Electronic Supplementary Information

for

Motorized, untethered soft robots via 3D printed auxetics

Pranav Kaarthik,[1] Francesco L. Sanchez,[1] James Avtges,[2] and Ryan L. Truby[1,2,3]*

[1]Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA
[2]Center for Robotics and Biosystems, Northwestern University, Evanston, IL, USA
[3]Department of Materials Science and Engineering, Northwestern University, Evanston, IL USA

Correspondence to: rtruby@northwestern.edu

Contents:

Table S1 – S3

Figures S1 – S6

Movies S1 – S4

Table S1. Mechanical Properties of EnvisionTec Print Resins

Material	Elongation at Break (%)	Shore Hardness	Tensile Strength (MPa)
Rigid PU Black	173	D73	20.6
Rigidform Charcoal	6-7	D87	68-73
ABS Tough	3.5	D86	66
HTM 140	3.5	N/A	56
Rigid PU White	120	D78	34

Table S2. Cyclic Extension Testing of HSAs

HSA Scaling	Number of extension cycles programmed for experiment	Cycle at first strut/hinge failing event	Cycle at complete HSA failure
1x	1000	480	N/A (no complete failure)
0.75x	1000	230	265
0.5x	1000	250	300
0.3x	1000	100	233

Table S3. Operating Time and Walking Speeds of Reported Untethered Soft Robots

Citation	Operating Time (min)	Speed (BL/s)	Actuation Category
He, Q., Z. Wang, Y. Wang, A. Minori, M. T. Tolley and S. Cai, *Science Advances*, 2019, 5, eaax5746.	30	0.017	LCE
Huang, X., K. Kumar, M. K. Jawed, A. M. Nasab, Z. Ye, W. Shan and C. Majidi, *Science Robotics*, 2018, 3, eaau7557.	23	1	SMA
Huang, X., K. Kumar, M. K. Jawed, A. Mohammadi Nasab, Z. Ye, W. Shan and C. Majidi, *Advanced Materials Technologies*, 2019, 4, 1800540.	23	0.56	SMA
Ji., X., X. Liu, V. Cacucciolo, M. Imboden, Y. Civet, A. El Haitami, S. Cantin, Y. Perriard and H. Shea, *Science Robotics*, 2019, 4, eaaz6451.	1	0.3	DEA
Cao, L. Qin, H. P. Lee and J. Zhu, *Electroactive Polymer Actuators and Devices (EAPAD) 2017*, 2017, pp. 322–328.	30	0.02	DEA
Duggan, T., L. Horowitz, A. Ulug, E. Baker and K. Petersen, *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*, 2019, pp. 200-205.	28 12	0.019 0.00139	DEA DEA
Must, I. F., I. Kaasik, L. Põldsalu, U. Mihkels, A. Johanson, A. Punning, and A. Aabloo, *Advanced Engineering Materials*, 2015, 17, 84-94.	8	0.016	EAP
Qi, M., Y. Zhu, Z. Liu, X. Zhang, X. Yan, and L. Lin, *2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS)*, 2017, pp. 761-764.	0.17	1.5	EAP
Goldberg, B., R. Zufferey, N. Doshi, E. F. Helbling, G. Whittredge, M. Kovac, R. J. Wood, *IEEE Robotics and Automation Letters*, 2018, 3, 987-993.	4.5	3.8	EAP
Bartlett, N. W., M. T. Tolley, J. T. B. Overvelde, J. C. Weaver, B. Mosadegh, K. Bertoldi, G. M. Whitesides and R. J. Wood, *Science*, 2015, 161–165.	0.033	0.83	Combustion
Yang, L. Chang and N. O. Pérez-Arancibia, *Science Robotics*, 2020, 5, eaba0015.	3.33	0.023	Combustion
Drotman, D., S. Jadhav, D. Sharp, C. Chan and M. T. Tolley, *Science Robotics*, 2021, 6, eaay2627.	4	0.09	Pneumatic
Rafsanjani, A., Y. Zhang, B. Liu, S. M. Rubinstein and K. Bertoldi, *Science Robotics*, 2018, 3, eaar7555.	30	0.025	Pneumatic
Tolley, M. T., R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood and G. M. Whitesides, *Soft Robotics*, 2014, 1, 213–223.	120	0.0078	Pneumatic
Li, S., A. Awale, K. E. Bacher, T. J. Buchner, C. Della Santina, R. J. Wood and D. Rus, *Soft Robotics*, 2022, 9, 324–336.	45	0.0106	Pneumatic
Usevitch, N. S., Z. M. Hammond, M. Schwager, A. M. Okamura, E. W. Hawkes and S. Follmer, *Science Robotics*, 2020, 5, eaaz0492.	32	0.035	Motorized
Gong, S., J. Wu, T. Zheng, W.-M. Zhang and L. Shao, 2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP), 2021, pp. 417–422.	18	0.65	Motorized
This work	65	0.031	HSA robot

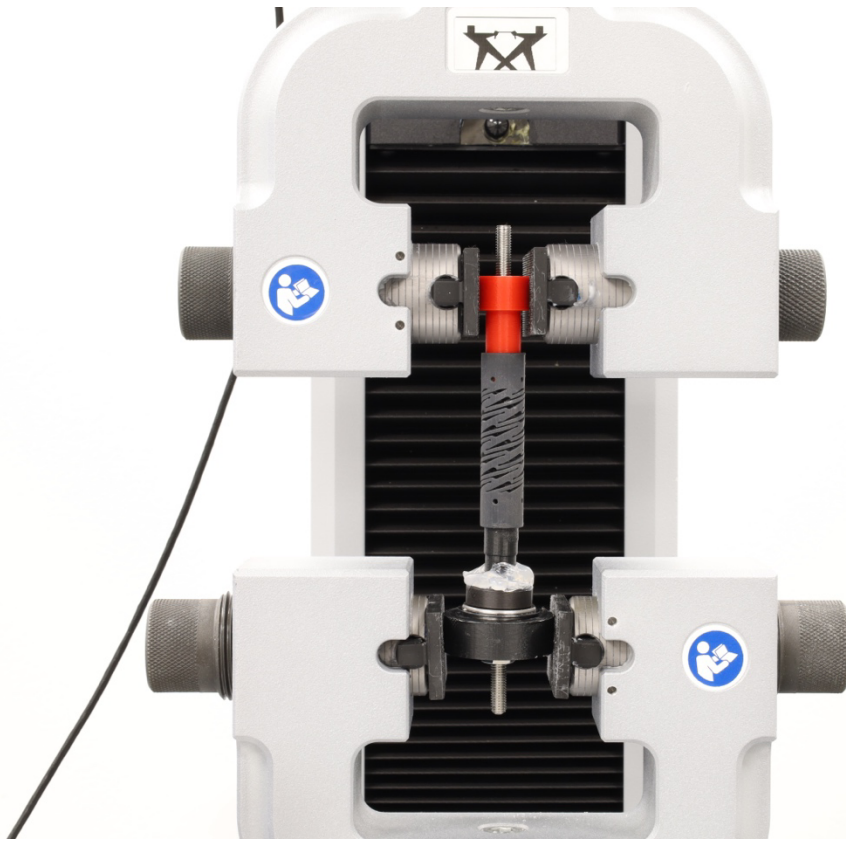**Figure S1.** Photograph of two 1x HSAs immediately after printing. Scale bar represents 20 mm.

Figure S2. Mechanical testing set-up for tensile and cyclic extension characterization of HSAs. A 0.5x HSA is shown.
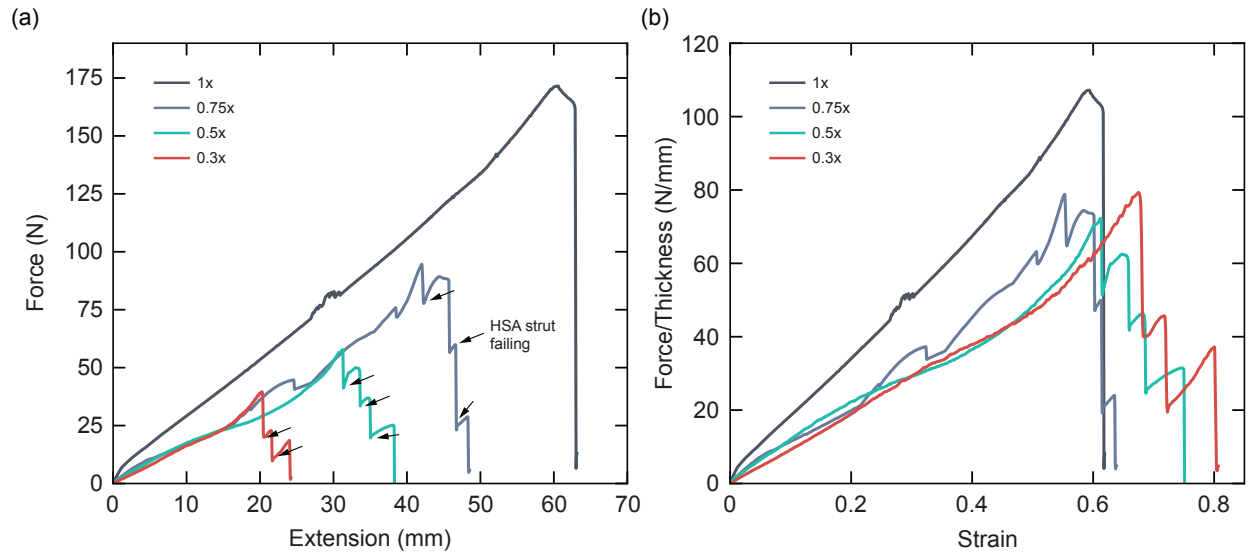
Figure S3. Mechanical characterization of HSAs. (a) Force versus extension data from tensile extension tests to failure are shown for 1x, 0.75x, 0.5x, 0.3x HSAs. Data for one HSA of each scaling is shown, with arrows indicating failures of individual struts prior to critical failure. (b) The same force data from (a) is shown normalized by HSA thickness and plotted versus strain.
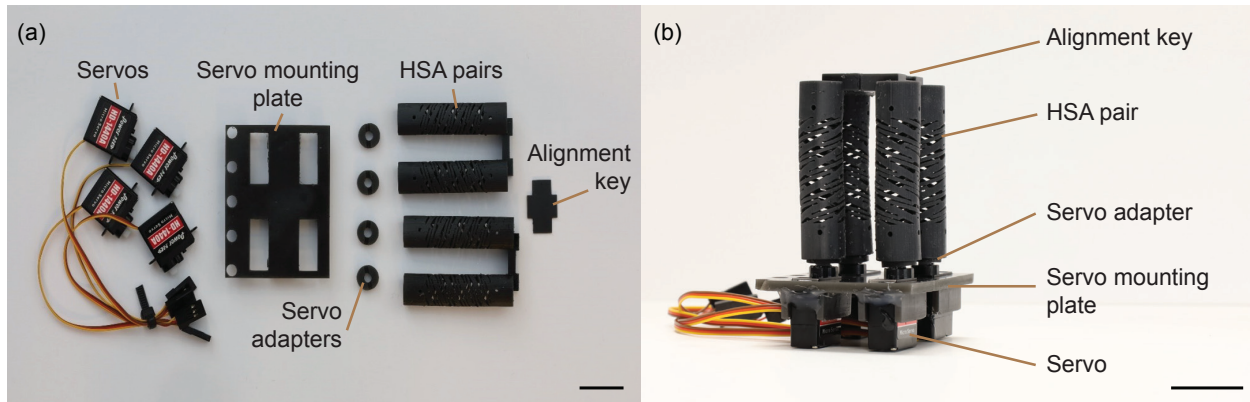
Figure S4. HSA leg assembly. (a) An unassembled HSA leg is shown with all its constituent components. (b) An assembled HSA leg is shown. It consists of two HSA pairs mounted to four servo motors via 3D printed adapters. The alignment key aligns the two HSA pairs at the distal end of the leg. Scale bars are 20 mm.
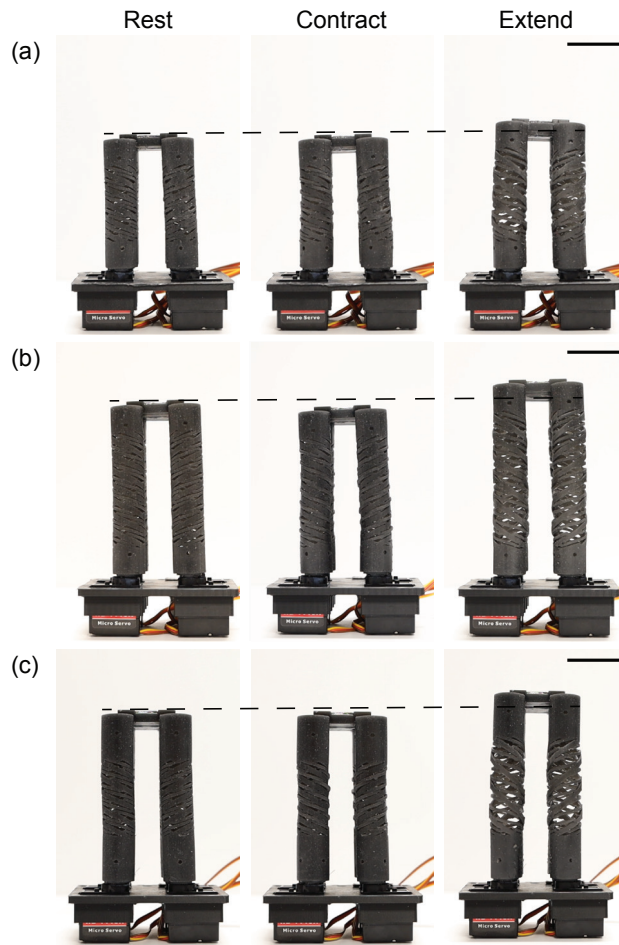
Figure S5. Multi-DOF HSA leg contraction and extension. The (a) 0.5x Leg, (b) Elongated 0.5x Leg, and (c) Stilted 0.5x Leg are shown at rest, and in their contracted and extended states. Dashed lines indicate the position of the distal end of each leg at rest for comparison with the contracted and extended states. The photographs are stills from Movies S1-S3 in the ESI. Scale bars are 20 mm.
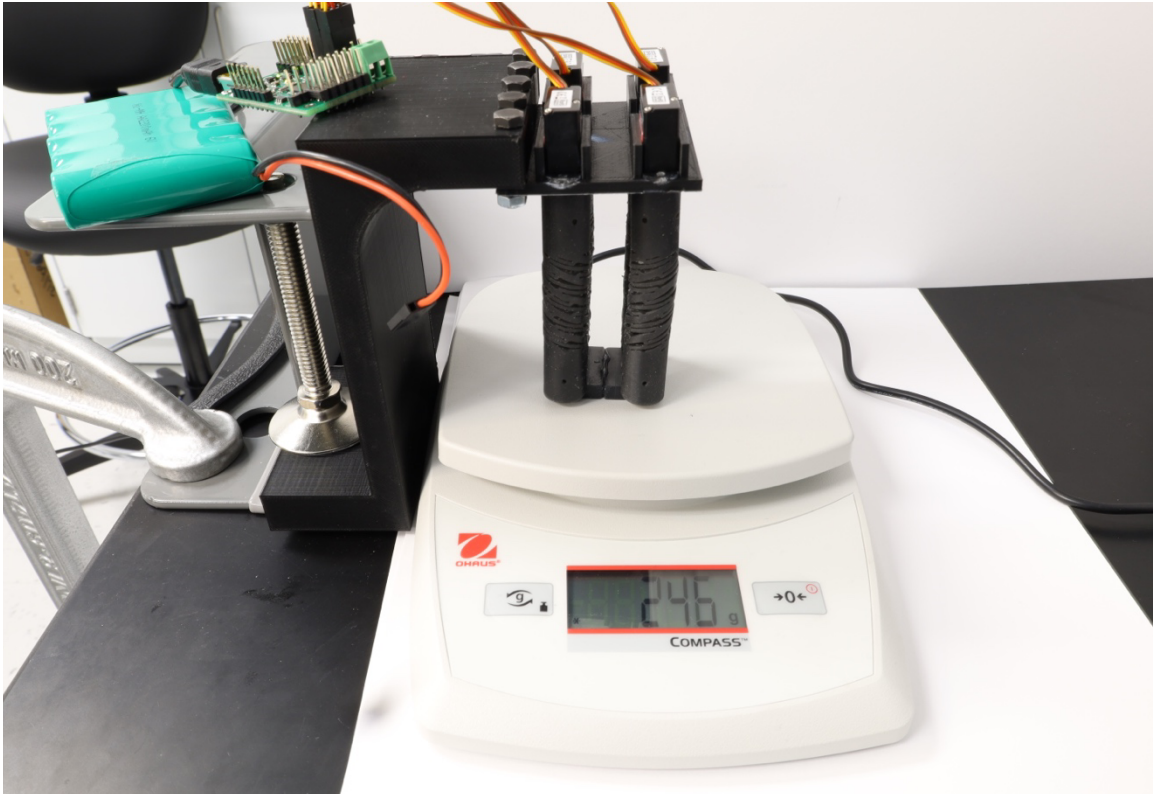
Figure S6. Blocked force testing set-up. A Stilted 0.5x Leg is shown.

Movie S1. Multi-DOF actuations of the 0.5x HSA Leg (stills are shown in Fig. 4b).

Movie S2. Multi-DOF actuations of the Elongated 0.5x HSA Leg (stills are shown in Fig. 4c).

Movie S3. Multi-DOF actuations of the Stilted 0.5x HSA Leg (stills are shown in Fig. 4d).

Movie S4. Untethered soft robots walking on concrete sidewalk. The top and bottom clips show the quadrupeds constructed from the 0.5x Legs and Stilted 0.5x Legs, respectively. Video playback is 5x.