SOFT ROBOTICS
Volume 00, Number 00, 2017

DOI: 10.1089/soro.2016.0078

ORIGINAL ARTICLE

A Soft Tube-Climbing Robot

Mohit S. Verma,[1,*] Alar Ainla,[1,*] Dian Yang,[1,2,*] Daniel Harburg,[1] and George M. Whitesides[1,3,4]

Abstract

This article demonstrates a pneumatically actuated soft robot capable of navigating the inside of a tube. This robot was built using buckling pneumatic actuators (vacuum-actuated muscle-inspired pneumatic structures, or VAMPs). The tube climber can navigate through a tube with turns, inclines, and varying diameters. The robot is also able to remove obstacles (of more than 10 times its own weight) from tubes to perform a clearing function. It maintains climbing and clearing performance in wet conditions and under water. The tube climber is lightweight and completely soft and thus has the potential to be collaborative (i.e., work with humans) and also to interact safely with delicate environments.

Keywords: locomotion, muscle, vacuum, pneumatic, elastomer, buckling

Introduction

The development of soft pneumatic actuators[1–5] driven by vacuum[6–10] and buckling of elastomeric beams[11–17] has made possible a number of new types of motions—and of devices and machines that utilize these new motions—in soft actuators, machines, and robots. These devices (to which collectively we refer as ''buckling actuators'') take useful advantage of a phenomenon—buckling—that has historically (in the context of ''hard'' structures made of metals, concrete, and other materials with limited elasticity) been regarded as a mechanism of failure.[18,19] These soft actuators are elastomeric structures—structures that are ''soft'' by virtue of the fact that they are fabricated entirely in compliant materials such as elastomeric organic polymers, and contain no rigid, unyielding components—that achieve torsional,[14] linear,[8] shearing,[9] or cyclical[10] motions. Those we describe here are unusual in the sense that they are actuated by application of negative differential pressure (e.g., vacuum), rather than positive differential pressure (as in PneuNet-based devices,[2,3] McKibben actuators,[20] actuators harnessing snap-through,[15] etc.). (The early work by Jaeger and colleagues[21,22] on ''jamming'' actuators also operate under negative differential pressure, but by a different mechanism.) Buckling actuators achieve their characteristic motions based on the cooperative, reversible, buckling of the structural equivalent of ''beams'' molded into elastomers. The mechanics of these motions have been analyzed in detail by Bertoldi, Boyce, and coworkers.[11–13]

This article demonstrates applications of a buckling actuator of a type that we have described previously.[8] This actuator exhibits a particularly useful kind of motion—a linear motion akin to the muscle in humans and animals. We refer to it as a vacuum-actuated muscle-inspired pneumatic structure, or a ''VAMP.''[8]

Here, we describe an application of VAMPs requiring motions that would be difficult (or more complicated) to achieve using PneuNets, and much more complicated to achieve (at least to achieve simply) with hard machines or robots. We have built a ''tube climber'' that is capable of navigating the inside of a tube.

Buckling actuators such as VAMPs are easy to fabricate, light in weight, ''collaborative'' (as the term is used in robotics—that is, able to operate safely with people, and with other soft and delicate objects, without concern for the harm that a hard robot or machine might do on contact), and inexpensive. Buckling actuators have a distant relationship with the systems of soft, inflatable actuators that we[2,3,23] and others[1,4,24] have described previously. These actuators and robots—whether based on PneuNets,[2,3,23,25,26] on other systems of pneumatically inflated channels embedded in elastomeric structures,[27–30] on McKibben ''air muscles,''[20]

[1]Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts.
[2]School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts.
[3]Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, Massachusetts.
[4]Kavli Institute for Bionano Science and Technology, Harvard University, Cambridge, Massachusetts.
*These authors contributed equally.

or jamming under negative differential pressure[6]—use the energy provided by $P\Delta V$ work to change the shape of a machine, and thus to enable it to grip, move, or perform other functions. The PneuNet-based systems are usually composed of composites to achieve structural control over motions such as bending or curling; the composite structures determine the mechanical properties of the structures and thus their motion on inflation. The structural problem occasionally encountered with delamination at interfaces can be eliminated by using single-piece fabrication or other appropriate designs.[31]

Buckling actuators, because they rely on negative differential pressure (vacuum), rather than positive differential pressure—bring new advantages and disadvantages. One major advantage is that because their void space contracts on actuation, they shrink rather than expand (i.e., for the same starting size of actuator, VAMPs will decrease in volume, whereas inflating actuators would increase in volume), and can thus be used in applications that would preclude an increase in volume (e.g., as here, movement inside an enclosed tube or pipe). In addition, vacuum-based actuators stop actuating when the chambers collapse and thus cannot burst as inflatable actuators could. Another benefit is that these actuators exhibit lower strain, and thus, greater lifetime, greater toughness, and better oxidative stability than positive-pressure actuators (which are often operated at high strain). In addition, VAMPs can still function after small punctures because the external pressure compresses the elastomers and supports self-sealing.[8] A limitation to buckling actuators (when they are operated in the ambient environment, and thus at atmospheric pressure) is that the maximum pressure available to provide work under ambient conditions is limited to that of the atmosphere ($\sim$100 kPa = 14.5 psi = 1 bar), although this limitation can be circumvented by using a soft mechanical advantage[9] (i.e., by amplifying the output force relative to the input force). (This limitation could, of course, become an advantage in a different environment: e.g., undersea, or in other hyperbaric environments.)

Results and Discussion

Experimental design

We built a simple robot with three degrees of freedom, consisting of a VAMP[8] in the middle, and a ring-shaped positive-pressure pneumatic actuator on each end of the VAMP (Fig. 1A and Supplementary Fig. S1; Supplementary Data are available online at www.liebertpub.com/soro). The VAMP consists of thin horizontal parallel elastomeric beams (1.5 mm thick) and thicker vertical beams (4 mm thick) that bridge the horizontal beams. (The directions ''horizontal'' and ''vertical'' describe the relative positions of beams in a VAMP when its direction of actuation is vertical.) The system of beams and voids is sealed inside a thin elastomeric membrane (1 mm thick), and thus forms void chambers in between the beams; the void chambers connect to a common source of negative differential pressure. As we apply a vacuum to these void chambers, the horizontal beams buckle, while the vertical beams slide past each other and produce a linear motion (in this case, as shown in Fig. 1B, in the vertical direction).

By expanding and contracting the three actuators (two rings and the VAMP) in a specific sequence (as illustrated in Fig. 1B, C) using the controller illustrated in Supplementary

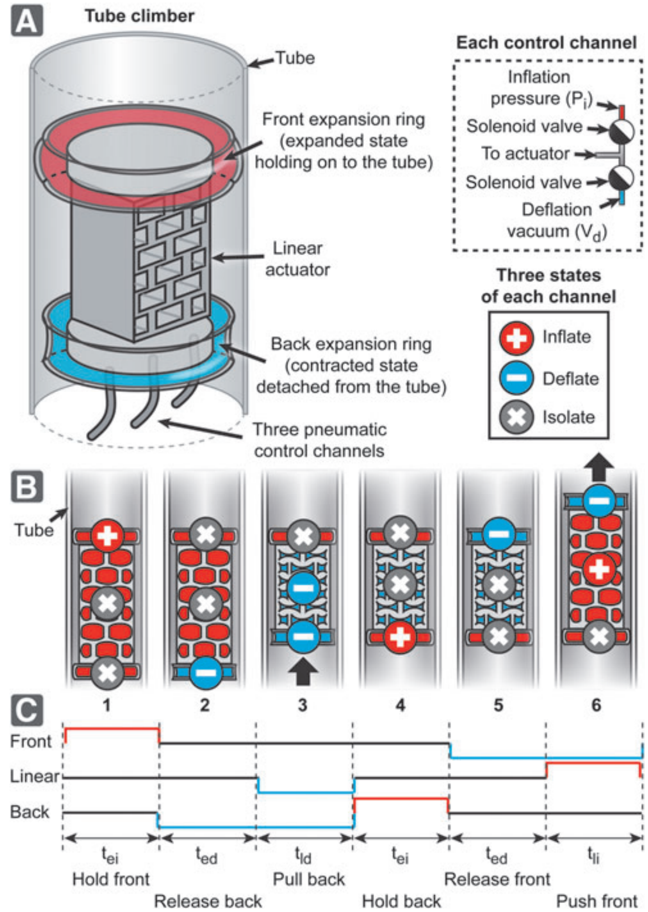

FIG. 1. Schematics of a tube-climbing robot powered with a VAMP. **(A)** Schematic of the tube climber comprising a VAMP[8] and two pressure-actuated rings (one in the front and one in the back). The tube climber is connected to three pneumatic control channels, one for the VAMP and one each for the rings. Each pneumatic channel can either be connected to inflation pressure (P_i), deflation vacuum (V_d), or sealed off. **(B)** Climbing is achieved by periodic actuation of six states. Inflation of the expansion ring holds the (front or back) end against the tube, while expansion and contraction of the linear actuator move the other, deflated loose end. **(C)** Sequence of pressure or vacuum used in each pneumatic control channel for climbing. Climbing is controlled by the supply pressures and the time constants: t_{ei} (inflation of expansion ring), t_{ed} (deflation of expansion ring), t_{li} (inflation of linear actuator), and t_{ld} (deflation of linear actuator). We varied the duration of each step to determine optimal climbing conditions.

Figure S2, this robot can move along a tube (using a motion distantly analogous to a rock climber moving up a crack by ''jamming''). Figure 2A and Supplementary Videos S1 and S2 demonstrate the climbing motion after optimizing the parameters of operation (i.e., duration of operation of each sequence in Fig. 1C) as shown in Supplementary Figure S3.

Capabilities of the tube-climbing robot

Existing tube-climbing systems are typically based on hard robots, or contain hard components,[32,33] although in some instances covered by a soft skin.[34] Our tube climber is

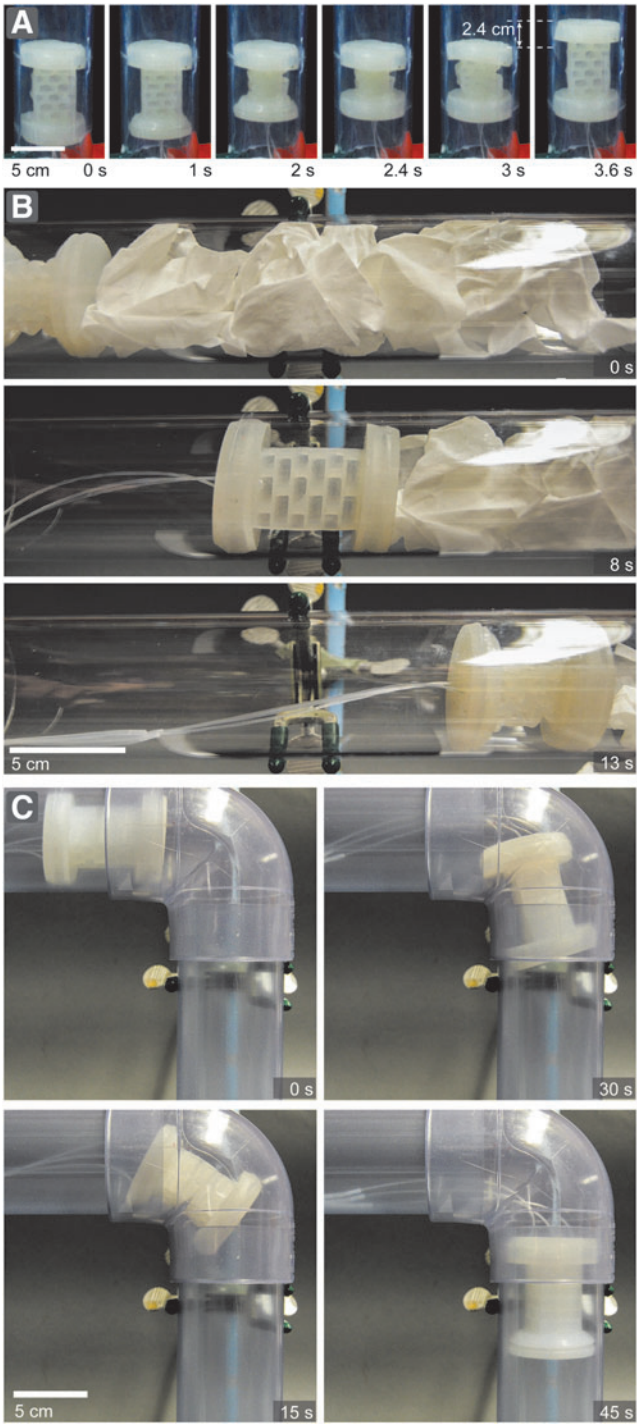

FIG. 2. Demonstrations of the tube-climbing robot in dry tubes. **(A)** One climbing cycle (each panel corresponds to the steps of the schematic in Fig. 1B). The climber moves in a vertical tube at the rate of 6 mm/s, with a period of 4 s (per cycle), and distance covered over one cycle was 2.4 cm. Here: $t_{ei} = 0.4$ s, $t_{ed} = 0.1$ s, $t_{li} = 1$ s, and $t_{ld} = 2$ s. **(B)** The tube-climbing robot performs a clearing task inside a tube to remove tissue paper. **(C)** The robot turns around a corner.

different from those previously described, in that it is completely soft, and thus has the potential to climb tubes with very smooth, hard surfaces, or tubes with changing radii or noncircular cross section (e.g., indoor air ducts that branch off into narrower ducts) by expanding or contracting the ring-shaped positive-pressure actuator. In the current design, the robot is able to move between two horizontal parallel plates while the distance between plates is varied from 60 to 64 mm, but gets stuck when the distance is less than 57 mm and does not reach the plates if the distance is greater than 66 mm. The tube climber also has the potential to withstand substantial punishment in terms of impact or pressure, or large strain in deformation—a task difficult for hard robots, or robots that contain hard components.

Some applications of this kind of robot might include inspecting or cleaning the interior of tubes, monitoring various parts of a building or tunnel, and search and rescue missions that involve climbing through tubes. Figure 2B and Supplementary Video S3 show an example of clearing, where the robot pushes tissue paper out of a short piece of transparent tube. The robot could carry an optical fiber (for visual inspection) or tubes to deliver or remove liquid cleaner or sampling agent, or to test vapors.[28] Figure 2C and Supplementary Video S4 show a demonstration of the robot turning a corner; this demonstration establishes that the robot could self-navigate when exposed to turns—at least when there is only one choice for the path. (Other designs could make guided or autonomous choices.)

The robot is able to operate under a load (mass = 1381 g, Supplementary Fig. S4 and Supplementary Video S5) of more than 10 times its own weight (mass = 98 g), but as expected, increasing the load leads to a decrease in the climbing speed (Fig. 3).

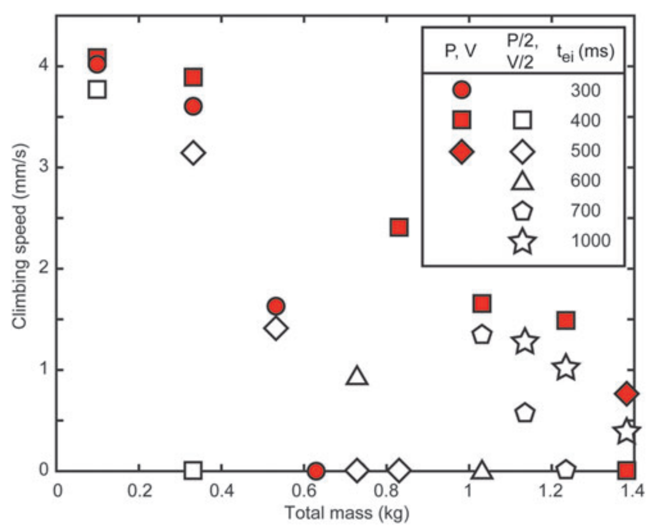

FIG. 3. Characterization of vertical climbing speed as a function of total weight that the tube climber carries, supply pressure, and inflation time of the expansion ring (t_{ei}). Initial pressure (P) and vacuum (V) are 100 and −95 kPa, respectively. Another set of experiments was performed with supply pressure reduced by half, thus P/2 is 50 kPa and V/2 is −47 kPa. Expansion ring inflation time determines how strongly the climber grips to the tube and thus how much weight it can carry. We can see that both pressure levels could carry similar loads, but as expected, lower pressures require longer times to achieve same actuation and have slower net speed. Here $t_{ed} = 1$ s, $t_{li} = 1$ s, $t_{ld} = 2$ s, and t_{ei} were varied as shown in the legend.

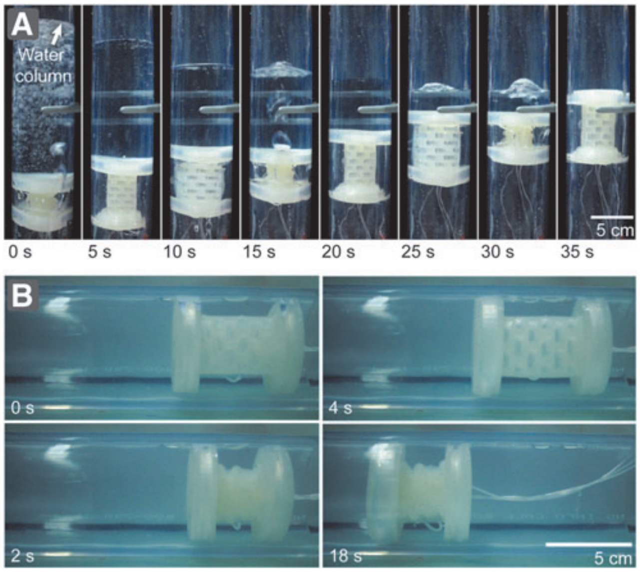

FIG. 4. Demonstrations of the tube-climbing robot in wet conditions. **(A)** Tube climber moves vertically after a column of water is poured on top (initial height of the column is ~17 cm, with a mass of ~480 g). The column of water exerts about 1.7 kPa of pressure. As the tube climber moves, water pours through the climber because the seal between the robot (the deflated ring) and the tube is broken. **(B)** The tube-climbing robot moves horizontally through a tube that is submerged in a tank of water and thus demonstrates underwater operation.

The tube climber can also operate in wet conditions, for example, in a tube that was freshly drained (Supplementary Fig. S5), through a column of water (Fig. 4A and Supplementary Video S6), or in a tube submerged underwater (Fig. 4B and Supplementary Video S7), without adversely affecting the performance. If the climber and the tube are coated in oil, the performance of the climber does suffer a decrease in the speed by about 3.3 times but with minimal load, the tube climber can still operate (Supplementary Fig. S6 and Supplementary Video S8). A very smooth surface, such as glass or plastic, covered in oil is a very demanding environment. We expect the tube climber to perform better in oil-covered *rough* surfaces (such as those containing corroded metal or scale deposits).

Conclusions

The tube-climbing robot described here has seven potentially useful characteristics: (1) it is fabricated entirely of soft materials (and can thus withstand large strains, deformations, and impact), (2) it can tolerate changes in tube diameter (how tolerant it would be would depend on the elasticity of the material used for fabricating the rings, and on the details of their design), (3) it is lightweight (the density of elastomers is typically ~1 g/cm^3, and the operating fluid is air), (4) it is (in principle) compatible with soft tubes and slippery surfaces, for example, blood vessels, tracheae, or intestines, (5) the sticking force exerted by the robot depends on the area of contact with the tube and thus can be increased by designing longer rings, (6) it has the potential to deliver fluids (e.g., detergent for cleaning, methane for burning off obstacles) or to carry optical fibers for inspection, and (7) it can operate in a liquid-filled tube.

Experimental

Fabrication and operation of the tube-climbing robot

The robot was fabricated according to previously described methods.[8,9] Briefly, the tube-climbing robot comprises three functional units: a VAMP and two pressure-actuated expansion rings. All three of these units were created by replica molding. We designed the molds for these units using computer-aided design (SolidWorks®) and fabricated them in acrylonitrile butadiene styrene plastic using a 3D printer (Stratasys Fortus 250mc). Curing a silicone-based elastomer (Dragon Skin® 10 Medium) against the molds at room temperature (5 h) produced the two halves of the VAMP. These two halves were aligned and bonded together by applying uncured elastomer at their interface, before placing them in an oven and curing at 60°C for 15 min. Similarly, two pressure-actuated expansion rings were cured and then attached to the VAMP (one on each end of the VAMP). Three pneumatic tubes (Intramedic polyethylene tubing, ID 0.76 mm) were attached to the structure, one for each of the rings and another for the VAMP (as shown in Fig. 1).

The pneumatic inputs were connected to either house vacuum or pressure sources via valves that were controlled using an Arduino Uno board (Supplementary Fig. S2 and Supplementary Table S1). The three functional units (rings and VAMP) were actuated in sequence (Fig. 1B, C) to allow the robot to climb inside a tube as shown in Figure 2 and Supplementary Video S1.

The tube used for characterizing the climbing experiments was a polyvinyl chloride tube with an inner diameter of 64 mm and length 315 mm. The mass of tube climber by itself was 98 g.

Acknowledgments

Work on actuation by buckling was funded by the DOE, Division of Materials Sciences and Engineering, grant number ER45852. M.S.V. was funded by the Banting Postdoctoral Fellowship from the Government of Canada. A.A. was funded by the Swedish Research Council (VR) postdoctoral fellowship. D.Y.'s work on biomimetic design was funded by a subcontract from Northwestern University under DOE award number DE-SC0000989. D.H. acknowledges Transient Electronics for salary support.

Authors' Contributions

M.S.V., A.A., and D.Y. designed the experiments. D.Y. designed the robot, while D.H. assisted with the pressure-actuated ring. D.Y. fabricated the robot. D.Y. and A.A performed demonstrations and characterization. M.S.V. and A.A. analyzed the results. M.S.V., A.A., D.Y., and G.M.W. wrote the article.

Author Disclosure Statement

No competing financial interests exist.

References

1. Suzumori K, Iikura S, Tanaka H. Development of flexible microactuator and its applications to robotic mechanisms. Proc 1991 IEEE Int Conf Robot Autom 1991;2:1622–1627.

2. Ilievski F, Mazzeo AD, Shepherd RF, Chen X, Whitesides GM. Soft robotics for chemists. Angew Chem Int Ed 2011; 50:1890–1895.
3. Mosadegh B, Polygerinos P, Keplinger C, Wennstedt S, Shepherd RF, Gupta U, et al. Pneumatic networks for soft robotics that actuate rapidly. Adv Funct Mater 2014;24: 2163–2170.
4. Rus D, Tolley MT. Design, fabrication and control of soft robots. Nature 2015;521:467–475.
5. Jaeger HM. Celebrating soft matter's 10th anniversary: toward jamming by design. Soft Matter 2015;11:12–27.
6. Brown E, Rodenberg N, Amend J, Mozeika A, Steltz E, Zakin MR, et al. Universal robotic gripper based on the jamming of granular material. Proc Natl Acad Sci U S A 2010;107:18809–18814.
7. Wei Y, Chen YH, Ren T, Chen Q, Yan CX, Yang Y, et al. A novel, variable stiffness robotic gripper based on integrated soft actuating and particle jamming. Soft Robot 2016;3:134–143.
8. Yang D, Verma MS, So J-H, Mosadegh B, Keplinger C, Lee B, et al. Buckling pneumatic linear actuators inspired by muscle. Adv Mater Technol 2016;1:1600055.
9. Yang D, Verma MS, Lossner E, Stothers D, Whitesides GM. Negative-pressure soft linear actuator with a mechanical advantage. Adv Mater Technol 2016;2:1600164.
10. Ainla A, Verma MS, Yang D, Whitesides GM. Soft, rotating pneumatic actuator. Soft Robot 2017;4:297–304.
11. Mullin T, Deschanel S, Bertoldi K, Boyce MC. Pattern transformation triggered by deformation. Phys Rev Lett 2007;99:084301.
12. Bertoldi K, Boyce MC, Deschanel S, Prange SM, Mullin T. Mechanics of deformation-triggered pattern transformations and superelastic behavior in periodic elastomeric structures. J Mech Phys Solids 2008;56:2642–2668.
13. Coulais C, Overvelde JTB, Lubbers LA, Bertoldi K, van Hecke M. Discontinuous buckling of wide beams and metabeams. Phys Rev Lett 2015;115:044301.
14. Yang D, Mosadegh B, Ainla A, Lee B, Khashai F, Suo Z, et al. Buckling of elastomeric beams enables actuation of soft machines. Adv Mater 2015;27:6323–6327.
15. Overvelde JT, Kloek T, D'Haen JJ, Bertoldi K. Amplifying the response of soft actuators by harnessing snap-through instabilities. Proc Natl Acad Sci U S A 2015;112:10863–10868.
16. Yang D, Jin L, Martinez RV, Bertoldi K, Whitesides GM, Suo Z. Phase-transforming and switchable metamaterials. Extreme Mech Lett 2016;6:1–9.
17. Liu J, Gu TY, Shan SC, Kang SH, Weaver JC, Bertoldi K. Harnessing buckling to design architected materials that exhibit effective negative swelling. Adv Mater 2016;28: 6619–6624.
18. Gordo JM, Soares CG, Faulkner D. Approximate assessment of the ultimate longitudinal strength of the hull girder. J Ship Res 1996;40:60–69.
19. Bruzek R, Biess L, Al-Nazer L. Development of rail temperature predictions to minimize risk of track buckle derailments. Proc ASME Joint Rail Conf 2013;2013:V001T001 A007.
20. Daerden F, Lefeber D. Pneumatic artificial muscles: actuators for robotics and automation. Eur J Mech Environ Eng 2002;47:11–21.
21. Steltz E, Mozeika A, Rodenberg N, Brown E, Jaeger HM. JSEL: jamming skin enabled locomotion. 2009 IEEE-RSJ International Conference on Intelligent Robots and Systems, St. Louis, MO, 2009:5672–5677.
22. Steltz E, Mozeika A, Rembisz J, Corson N, Jaeger HM. Jamming as an enabling technology for soft robotics. Electroactive Polymer Actuators and Devices (EAPAD) 2010, 2010;7642:764225
23. Shepherd RF, Ilievski F, Choi W, Morin SA, Stokes AA, Mazzeo AD, et al. Multigait soft robot. Proc Natl Acad Sci U S A 2011;108):20400–20403.
24. Kim S, Laschi C, Trimmer B. Soft robotics: a bioinspired evolution in robotics. Trends Biotechnol 2013;31:23–30.
25. Wehner M, Tolley MT, Menguc Y, Park YL, Mozeika A, Ding Y, et al. Pneumatic energy sources for autonomous and wearable soft robotics. Soft Robot 2014;1:263–274.
26. Martinez RV, Glavan AC, Keplinger C, Oyetibo AI, Whitesides GM. Soft actuators and robots that are resistant to mechanical damage. Adv Funct Mater 2014;24:3003–3010.
27. Martinez RV, Fish CR, Chen X, Whitesides GM. Elastomeric origami: programmable paper-elastomer composites as pneumatic actuators. Adv Funct Mater 2012;22:1376–1384.
28. Martinez RV, Branch JL, Fish CR, Jin L, Shepherd RF, Nunes RM, et al. Robotic tentacles with three-dimensional mobility based on flexible elastomers. Adv Mater 2013; 25:205–212.
29. Morin SA, Shevchenko Y, Lessing J, Kwok SW, Shepherd RF, Stokes AA, et al. Using ''Click-E-Bricks'' to make 3d elastomeric structures. Adv Mater 2014;26:5991–5999.
30. Morin SA, Kwok SW, Lessing J, Ting J, Shepherd RF, Stokes AA, et al. Elastomeric tiles for the fabrication of inflatable structures. Adv Funct Mater 2014;24:5541–5549.
31. Galloway KC, Lessing JA. Soft retractors. 2015; US2015 0366547 A1. https://www.google.com.na/patents/US2015 0366547?cl=en (accessed November 15, 2017).
32. Tur JMM, Garthwaite W. Robotic devices for water main in-pipe inspection: a survey. J Field Robot 2010;27:491–508.
33. Roh SG, Choi HR. Differential-drive in-pipe robot for moving inside urban gas pipelines. IEEE Trans Robot 2005; 21:1–17.
34. Alcaide JO, Pearson L, Rentschler ME. Design, modeling and control of a SMA-actuated biomimetic robot with novel functional skin. 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 2017:4338–4345.

Address correspondence to:
George M. Whitesides
Department of Chemistry and Chemical Biology
Harvard University
12 Oxford Street
Cambridge, MA 02138

E-mail: gwhitesides@gmwgroup.harvard.edu