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Negative-Pressure Soft Linear Actuator with a Mechanical Advantage

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Soft, linear actuators (those that generate motions in a straight line, for example, the muscles of animals[1]) have emerged from evolution as the best solution for moving limbed organisms such as vertebrates and arthropods (as well as many organisms without limbs, such as mollusks, annelids, and jellyfish) in an unstructured environment. Their compliance enables adaptive interactions with the environment, and nondamaging (if required) contact with one another. At the same time, this compliance reduces the cost to the organism of precise controls and feedback loops.[2,3] Linear actuation is also particularly compatible with a limbed body-plan in its geometric adaptability since this body-plan is often based on rigid or semi-rigid structural elements (the skeleton), which move relative to one another by linear contraction of muscles around fulcra (e.g., joints). Hard, human-engineered machines now often use the rotary motion of electric motors, although pneumatic and hydraulic pistons (based on force generated by expansion of hot gas, pressurized air, vacuum, or pressurized liquid), other actuators (e.g., magnetic solenoids), and transducers of biomechanical forces (e.g., screw drivers) are also important. A key characteristic of soft machines is that they can be made collaborative (e.g., intrinsically safe in close proximity to humans).

Devices or systems that generate a mechanical advantage, levers, gears, chain drives, block and tackles, and others, are useful in amplifying either force or displacement in hard machines. Humans and other vertebrates also use hard levers, system of bones, articulated joints, and tendons, to amplify the displacement that muscles generate (albeit at the cost of reduced force).[1] A device that generates a mechanical advantage, i.e., amplifies force, in a soft system would expand the capabilities of soft robots and machines. This paper reports the first of such devices. The compliance of pneumatic soft actuators allows them to distribute their stress over large areas,[2] but it also means the pressure output of these systems is often limited by their pressure input, and thus also by the mechanical characteristics, especially the Young's Modulus, of the material of which they are made.[4] A soft pneumatic actuator designed to generate a mechanical advantage would help to overcome this limitation.

Our goal was to introduce mechanical advantage into a soft pneumatic actuator. **Figure 1**A is a conceptual picture summarizing this goal. Compared to lifting a weight (generating $mg\Delta h$ work) directly using a pneumatic piston (supplying $P\Delta V$ work), pulling a weight on a slope increases the weight m pulled per applied pressure P, while decreasing the height Δh per volume change ΔV. The objective here is to realize this mechanical advantage in a soft actuator without using an external slope.

This paper demonstrates a new design of a soft linear actuator that generates a tunable mechanical advantage. For simplicity, we call these structures "shear-mode vacuum-actuated machines," and abbreviate them with the acronym "shear-vacuum-actuated machines (VAMs)." A shear-VAM comprises two flexible but inextensible strips bridged by tilted parallel beams. These beams can be fabricated of an elastomer, a composite of soft and rigid material, or rigid structures (trusses) that can pivot on their ends; the system we have explained are of the first (elastomeric) class. The spaces between the beams are sealed pneumatically with two thin elastomeric membranes, and thus form void chambers within. These chambers are connected to a single external vacuum source (or, in more complex devices, multiple independently controllable sources). Through a network of channels embedded in the structure, a shear-VAM operates by reducing the pressure of void chambers in an elastomeric structure to below that of atmospheric pressure (that is, to negative pressure, or partial vacuum). When the chambers are evacuated, ambient atmospheric pressure compresses the two inextensible strips together. The design, in which the beams bend more easily than they compress, causes these beams to tilt further; this increase in tilt, in turn, causes the strips to translate parallel to one another, and to generate force (see Figure 1B and Movie S1 in the Supporting Information).

These structures, together with soft actuators that we (in the form of pneu-nets,[5–9] buckling actuators,[10] vacuum-actuated muscle-inspired pneumatic structures[4]), and others (flexible microactuators,[11] jamming grippers,[12] dielectric elastomer-driven actuators,[13,14] shape memory and cable-driven soft arms,[15] etc.) have described, belong to a new class of machines, soft machines,[2,16] which are more collaborative, often more adaptive to irregular targets,[16] and sometimes simpler to control[16] than more familiar hard machines.

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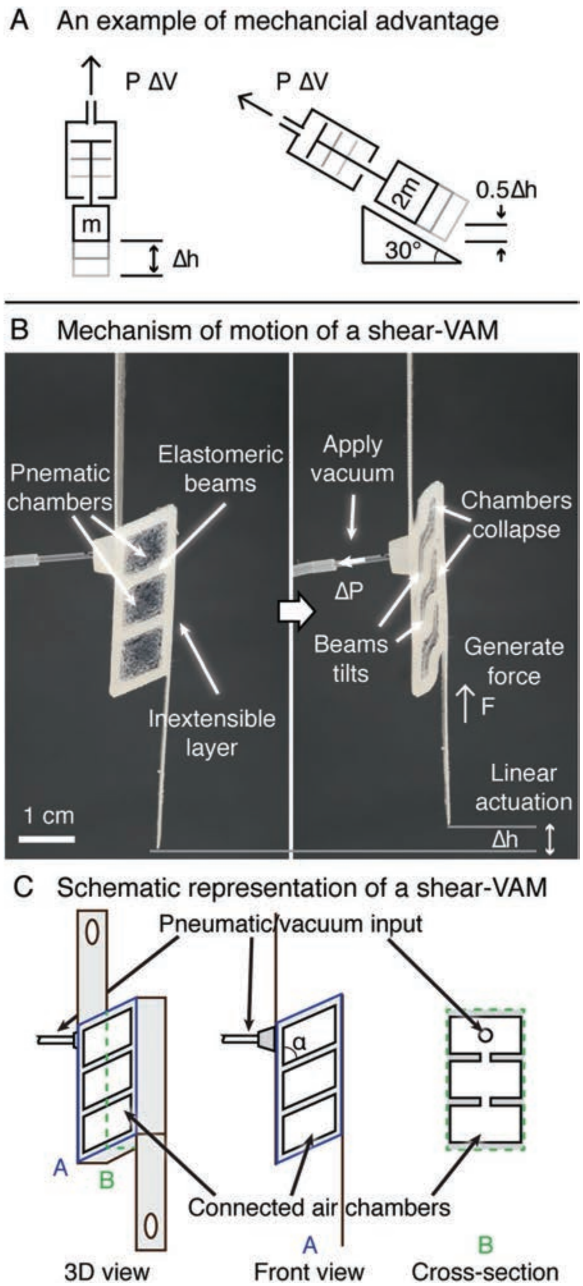

Figure 1. Schematic description of a shear-mode vacuum-actuated machine (shear-VAM). A) An example of mechanical advantage in pneumatic actuation (ignoring effects of friction). B) Mechanism of motion of a shear-VAM. A shear-VAM consists of two flexible but inextensible strips bridged by tilted parallel elastomeric beams, with the closed chambers connected pneumatically to a source of vacuum. When the chambers are evacuated, the two strips come together, while the beams tilt further and push the strips to move parallel to one another, and generate a distance of actuation Δh and/or a force of actuation F (depending on the loading condition). C) Schematic representation of a shear-VAM.

Among these soft pneumatic actuators, we refer to those powered by negative pressure (vacuum) rather than positive pressure as VAMs. These devices allow a range of functions that can sometimes be difficult to achieve by their conventional pressure-driven counterparts. Examples of VAMs include rotary actuators that combine vacuum and reversible buckling of elastomeric beams as their mechanism of action (rotary-VAMs),[10] and linear actuators (using the same mechanism) that mimic the performance, and many useful functions, of human muscle (linear-VAMs).[4]

VAMs such as shear-VAMs are safer around humans than many "hard" actuators, and even ostensibly soft actuators that operate under high positive pressure (e.g., McKibben actuators and many of their relatives[17]). Actuators powered by pneumatics are also safer and less likely to fail than those powered by high voltages (e.g., actuators made with dielectric elastomer, such as those explored by SRI,[13,14] which can fail by dielectric breakdown).

Experimental design of shear-VAMs: A design representative of a simple shear-VAM consists of two flexible but inextensible strips (1.5 mm thick, 17 mm wide, and 10 mm apart) bridged by four tilted parallel elastomeric beams (1.8 mm wide, 8.9 mm long, at 63° angle to the strips, and spaced in 10 mm intervals along the strips, in Figure 1C). We used a Nylon mesh embedded in an elastomer, Ecoflex 00-30 (Young's modulus E = 43 kPa), Dragon Skin 10 Slow (E = 153 kPa), or Elastosil M4601 (E = 520 kPa), for the inextensible layer. We used the same elastomer in the elastomeric beams in shear-VAMs. The empty spaces in between the beams were converted into enclosed chambers by sealing (front and back) with thin membranes made of the same elastomer (1 mm thick). The final structure comprises a pneumatic structure with several chambers connected to a common source of negative pressure (e.g., vacuum, or pressure less than the ambient pressure). The beams each had an opening in the middle (a 3 mm wide slit) such that the chambers were pneumatically connected. The chambers were further connected to an external source of vacuum through a piece of tubing that pierces one of the strips. (Figure S1 in the Supporting Information summarizes details of fabrication.)

Characterizing the maximum force of actuation of shear-VAMs: A shear-VAM is similar to a pneumatic or hydraulic piston, in that it works by converting an applied pneumatic pressure ΔP to an output force F. As we apply an increasing difference of pressure ΔP (as defined in Equation (1)) between that of the atmosphere external to the shear-VAM (P_{ext}), and that of the partial vacuum inside it (P_{int}), its void chambers deflate, and the two inextensible strips translate relative to each other (as shown in Figure 1B and Movie S1 in the Supporting Information)

$$\Delta P = P_{ext} - P_{int} \tag{1}$$

The two inextensible strips move until, at a critical difference of pressure ΔP_{crit}, the void chambers collapse completely (or as completely as they can within the limits of the design) and bring the actuator to a stop. The actuation of a shear-VAM results in a decrease in its length Δh (also indicated in Figure 1). We defined this change in length Δh, effectively the relative distance of translation between the two inextensible strips, to be the distance of actuation of a shear-VAM. The actuation of a shear-VAM also applies a force F, as indicated in Figure 1B and defined in Equation (2), where m is the mass of a test object, and a is the acceleration of that object. We defined this force, the force that lifts and accelerates a load, to be the force of actuation of a shear-VAM

$$F = mg + ma \tag{2}$$

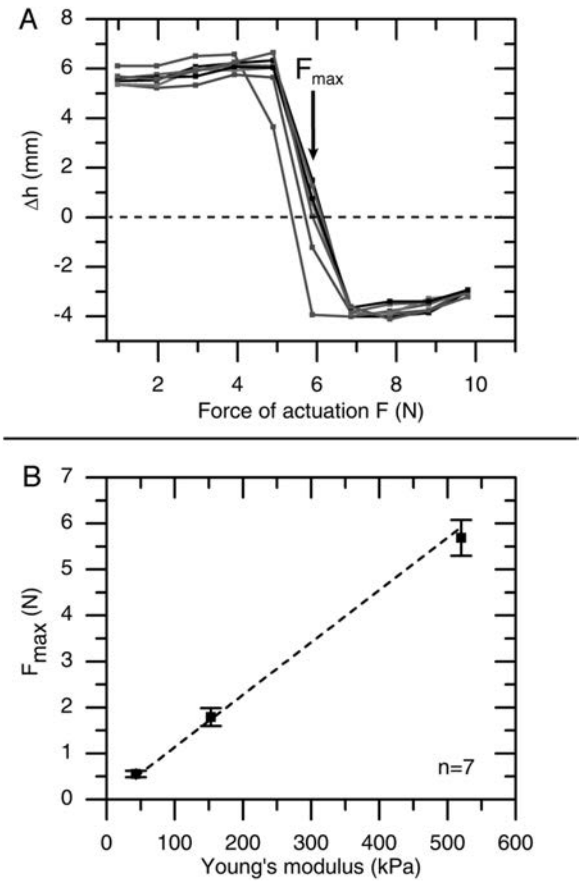

Figure 2. Characterizing the maximum force of actuation of shear-VAMs. A) The relationship between the distance of actuation Δh (in mm) and the force of actuation F (in N) on shear-VAMs, measured on seven different samples made of Elastosil ($E = 520$ kPa). A sufficient difference of pressure $\Delta P = 90\ kPa > \Delta P_{crit}$ is applied to collapse the void chambers completely. B) The relationship between the maximum force of actuation F_{max} of shear-VAMs (in N) and the Young's Modulus E (in kPa) of the elastomer used in fabricating the shear-VAMs.

The distance of actuation Δh (upon application of a difference of pressure $\Delta P > \Delta P_{crit}$) is determined primarily by the geometry of the shear-VAM. **Figure 2**A shows that this distance Δh stays roughly constant when various loading forces F (in N, given by a hanging weight) are applied to the shear-VAM while it actuates, as long as the loading force is less than a certain maximum value F_{max}. We define F_{max} to be the maximum force a shear-VAM of this particular design can generate. For a load F greater than F_{max}, the beams in the shear-VAM will tilt in the opposite direction when the pressure ΔP is increased. In other words, the shear-VAM lifts the weight for a distance of Δh while $F < F_{max}$ (i.e., produces a contraction), and it lowers the weight for a distance of $\Delta h'$ while $F > F_{max}$ (i.e., produces an elongation). Figure S2 and Movie S2 in the Supporting Information demonstrate this effect. The distance of elongation $\Delta h'$ is again roughly constant under various constant loads F greater than F_{max}, as $\Delta h'$ is also determined primarily by the geometry of the shear-VAM.

The value of F_{max} is dependent on various characteristics (geometry and materials parameters) of the actuator. For example, for shear-VAMs that have the same geometry, ones that are stiffer (i.e., made of elastomers with higher Young's modulus) generate a higher force upon actuation than those that are less stiff. Figure 2B shows that the maximum force of actuation F_{max} (in N) of a shear-VAM is proportional to the Young's modulus E (in Pa) of the material of which it is fabricated (Equation (3))

$$F_{max} = kEL^2 \tag{3}$$

where L is the length scale (in this case the length) of the shear-VAM, and k is a dimensionless constant. Figure S3 and Movies S3, S4 in the Supporting Information show shear-VAMs with indistinguishable geometries, but made in different materials, lift different weights.

This linear relationship (Equation (3)) is confirmed theoretically though dimensional considerations (a detailed theoretical analysis is in the Supporting Information). This scaling property (Equation (3)) allows one to construct shear-VAMs capable of generating a high force simply by choosing a stiff elastomer during fabrication.

Characterizing the thermodynamic efficiency of shear-VAMs: The thermodynamic efficiency of transduction of the pressure-volume work required to actuate shear-VAM into mechanical (force × distance) work (e.g., lifting a weight) is primarily governed by the work required to compress the elastomer. (Here, we only account for the pressure–volume work and not the electrical energy required to operate the vacuum pump). The loss of energy due to hysteresis is small relative to the work done to compress the elastomer (details are Figure S6 in the Supporting Information). Our experimental data yield a thermodynamic efficiency of 35% for a distance of actuation of ≈4.7 mm at 200 g loading for the shear-VAM shown in Figure 1B. (For comparison, the corresponding value of a human skeletal muscle is ≈40%).[18] Repeated cycles of actuation can lead to higher efficiency because the energy stored in the deformed, elastomeric components can, in principle, be at least partially recovered during unloading. Another similar VAM, a linear VAM,[4] has a similar potential for recovery of energy (the ability of soft actuators to store and recover energy over repeated cycles of actuation has been reported in a number of designs[18]).

Characterizing the mechanical advantage of shear-VAMs: We define the geometrical parameters that characterize a shear-VAM (**Figure 3**A), where: L is the length of the elastomeric body of the actuator (i.e., the long dimension of the parallelepiped), a is the length of the tilted beams, b is the width of the actuator (i.e., the third dimension of the parallelepiped), α is the angle between the strips and the beams, and $A = L * b$ is the "lateral area" of the shear-VAM (the shaded area in Figure 3A). The force of actuation is approximately given by Equation (4) (the Supporting Information includes a theoretical derivation, and a comparison to conventional pneumatic/hydraulic systems)

$$F = \eta(\alpha) A \Delta P / \tan(\alpha) \tag{4}$$

where $\eta(\alpha)$ is the thermodynamic efficiency of the shear-VAM for an infinitesimal movement near angle α. This value is approximately equal to the total thermodynamic efficiency of the shear-VAM η.

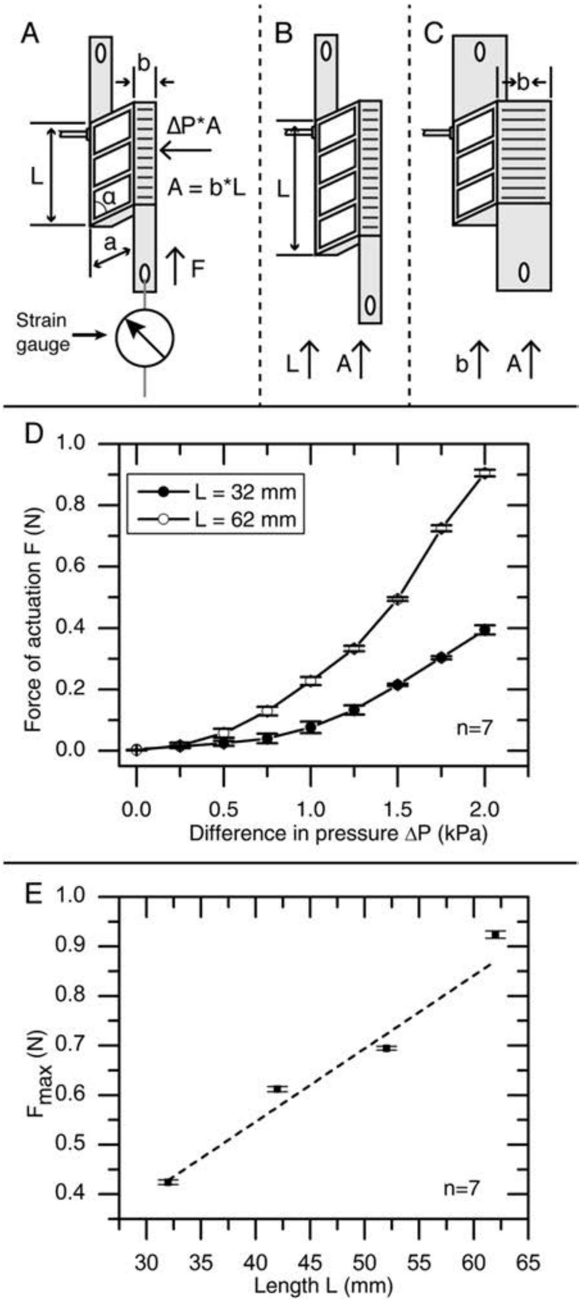

Figure 3. Characterizing the mechanical advantage of shear-VAMs. A) A schematic diagram marks different dimensions of a shear-VAM (length L, beam length a, width b, beam angle α, and lateral area A). B, C) Schematic drawings illustrate increasing either the length L or width b of a shear-VAM increases its lateral area A, and thus increases the force of actuation F (Equation (4)). D) The relationship between the force of actuation F of shear-VAMs of two different lengths L = 62 and 32 mm (each connected to a fixed strain gauge), and the difference of pressure ΔP (in kPa) applied across these shear-VAMs (see Figure S6 in the Supporting Information for details of this measurement). Data shown are mean ± S.D. ($n = 7$ repeated measurements). E) The maximum force of actuation of shear-VAMs F_{max} (in N) made of Ecoflex (E = 43 kPa) versus their length L.

Equation (4) indicates that we can increase the force of actuation of a shear-VAM by increasing the lateral area of the shear-VAM $A = Lb$ (Figure 3A). Assuming the pneumatic source (not shown in Figure 3A) has a fixed working area (e.g., area of the diaphragm of a pump, or the area of the plunger of a syringe) of A_0, it generates a driving force of $F_{in} = A_0\,\Delta P$. The shear-VAM demonstrates a net mechanical advantage (MA) given by Equation (5)

$$\mathrm{MA} = F/F_{in} = \eta A/\left(A_0 \tan(\alpha)\right) \tag{5}$$

We note that the mechanical advantage of a shear-VAM can be, in principle, increased indefinitely as we increase the lateral area A (although the MA is, of course, limited by the tensile strength of the strips). Figure 3B,C illustrates two cases where we increase either the length L or the width b to increase the lateral area A, and consequently, to boost the force of actuation F.

In particular, increasing the length L allows a shear-VAM to increase its force of actuation F without increasing the apparent cross-sectional area $ba\sin(\alpha)$. This feature allows shear-VAMs to have a mechanical advantage not only for force, but also for pressure. This mechanical advantage ($\mathrm{MA_p}$) is defined as the ratio of the pressure that performs useful work to the pressure that is applied (Equation (6))

$$\mathrm{MA_p} = P_{out}/P_{in} = \eta L/\left(a\sin(\alpha)\right) \tag{6}$$

where $P_{out} = \dfrac{F}{ba\sin(\alpha)}$, and $P_{in} = \Delta P$

Equation (5) also indicates another source of mechanical advantage, which comes by changing the angle α. Due to the inverse relationship between mechanical advantage MA and $\tan(\alpha)$, one can increase the mechanical advantage of any shear-VAM simply by reducing the angle α. When the angle α is small, the distance of actuation Δh per unit of change in angle $\Delta\alpha$ is also smaller, a tradeoff of smaller distance for larger force of actuation F.

Figure 3D shows the relationship between the force of actuation F of shear-VAMs of two different lengths L=62 and 32 mm (each connected to a fixed strain gauge), and the difference of pressure ΔP (in kPa) applied across the inside and outside (the ambient atmosphere) of the void chambers of these shear-VAMs (Figure S6 in the Supporting Information for details of this measurement). At the same ΔP, the curves show a near doubling of force of actuation F, when the length L is doubled, a result consistent with Equation (4). Figure 3E shows that the maximum force of actuation of shear-VAMs F_{max} also increases with their length L, consistent with Equation (4). The plot verifies that the relationship is linear. Error bars in Figure 3D,E were measured from seven replicate measurements of the same sample (standard deviation of measurements on different devices are larger than those from repeated measurements of the same device, as shown in Figure S4 in the Supporting Information, but can in principle be greatly reduced in machine-made devices as opposed to handmade ones).

Parallel actuation and stackability of the shear-VAMs: Multiple shear-VAM units can be positioned in parallel or in series and actuated together to generate more force or more distance of actuation (see **Figure 4** and Movies S5 and S6 in the Supporting Information). Figure 4A shows two shear-VAMs working in parallel in a mirror configuration. This configuration generates about twice as much force (≈2F) as a single shear-VAM of the

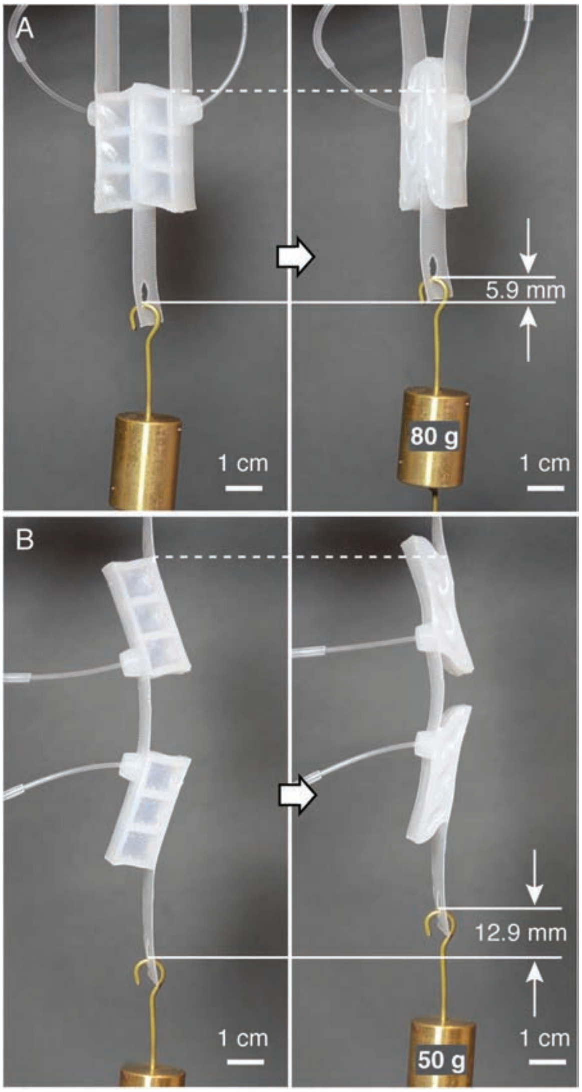

Figure 4. Multiple shear-VAMs working in combination. A) Two shear-VAMs working in parallel in a mirror configuration. This configuration generates about twice as much force compared to a single shear-VAM of the same geometry, but has about the same distance of actuation. B) Two shear-VAMs working in series. This configuration has about twice as much distance of actuation as a single shear-VAM of the same geometry, but generates about the same force.

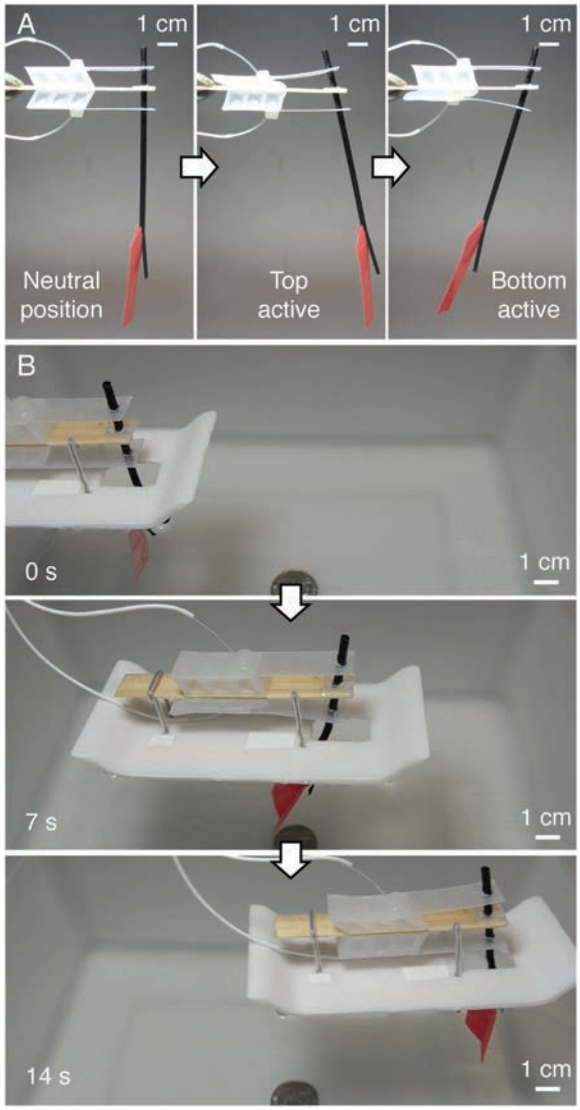

Figure 5. Soft robot actuated with shear-VAMs. A) Two shear-VAMs in an agonist–antagonist arrangement can drive a paddle back and forth. The paddle can pivot around its connection backward but not forward. This mechanism can be used in a soft machine that paddles. B) A soft robotic swimmer with a paddle powered by two shear-VAMs in an agonist–antagonist arrangement. Scale bars are 1 cm long. A quarter coin in the water also marks the scale.

same length L, but has about the same distance of actuation ($\approx\Delta h$). Figure 4B shows two shear-VAMs working in series. This configuration has about twice the distance of actuation ($\approx 2h$) as a single shear-VAM of the same geometry, but generates about the same force ($\approx F$). These force or distance scaling relationships are universal to parallelizing or stacking of any linear actuator. Shear-VAMs, in particular, are naturally fit for parallelization, as their lateral areas remain flat during actuation (as shown in Figure 4A; the same is not true for other pneumatic linear actuators such as McKibben actuators).

Using shear-VAMs in robots that locomote: The agonist–antagonist arrangement is useful in the muscle of animals in enabling more effective movements. Since shear-VAMs resemble biological muscle in that they are soft linear actuators, this arrangement can be borrowed in making devices with shear-VAMs that move or locomote. **Figure 5** and Movies S7, S8 in the Supporting Information show a swimming device that uses a pair of shear-VAMs in an agonist–antagonist arrangement to drive its paddle. The paddle moves either forward or backward when the corresponding shear-VAMs actuate and pull the lever that is connected to the paddle. The paddle can pivot around its connection backward but not forward, this design helps to generate a hysteresis that is required to propel the swimmer forward in water.

In conclusion, shear-VAMs have three characteristics that are useful for making soft machines. (i) They provide a tunable mechanical advantage. (ii) They can be easily used in series or

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in parallel. (iii) They contract rather than expand in volume on actuation. Shear-VAMs and other soft pneumatic actuators are useful in supplementing more familiar hard machines with the following advantages: (i) increased safety in use around humans or animals, and nondamaging interactions with delicate objects; (ii) low cost of fabrication; (iii) light weight and low density (the actuating fluid is air, and the elastomers we use have densities around ≈1 g cm^{-3}).

A shear-VAM is a soft linear actuator that works by converting the pneumatic pressure applied perpendicular to its inextensible lateral surfaces to a force parallel to them via tilted elastomeric beams. It provides a mechanical advantage (that is, magnification) in terms of both force and pressure relative to the input. It does so by increasing its length (for both force and pressure) or width (for only force). The design of shear-VAM provides a new tool for making biomimetic and/or functional soft machines. Shear-VAMs could, in particular, be useful for generating high forces or generating reasonable forces with a small input pressure in a soft structure.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgments

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