1. A tunable jamming brake device comprising:

first and second endcaps;

at least three interdigitated layer segments connected to, and extending between, the
5 two endcaps; and

a first enclosure enclosing the at least three interdigitated layer segments such that a vacuum pressure can be applied around the at least three interdigitated layer segments;

wherein each interdigitated layer segment comprises a plurality of stacked layers with
interfaces between respective portions of pairs of adjacent layers for friction jamming of the
10 layers, wherein a first layer of each pair of adjacent layers is connected to the first endcap and
a second layer of each pair of adjacent layers is connected to the second endcap; and

wherein the at least three interdigitated layer segments are disposed around a longitudinal
axis of the device with at least two different orientations of the stacked layers.

2. The device of claim 1, comprising a second enclosure enclosing the first enclosure such
15 that a positive pressure equal to or greater than atmospheric pressure can be applied around
the first enclosure, whereby the tunable stiffness device can function as a contractile braker.

3. The device of claims 1 or 2, wherein the first endcap comprises a first duct formed therein
for applying the vacuum pressure around the at least three interdigitated layer segments, and
the second endcap having a second duct formed therein for applying the positive pressure
20 around the first enclosure.

4. The device of claims 1 or 2, wherein the first endcap is a closed endcap and the second
endcap comprises a first duct formed therein for applying the vacuum pressure around the at
least three interdigitated layer segments and a second duct formed therein for applying the
positive pressure around the first enclosure.

25 5. The device of claim 4, wherein the second duct comprises two pneumatic airflow ports.

6. The device of any one of the preceding claims, wherein each of the first and second
endcaps comprise at least three mounting surfaces for mounting respective ones of the at least
three interdigitated layer segments, wherein the at least three mounting surfaces are disposed
in respective orientations of the stacked layers of the respective at least three interdigitated
30 layer segments around the longitudinal axis of the tunable stiffness device.

7. The device of any one of the preceding claims, wherein the device is configured for use in
an system for rotational damping, wherein an overshoot of the under-damped system is
tunable by varying the vacuum pressure.

8. The device of any one of the preceding claims, wherein the device is configured for use in a system for linear force generation, wherein a magnitude of the generated linear force is tunable by varying the vacuum pressure.
9. The device of any one of the preceding claims, wherein the device is configured for use in a system for torque force generation, wherein a magnitude of the generated torque force is tunable by varying the vacuum pressure.
10. The device of any one of the preceding claims, wherein the device is configured for use in a system for linear damping, wherein damping properties of the linear damping system are tunable by varying the vacuum pressure.
11. The device of any one of the preceding claims, wherein the device is configured for use in a system for rotational damping, wherein damping properties of the rotational damping system are tunable by varying the vacuum pressure.
12. The device of any one of the preceding claims, wherein the device is configured for use in a system for contractile breaking force generation, wherein a magnitude of the generated contractile breaking force is tunable by varying the vacuum pressure and/or the positive pressure.
13. A method of fabricating tunable jamming brake device, comprising the steps of:
- providing first and second endcaps;
- providing at least three interdigitated layer segments connected to, and extending between, the two endcaps, wherein each interdigitated layer segment comprises a plurality of stacked layers with interfaces between respective portions of pairs of adjacent layers for friction jamming of the layers, and wherein a first layer of each pair of adjacent layers is connected to the first endcap and a second layer of each pair of adjacent layers is connected to the second endcap;
- providing a first enclosure enclosing the at least three interdigitated layer segments such that a vacuum pressure can be applied around the at least three interdigitated layer segments; and
- disposing the at least three interdigitated layer segments around a longitudinal axis of the device with at least two different orientations of the stacked layers.
14. The method of claim 13, comprising providing a second enclosure enclosing the first enclosure such that a positive pressure equal to or greater than atmospheric pressure can be applied around the first enclosure, whereby the tunable stiffness device can function as a contractile braker.
15. The method of claims 13 or 14, wherein the first endcap comprises a first duct formed therein for applying the vacuum pressure around the at least three interdigitated layer

segments, and the second endcap having a second duct formed therein for applying the positive pressure around the first enclosure.

16. The method of claims 13 or 14, wherein the first endcap is a closed endcap and the second endcap comprises a first duct formed therein for applying the vacuum pressure around the at least three interdigitated layer segments and a second duct formed therein for applying the positive pressure around the first enclosure.

17. The method of claim 16, wherein the second duct comprises two pneumatic airflow ports.

18. The method of any one of claim 13 to 17, wherein each of the first and second endcaps comprise at least three mounting surfaces for mounting respective ones of the at least three interdigitated layer segments, wherein the at least three mounting surfaces are disposed in respective orientations of the stacked layers of the respective at least three interdigitated layer segments around the longitudinal axis of the tunable stiffness device.

19. The method of any one of claims 13 to 18, wherein the device is configured for use in a system for rotational damping, wherein an overshoot of the under-damped system is tunable by varying the vacuum pressure.

20. The method of any one of claims 13 to 19, wherein the device is configured for use in a system for linear force generation, wherein a magnitude of the generated linear force is tunable by varying the vacuum pressure.

21. The method of any one of claims 13 to 20, wherein the device is configured for use in a system for torque force generation, wherein a magnitude of the generated torque force is tunable by varying the vacuum pressure.

22. The method of any one of claims 13 to 21, wherein the device is configured for use in a system for linear damping, wherein damping properties of the linear damping system are tunable by varying the vacuum pressure.

23. The method of any one of claims 13 to 22, wherein the device is configured for use in a system for rotational damping, wherein damping properties of the rotational damping system are tunable by varying the vacuum pressure.

24. The method of any one of claims 13 to 23, wherein the device is configured for use in a system for contractile breaking force generation, wherein a magnitude of the generated contractile breaking force is tunable by varying the vacuum pressure and/or the positive pressure.

1/18

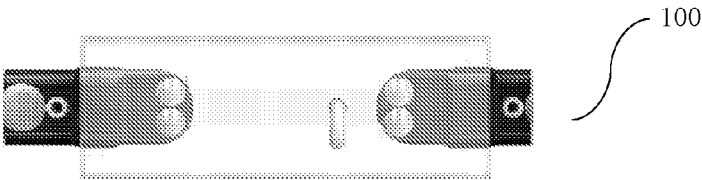


FIG. 1A

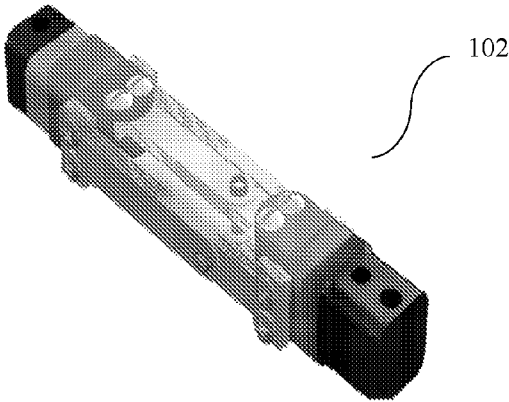


FIG. 1B

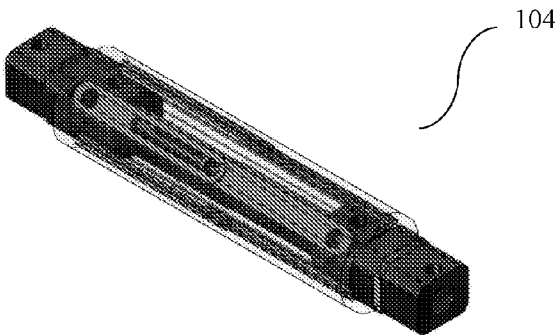


FIG. 1C

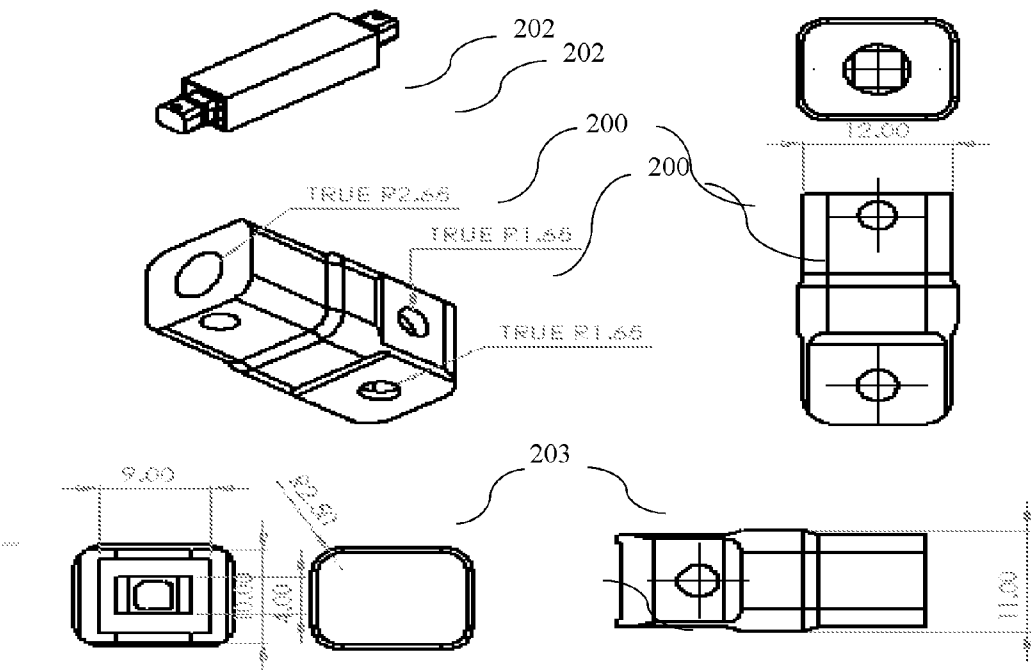


FIG. 2A

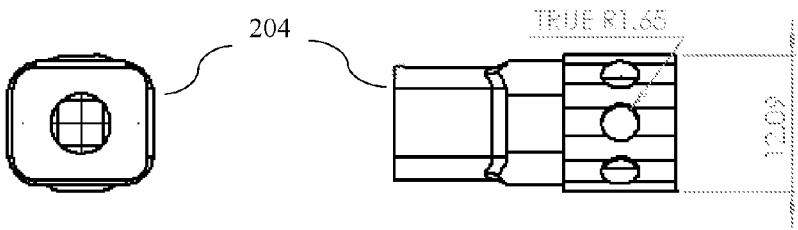


FIG. 2B

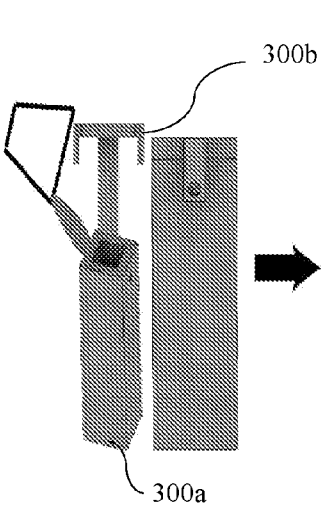


FIG. 3A

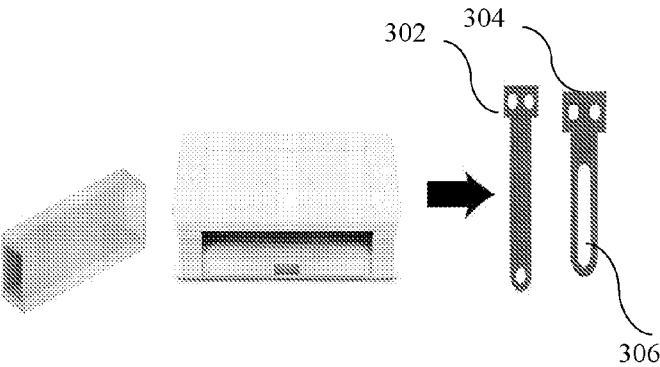


FIG. 3B

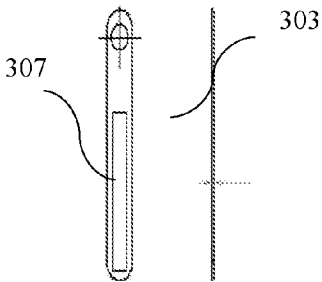


FIG. 3C

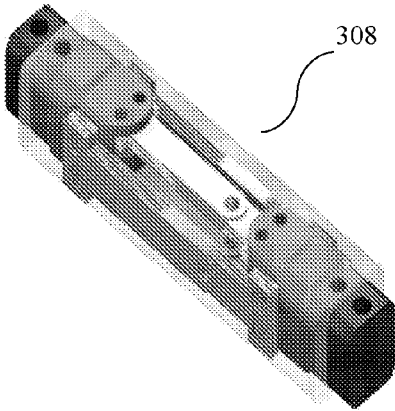


FIG. 3D

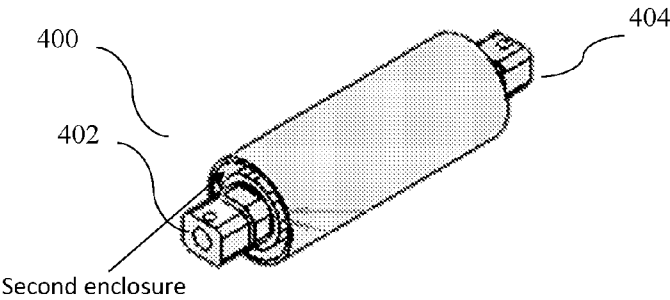


FIG. 4A

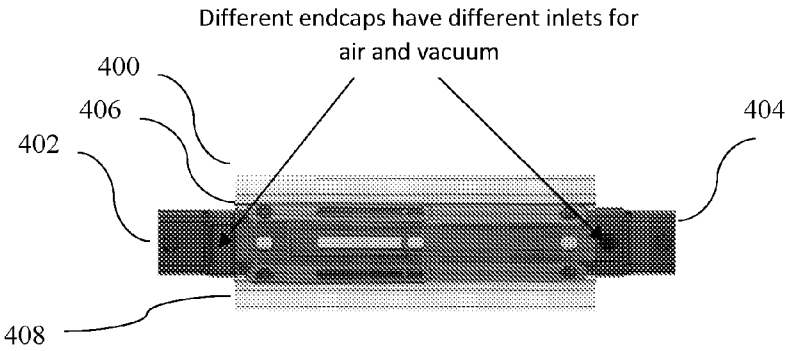


FIG. 4B

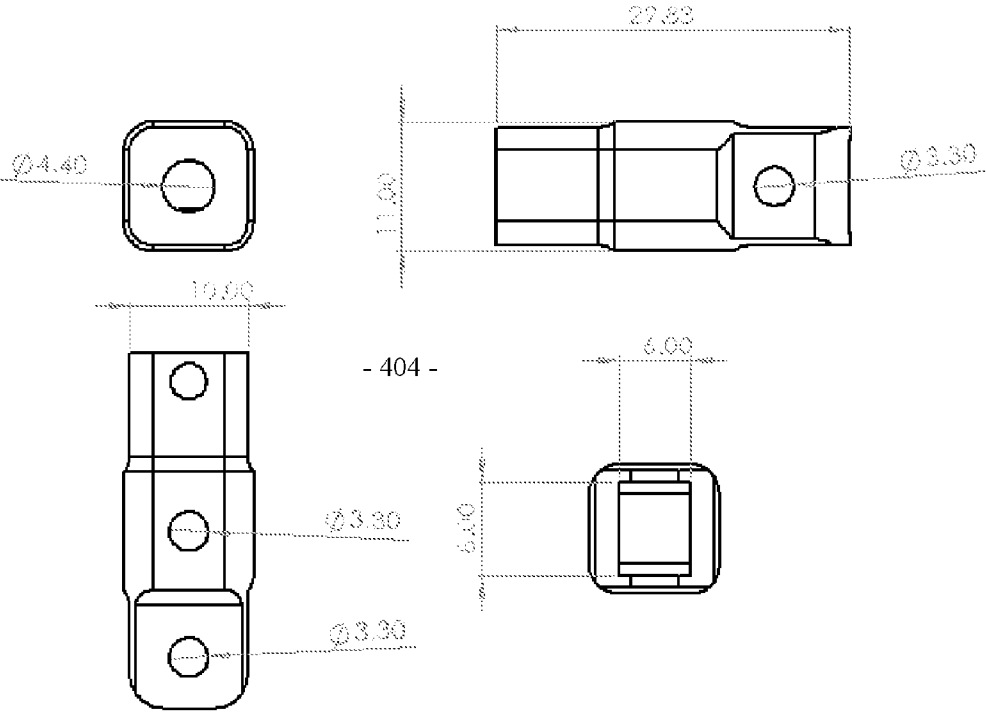


FIG. 4C

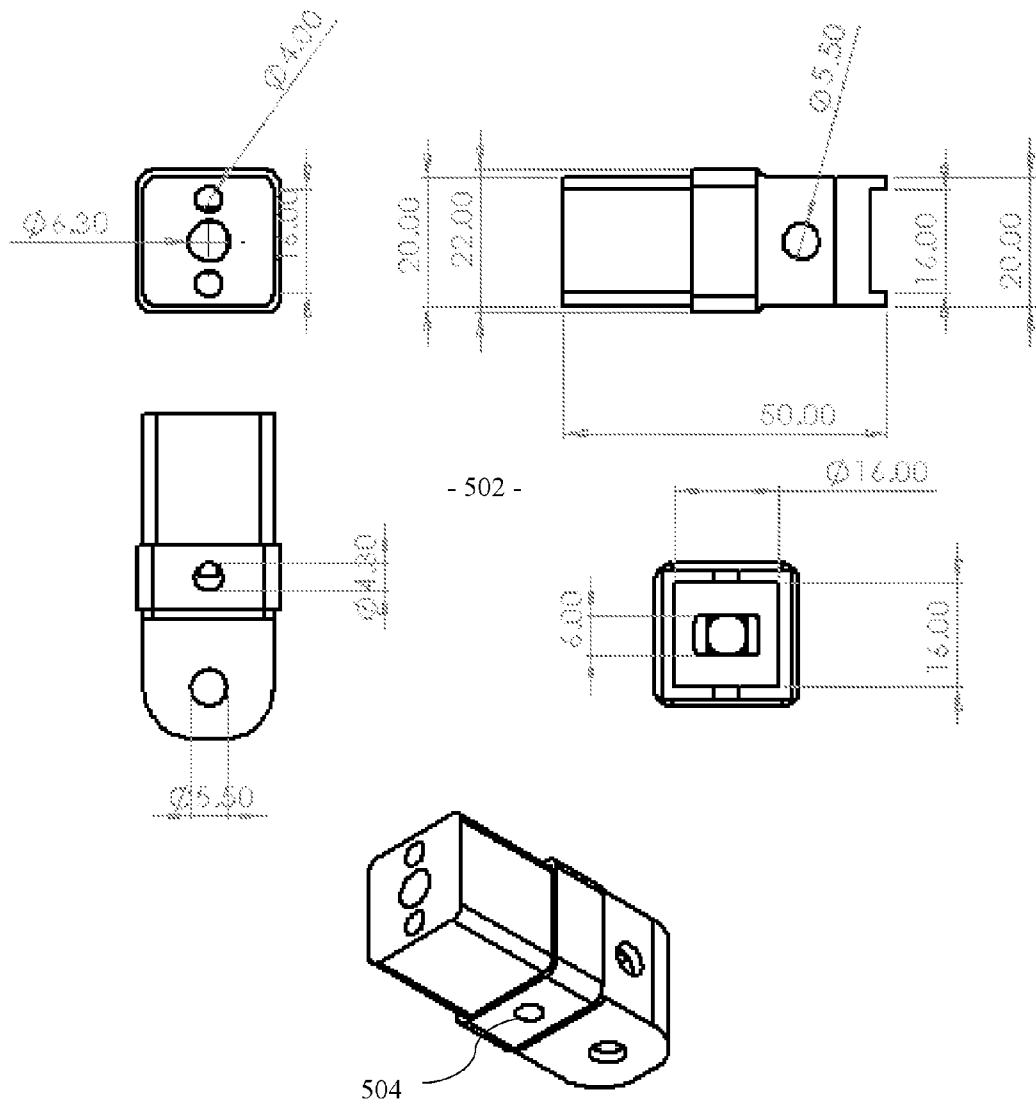


FIG. 5

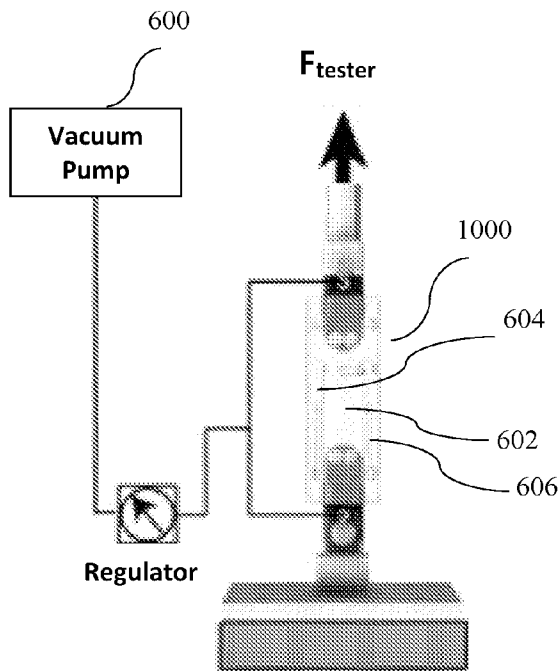


FIG. 6A

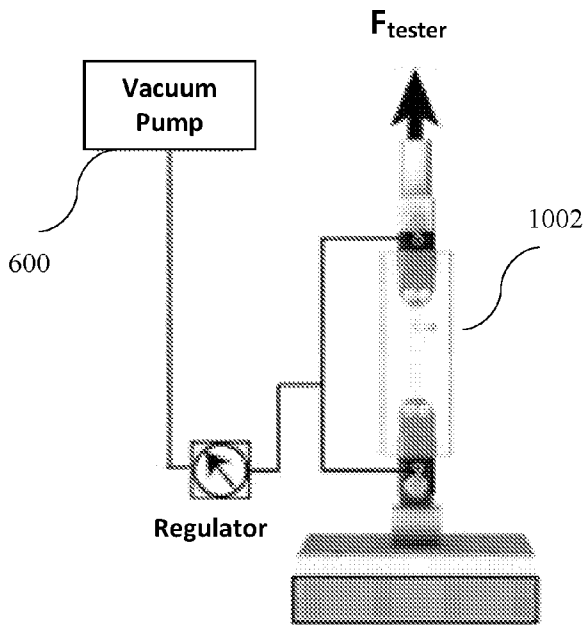


FIG. 6B

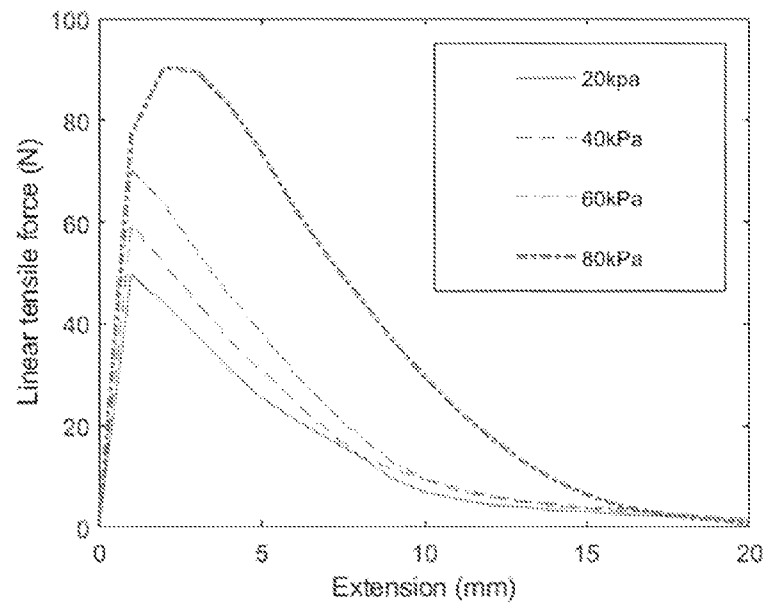


FIG. 7A

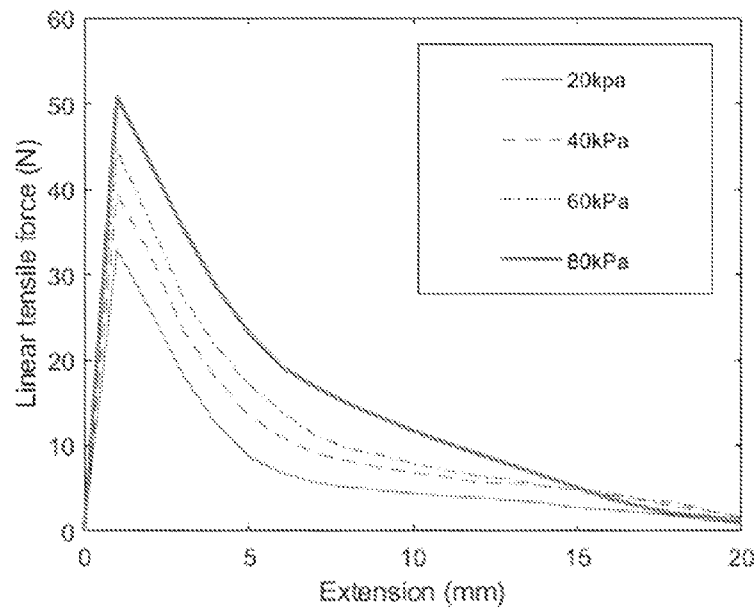


FIG. 7B

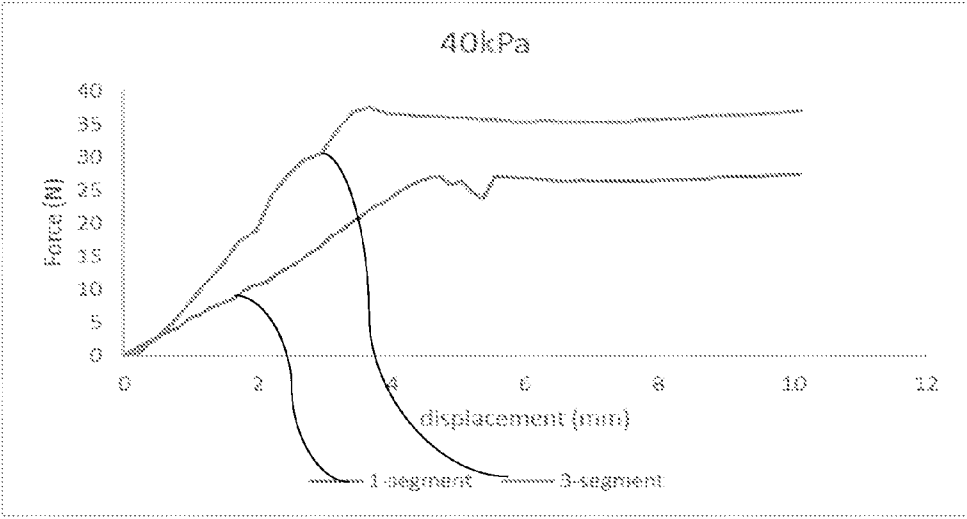


FIG. 8A

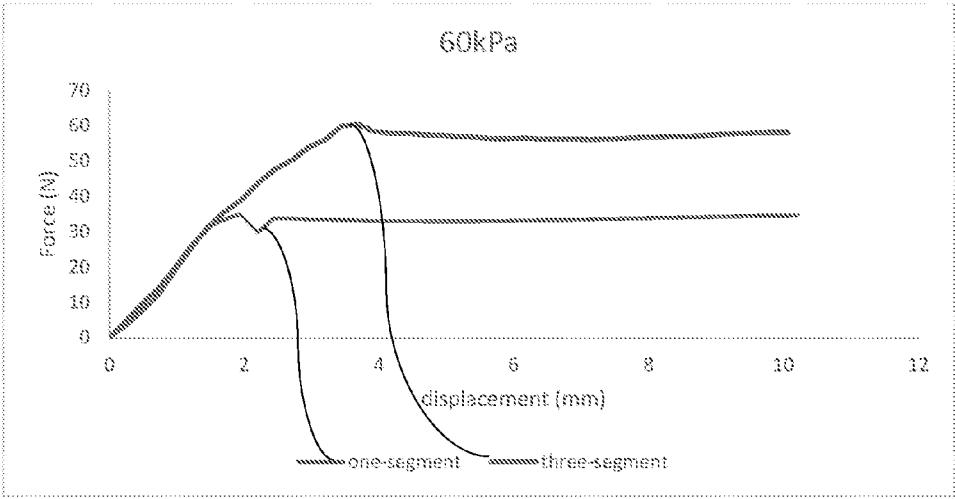


FIG. 8B

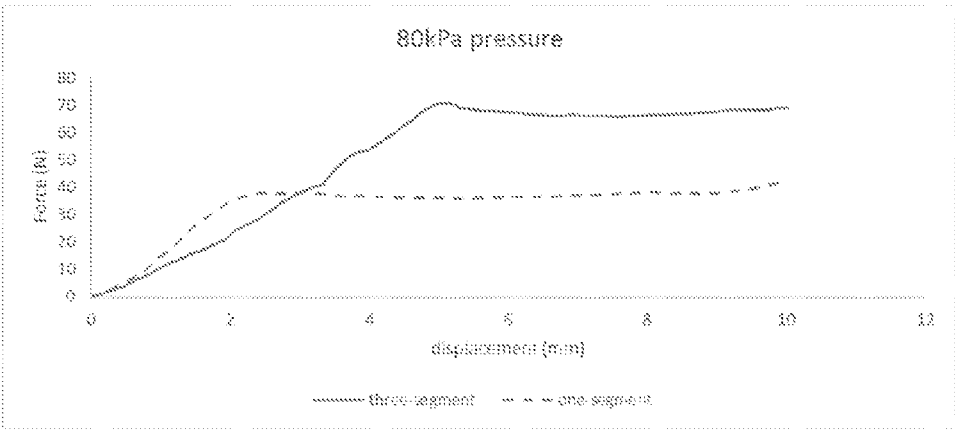


FIG. 8C

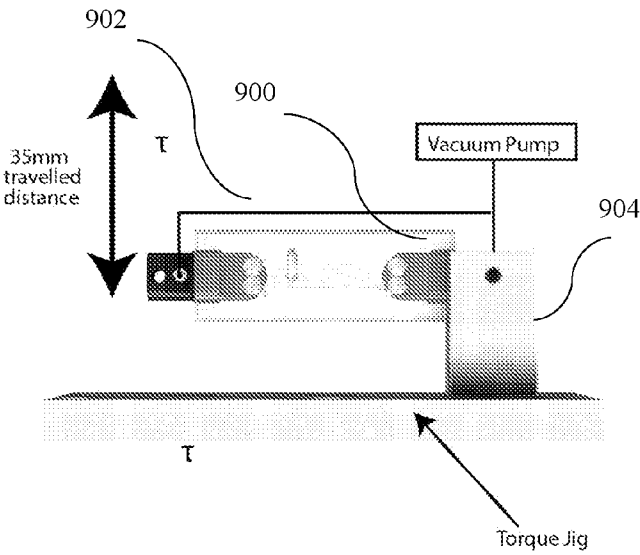


FIG. 9

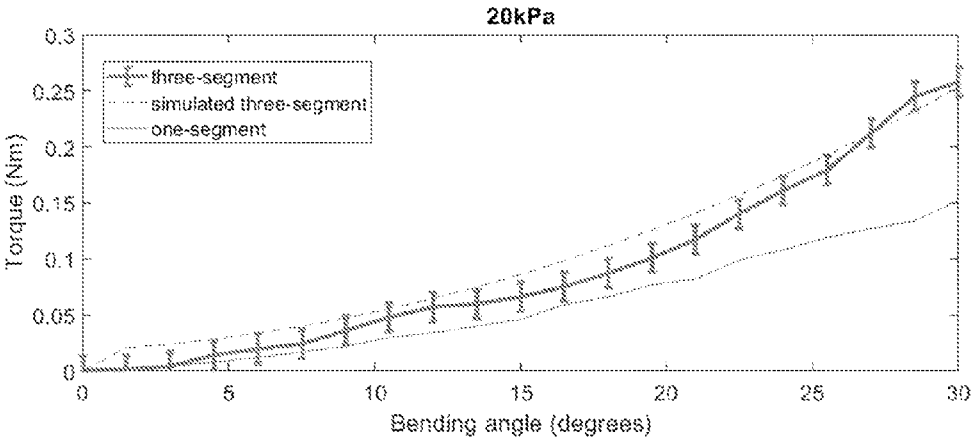


FIG. 10

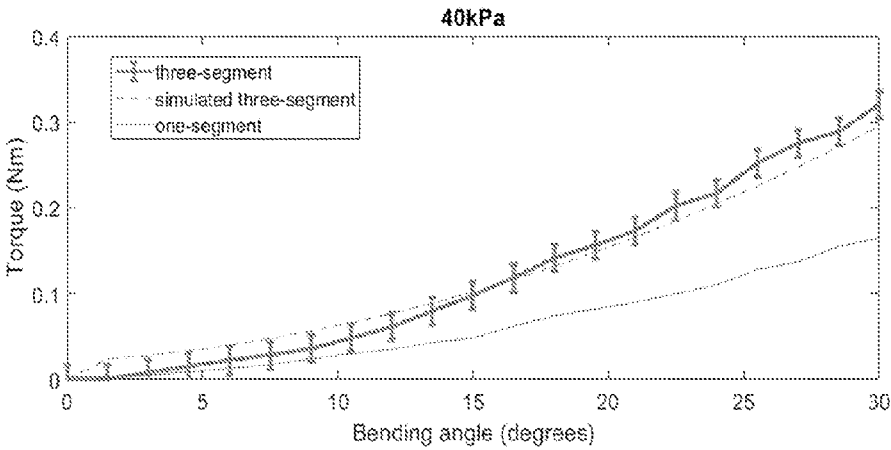


FIG. 11

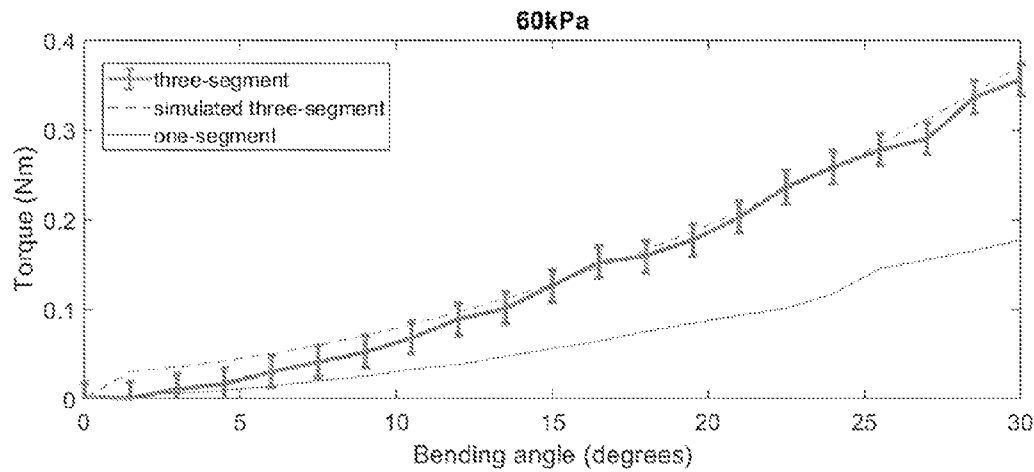


FIG. 12

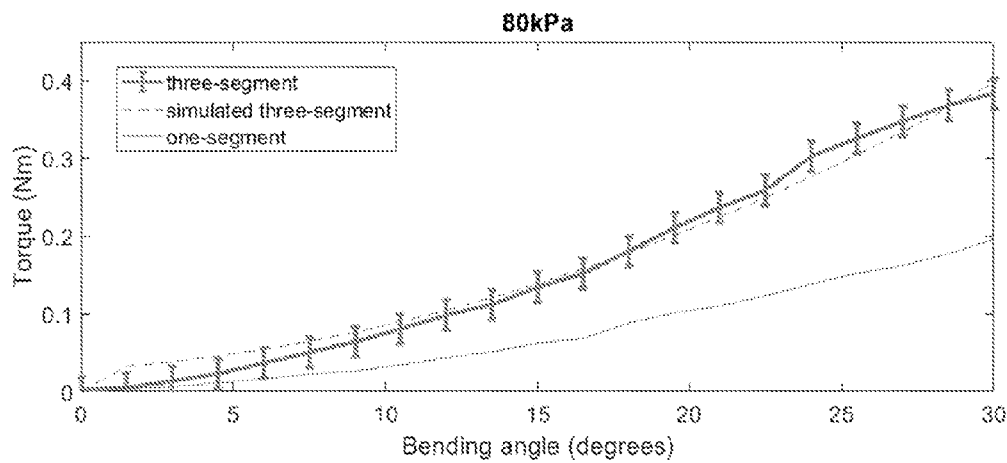


FIG. 13

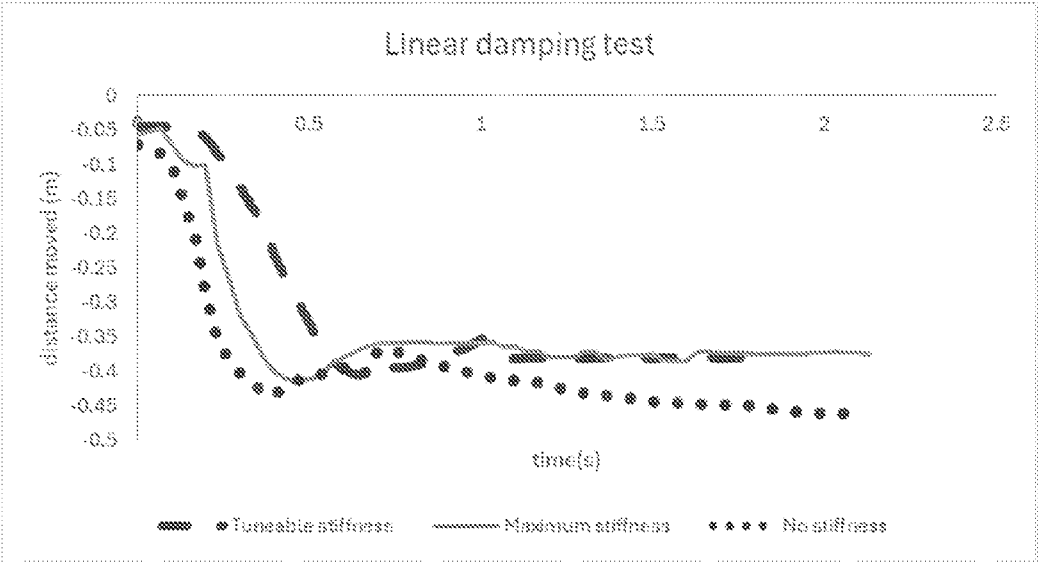


FIG. 14

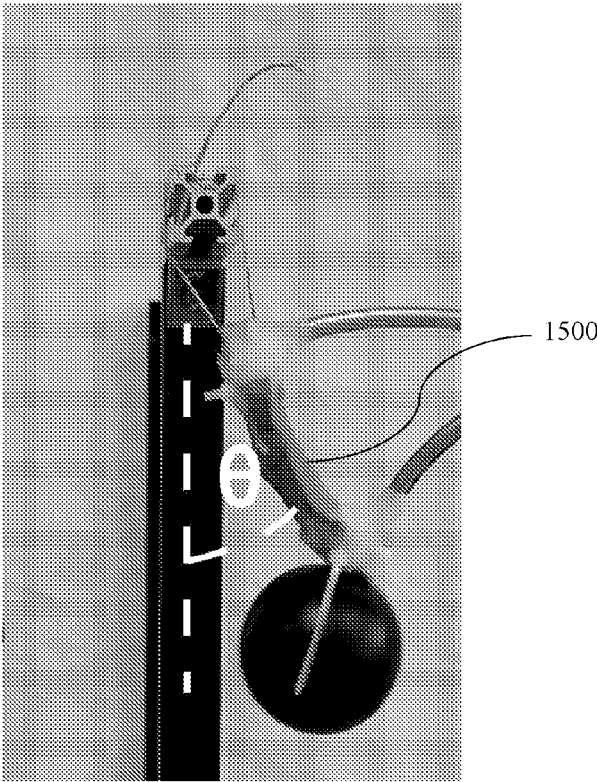


FIG. 15

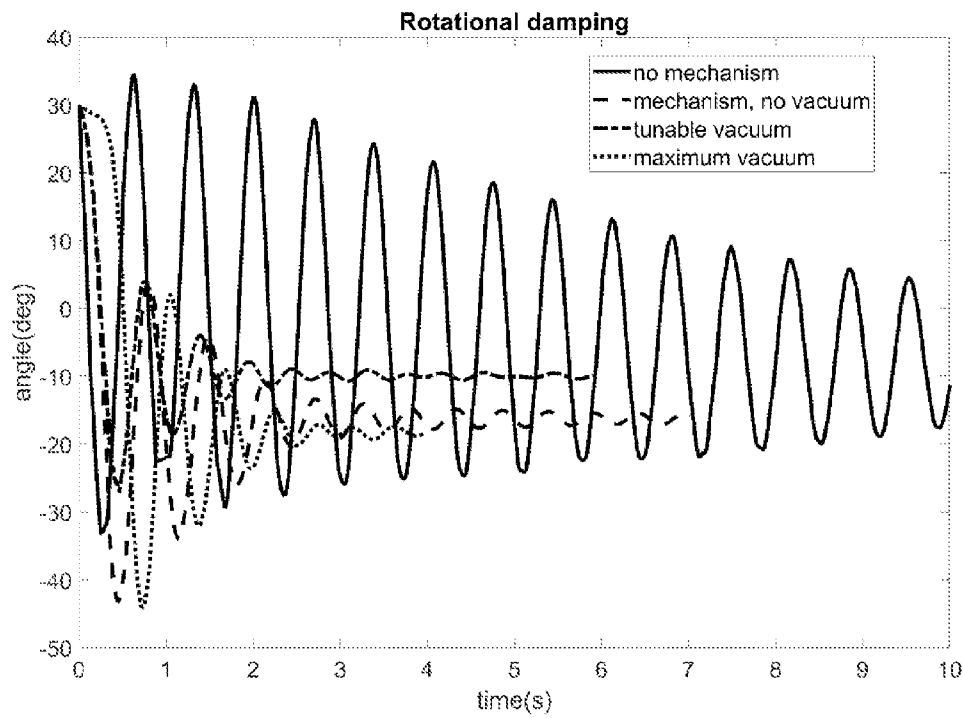


FIG. 16

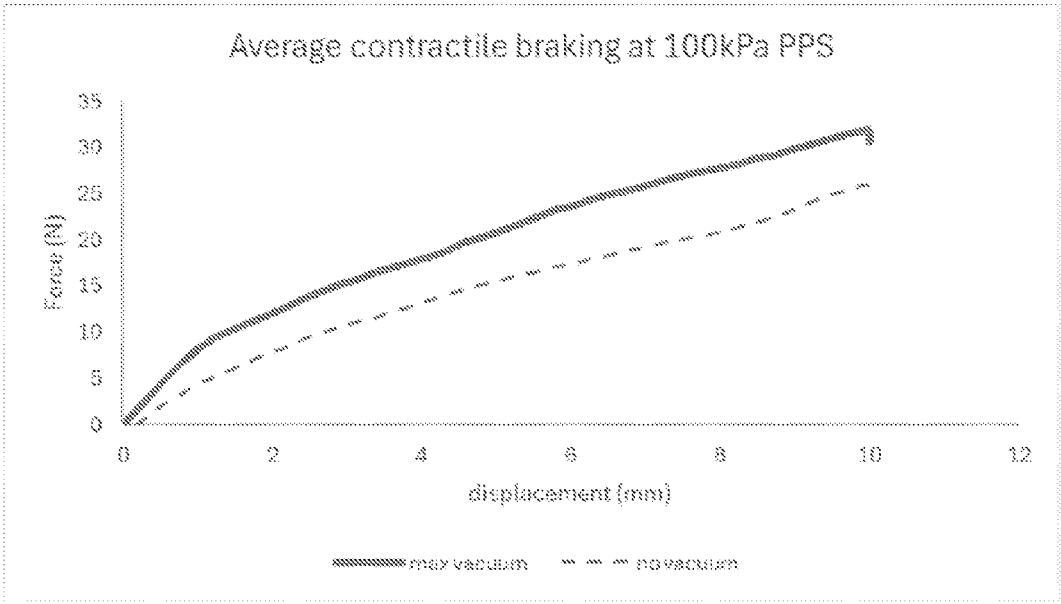


FIG. 17A

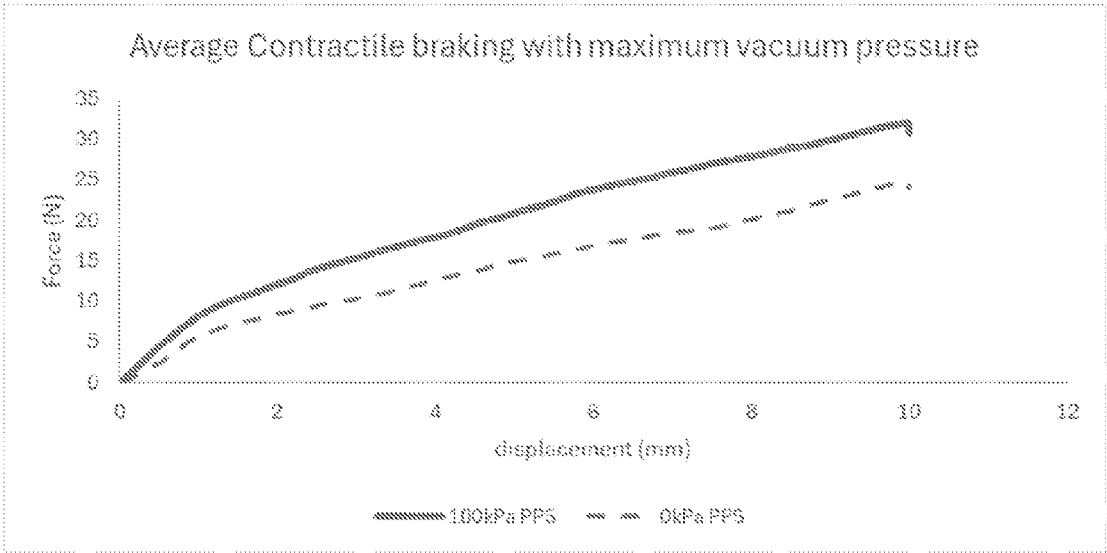


FIG. 17B

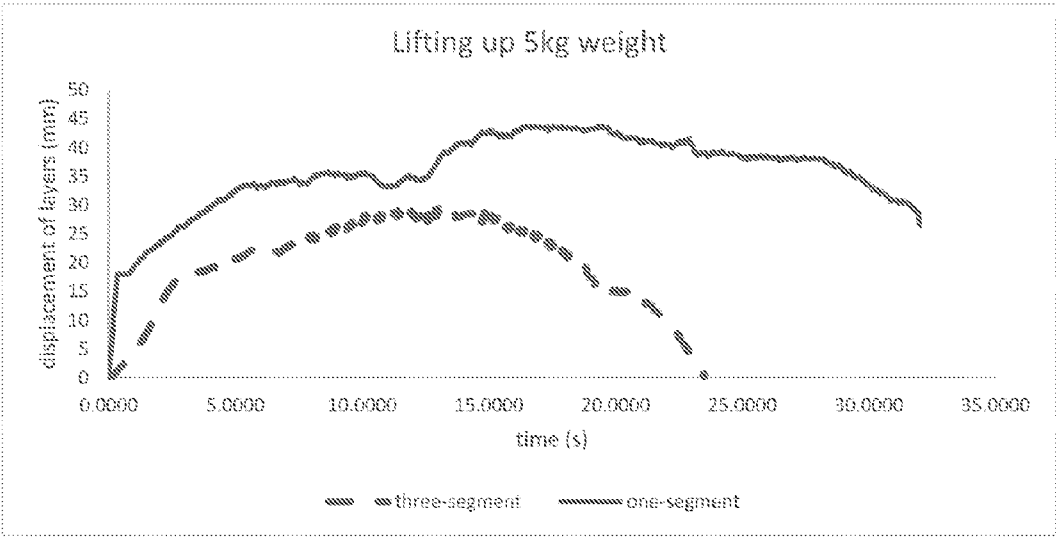


FIG. 18

17/18

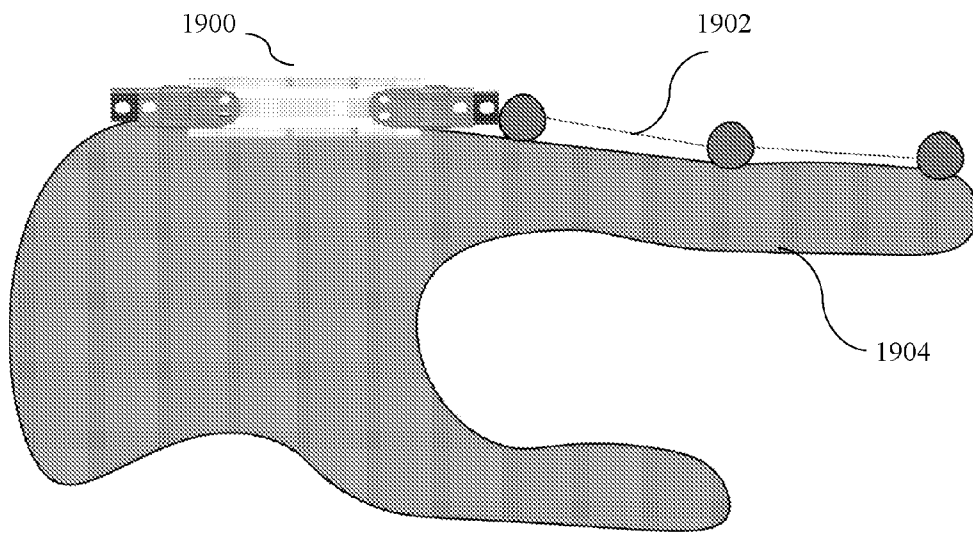


FIG. 19

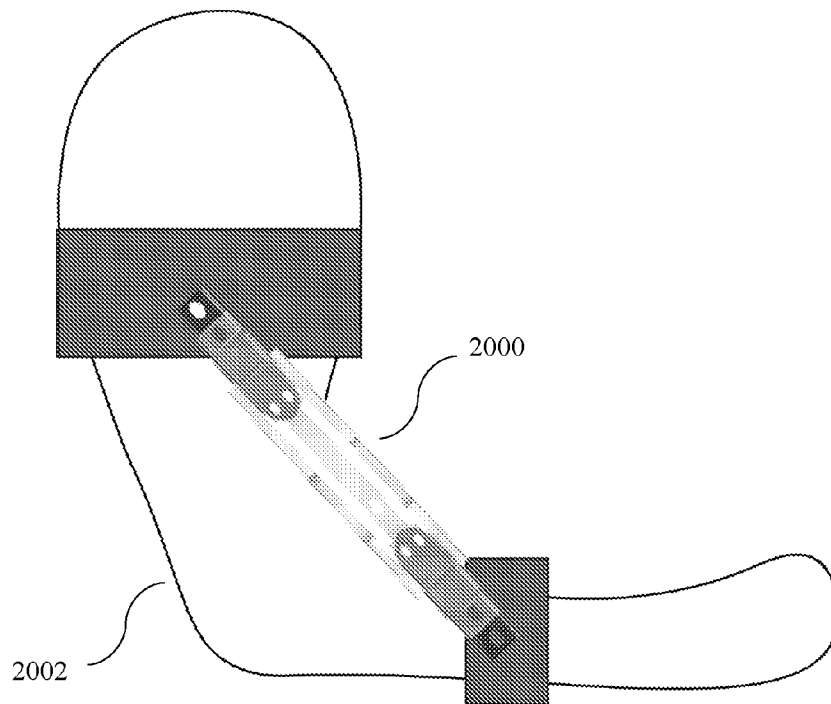


FIG. 20

18/18

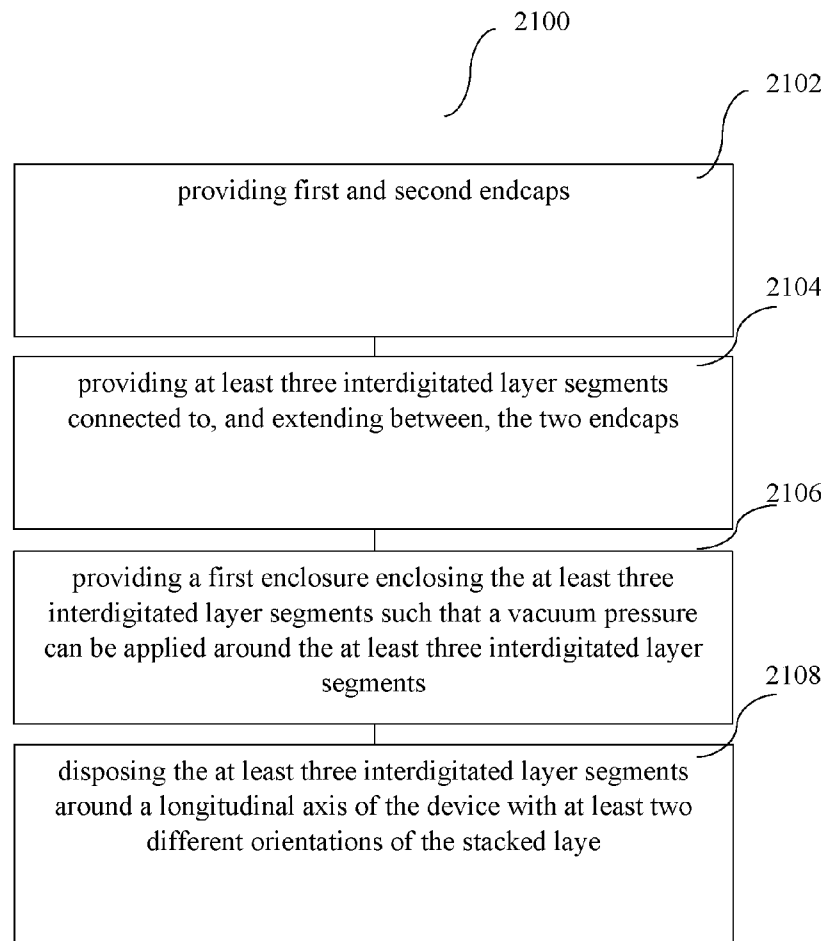


FIG. 21

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2024/050372

A. CLASSIFICATION OF SUBJECT MATTER**B25J 9/14 (2006.01) B25J 11/00 (2006.01) F15B 15/00 (2006.01)**

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B25J, F15B

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT and internet-based database:

robot, manipulator, layer, jamming, brake, stiffness, vacuum, negative, positive, pressure, orientation, direction, axis, 机器人, 机械臂, 片层, 阻塞, 刚度, 硬度, 正压, 负压, 方向 and similar relevant terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2021/0206005 A1 (SU, H. ET AL.) 8 July 2021 Figs. 1A, 1F, 1G, 1K, para. [0071], [0074]	1,6-13, 18-24 2-5, 14-17
Y	US 2019/0106916 A1 (SUTHERLAND, I.J. ET AL.) 11 April 2019 Para. [0058]	2-5, 14-17
Y	DE 102018103893 A1 (DEUTSCH ZENTR LUFT & RAUMFAHRT ET AL.) 22 August 2019 Claim 1 of the machine translation	2-5, 14-17

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.***Special categories of cited documents:**

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

06/09/2024

(day/month/year)

Date of mailing of the international search report

09/09/2024

(day/month/year)

Name and mailing address of the ISA/SG

**Intellectual Property Office of Singapore**

1 Paya Lebar Link, #11-03

PLQ 1, Paya Lebar Quarter

Singapore 408533

Email: pct@ipos.gov.sg

Authorized officer

Chen Jiahe (Dr)

IPOS Customer Service Tel. No.: (+65) 6339 8616

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2024/050372

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2023/056434 A1 (UNIV YALE) 6 April 2023 Whole document	
A	CN 114670184 A (RIVER AND SEA UNIV) 28 June 2022 Whole document of the original non-English language document (a machine translation is enclosed only for your reference)	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2024/050372

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

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2021/0206005 A1	08/07/2021	US 2023/0381977 A1	30/11/2023
US 2019/0106916 A1	11/04/2019	DE 102018124921 A1 CN 109629939 A	11/04/2019 16/04/2019
DE 102018103893 A1	22/08/2019	NONE	
WO 2023/056434 A1	06/04/2023	NONE	
CN 114670184 A	28/06/2022	NONE	