# Popcorn-Driven Robotic Actuators

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***Abstract*— Popcorn kernels are a natural, edible, and inexpensive material that has the potential to rapidly expand with high force upon application of heat. Although this transition is irreversible, it carries potential for several robotic applications. Here, we examine relevant characteristics of three types of kernels including expansion ratio, transition temperature, popping force, compression strength, and biodegradability. We test the viability of popping by hot oil, hot air, microwaves, and direct contact with heated Nichrome wire. As kernels can change from regular to (larger) irregular shapes, we examine the change in inter-granular friction and propose their use as granular fluids in jamming actuators, without the need for a vacuum pump. Furthermore, as a proof-of-concept, we also demonstrate the use of popcorn-driven actuation in soft, compliant, and rigid-link grippers. Serving as a first introduction of popcorn into robotics, we hope this paper will inspire novel mechanisms for multi-functional designs.**

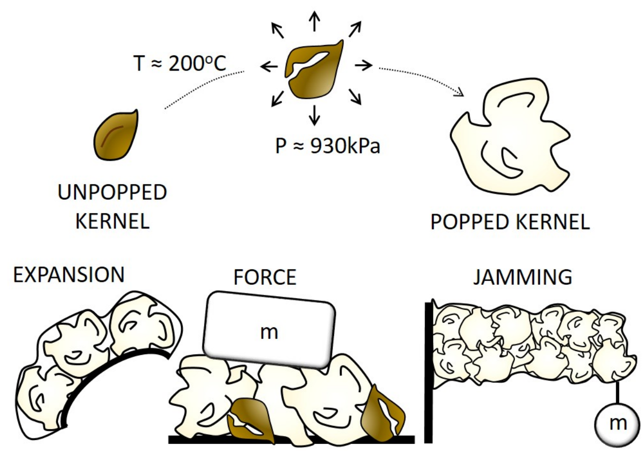


Fig. 1. This paper concerns the use of popcorn-driven robots. Upon heating, popcorn kernels have the ability to transition from regular-shaped kernels, to highly irregular shapes almost an order of magnitude greater than their original volume. The transition can be used to provide expansion, to apply force, and to change rigidity. It can also enable faster degradation. Here, we characterize kernel properties (Sec. II), and demonstrate their use with elastomeric manipulators (Sec. IV), origami manipulators (Sec. V), rigid-link manipulators (Sec. VI), and jamming actuators (Sec. III).

## I. INTRODUCTION

The field of robotics has embraced unorthodox power sources and actuation methods ranging from organic materials and muscle cells to pneumatics and combustible gases. In this paper, we propose to expand this library of actuators with a well-known consumable, namely popcorn. Upon application of heat, popcorn kernels are capable of large, instant expansion transitioning from regular to highly irregular granules with high force. Although the transition is irreversible it can be applied to many scenarios. For traditional rigid robots these actuators can be used to produce motion with high force. The ability of kernels to rapidly expand may be used to power miniature jumping robots along the lines of those presented by Shepherd et al. [1]. When combined with strain-limiting layers in soft robots [2], kernels may be used for their expansion capability. For compliant robots, kernels may function as multi-purpose, inexpensive granular fluids, able to change the rigidity of the body by expanding and jamming without the need for a pump or a compressor. For mobile construction robots [3], popcorn may serve as a readily available, expandable, bio-compatible and biodegradable building material. Furthermore, a recent publication from Shintake et al. [4] indicates an emerging field in edible robotics to which popcorn lends itself nicely.

Although there is no publication record of popcorn used to augment robotics, many researchers have studied the mechanical properties of popcorn kernels and their popping in the past. Hoseney et al. [5] explained the popping mechanism as follows. At 170-180 $^{o}$C, corresponding to $\sim$930 kPa of internal pressure, the moisture inside a kernel vaporizes and expands, causing the outer shell to break (Fig. 1). When this happens, the endosperm of the raw grain gelatinizes, expands, and dries into a three-dimensional matrix. An expansion ratio up to $\sim$200 % has been reported in literature [6], [7]. Essentially, the kernels represent an energy reservoir which can be deployed into mechanical motion when needed.

To demonstrate the wide-ranging potential of popcorn actuators, we first characterize relevant properties of popcorn (Sec. II), then show four proof-of-concept implementations (Sec. III- VI). Given three types of popcorn and four heating mechanisms, we characterize kernel volume, density, popping temperature, and expansion ratio (Sec. II-A). To further illustrate their potential for jamming actuators, we examine the force at which they pop and the inter-granular friction between kernels and between popped kernels (Sec. II-B). Furthermore, we characterize kernel compression strength and the change in biodegradability before and after popping, to highlight their potential as a construction material (Sec. II-C). Using the jamming concept, we then demonstrate the ability of a popcorn-imbibed elastomer beam to change rigidity (Sec. III). Finally, we demonstrate the use of popcorn actuators in three types of compliant grasping mechanisms

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with different heating methods. The first involves strain-limited silicone chambers as are commonly used in Fluid Elastomer Actuators (FEAs) [8], actuated using Nichrome wire (Sec. IV). The second involves paper membranes folded into programmable-shape origami structures, as previously demonstrated in [9], actuated with microwaves (Sec. V). The last demonstrator involves a rigid robot hand, much like that presented in [10], actuated using hot air (Sec. VI).

## II. Characterization of Popcorn

We identify the following desirable traits that will allow popcorn to be used with robotics: 1) Kernels are likely to be used in high quantities, therefore they must be cheap and readily accessible. 2) For mobile robots, a low density is preferable to avoid heavy payloads. 3) For reasons related to power and safety, lower popping temperature is better. 4) To act as a granular fluid with low viscosity, the un-popped kernels must be very regular in shape. Reversely, to act as a high-viscosity jamming medium, the popped kernels must have high expansion ratios and highly irregular shapes. 5) Furthermore, a higher popping force, will enable more rigid jamming. 6) For the popped kernels to support high loads they must have a high compression strength. In the following sections, we examine a range of properties towards these aims.

### A. Comparing kernels and heating methods

We measured the volume, density, popping temperature, and expansion ratio of Amish Country Medium White popcorn, Medium Yellow popcorn, and Extra Small popcorn with four types of heating methods (submersion in hot oil, hot air, microwave, and direct contact with heated Nichrome 60 wire). The Amish Country brand was chosen because of the lack of additives and post-harvest treatment.

To accurately measure the volume, $V$, of individual un-popped kernels, they were submerged in water in a fitted tube of radius, $r_{tube}$. The increase in water level, $\Delta h$, was measured using a caliber and the kernel volume was computed as $V = \Delta h \times \pi \times r_{tube}^2$. Popped kernels slowly dissolve in water, correspondingly their volume was measured by displacing fine grands of sand instead of water. The kernels were also weighed to reveal the density, $\delta$. To estimate their popping temperature, $T_{pop}$, we placed kernels on a heat-conducting metal surface, and heated them using a hot air gun. The temperature was measured using a non-contact IR laser gun from KingTop.

TABLE I

Kernel volume (V) and density ($\delta$), popping temperature (T$_{pop}$), and expansion ratio of three types of kernels heated with canola oil, air, microwaves, and direct contact with a Nichrome 60 wire. All reported values have an average and standard deviation for 10-20 samples ($\overline{x} \pm \sigma_x; n > 10$).

| Type / heating | V$_{kernel}$ [mm$^3$] | $\delta$ [g/cm$^3$] | T$_{pop}$ [$^o$C] | Expansion ratio, $\epsilon$ [-] |
|---|---|---|---|---|
| Medium white popcorn ($\sim$ $7.5/kg) | | | | |
| Air | 173.9±19.9 | 1.1±0.3 | 200.5±9.9 | 5.2±2.4 |
| Medium yellow popcorn ($\sim$ $8.4/kg) | | | | |
| Air | 211.6±48.1 | 0.9±0.1 | 203.2±8.6 | 7.9±4.7 |
| Extra small white popcorn ($\sim$ $4.8/kg) | | | | |
| Air | 126.0±24.0 | 0.8±0.3 | 202.2±14.3 | 9.7±4.8 |
| Oil | | | | 5.2±2.5 |
| Microwave | | | | 15.7±5.0 |
| Wire | | | | 12.6±5.1 |

The results of these tests are shown in Table I. All kernels pop at approximately the same temperature when heated with hot air ($T_{pop} \approx 200^oC$). However, the Extra Small White Popcorn have the highest expansion ratio ($\epsilon$ = 9.7±4.8), the lowest cost factor ($\sim$ $4.8/kg), and the lowest density ($\delta$ = 0.8±0.3 g/cm$^3$). Interestingly, the expansion ratio of the kernels change with different heating methods. In the following sections, experiments are done with Extra Small White popcorn, using the three heating methods that produce the highest expansion ratio (hot air, microwaves, and Nichrome wire).

### B. Popcorn Jamming Properties

Fluid-filled elastomer actuators are popular for their ability to interact safely with undefined shapes [2]. Because of their compliance, however, they also tend to suffer from low force profiles. Jamming actuators address this issue by replacing the fluid with irregular granules [11]. When vacuum is applied, these jam together, essentially creating a solid from a liquid. Other authors have presented reversible stiffness change in soft mechanisms using jamming [12], heating [13] and electric fields [14], [15]. Along the same line of reasoning, we propose to use popcorn kernels as a multi-functional granular fluid that can change viscosity dramatically upon heating. Although this transition is irreversible, this methodology does not rely on a pump or compressor to generate vacuum. Furthermore, because it relies on large granules, it is less susceptible to leaks.

Since it is not possible to measure the viscosity of large-granule granular fluids with a standard rheometer, we instead indicate the change in viscosity by the change in static friction between two layers of the granules. This method has been previously proposed by Forterre [16]. To measure the friction between two layers of granules we glued kernels onto a sheet and the downward facing side of a wooden block of mass, $m_{block}$. One end of a string was tied to the block, the other over a pulley and on to a free-hanging bucket which we slowly filled with sand. By measuring the mass of the bucket when the block started to slide, $m_{sand}$, we determined the coefficient of static friction to be: $\mu_{static} = m_{sand}/m_{block}$ = 0.33±0.06 for kernels versus 3.02±0.28 for popped kernels. 10 replicas were done for each experiment. With more than an order of magnitude difference in the static frication, this indicates great potential for transitions from a low viscosity to a high viscosity fluid, and in turn jamming applications.

To measure the force of expansion, kernels were placed under a thin steel beam ($L_{steel}$ = 15.4 mm, $W_{steel}$ = 20 mm, $t_{steel}$ = 0.3 mm, $E_{steel}$ = 203GPa), and popped using a hot air gun (Fig. 2). We then measure the deflection of the beam, $\Delta h$, and calculate the force using the standard beam deflection equation as follows:

$$F_{pop} = \frac{\Delta h_{steel} \times 3 \times E_{steel} \times \frac{W_{steel} \times t_{steel}^3}{12}}{L_{steel}^3} \quad (1)$$

With 10 replicas, we measure $F_{pop}$ = 38.0±0.9 mN, with a maximum and minimum value of 52.5 mN and 24.8 mN, respectively. The granules have an average volume of 126 $mm^3$ and after popping they distribute the measured force over an area of approximately 114 $mm^2$, resulting in a stress of 0.33 MPa. Comparing this to the tensile loading curve for a commonly used silicone such as Ecoflex 00-30, a kernel wrapped in a 0.4mm layer will result in a local stretch of 4-5 times [17]. We test this concept further in Sec. III.

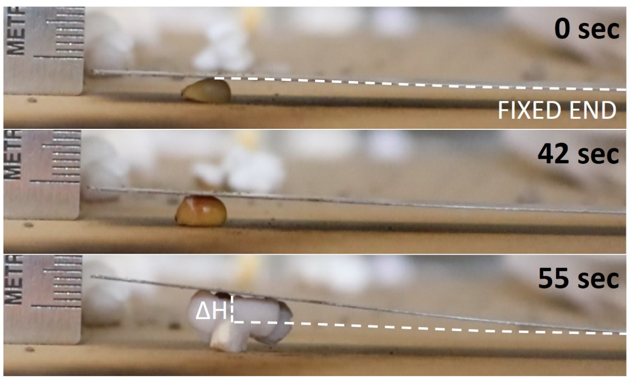


Fig. 2. Photo-sequence of experimental setup: the kernel is placed under a thin steel rod, and heated by a hot air gun; once popped, the deflection of the beam indicates the force of the pop.

### C. Popcorn as a Structural Element

To evaluate popcorn as a structural element, we performed compression tests of unpopped kernels and the gelatinized endosperm of popped kernels using a TA Instruments Dynamic Mechanical Analyzer Q-800. The results can be seen in Fig. 3. Using a linear fit on the linear portion of each plot, we find the elastic modulus to be $E_{kernel}$ = 24.12 ± 5.94 MPa for kernels, and $E_{popcorn}$ = 0.45 ± 0.13 MPa for the gelatinized endosperm. Popping the granules reduces their modulus of elasticity by approximately 50 times; however, as shown in the next section, the jamming properties allow for load-bearing applications where rigidity increases in a tightly packed group of kernels despite the individual lower rigidity.

In comparison, Expanded Polystyrene Foam used for construction has an elastic modulus of ∼0.76 MPa (data from Universal Construction Foam). Furthermore, compared to 2-component rigid Urethane foam which has previously been used for robotic construction [18], popcorn has the added advantage of curing instantly. As an example, Foam-It 5 from Smooth-On™, which has similar expansion properties as these kernels, has a recommended cure time of 2 hours.

Popcorn, of course, differ from normal construction material in its ability to bio-degrade. Interestingly, popping the kernels also changes this property. We left kernels and

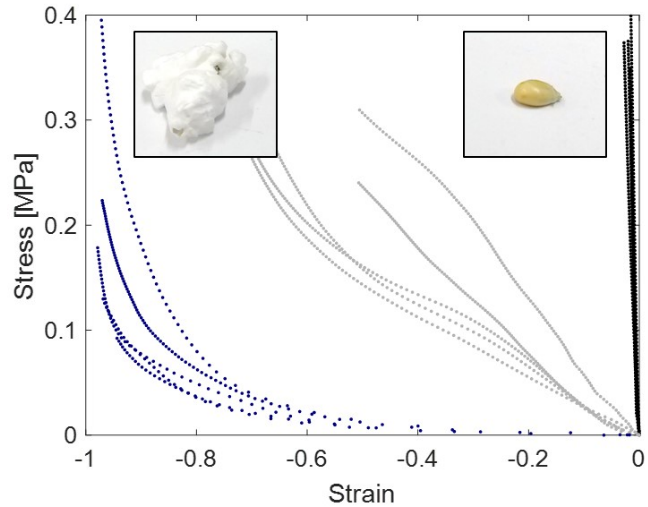


Fig. 3. Compression tests of kernels (black), unpopped kernels (grey), and popped kernels soaked in water (blue).

popped kernels in water to detect the difference; after two weeks the popped kernels had completely dissolved, whereas the unpopped kernels remained intact. Dynamic Mechanical Analysis of popcorn soaked in water clearly show this difference (Fig. 3).

## III. Popcorn-Driven Jamming Actuator

Given the characterization in Sec. II, we next demonstrate the ability of popcorn to jam upon heating with Nichrome wire in a flexible silicone beam. The procedure to assemble this beam is illustrated in Fig. 4.A-D. It involves the following steps: 1) 34AWG Nichrome 60 wire is wrapped around a 3.8 mm diameter rod to produce a coil of length 10 cm (37 turns). To this we add 10 cm straight leads on either side. 2) We insert approximately 12 kernels into the coil. 3) We wrap three of these coils independently in a 0.5mm layer of Ecoflex 00-30 from Smooth-On™ to avoid short-circuits between the coils. Ecoflex 00-30 is very soft with a tensile strength of 200 psi, and allows full deformation of the kernels. 4) Finally, we wrap all three silicone tubes in a 1mm layer of Oomoo 30 also from Smooth-On™. Oomoo 30 has a tensile strength of 240 psi, i.e. it is stiffer than Ecoflex 00-30, and exerts an inwards pressure to ensure jamming of the three tubes.

The heating occurs as follows: first, 14 V is applied for approximately 3 minutes, then the voltage is increased to 18 V until all kernels are popped. As the resistance of the wire changes with the temperature and contacting material, accurate estimation of the induced temperature is not trivial. The activation sequence used here was found experimentally. The slow increase of voltage is done to prevent the popcorn from burning; The entire sequence takes ∼6 minutes. By fixing one of the sides of the beam in place, and hanging a 100g weight from the other end before and after popping (Fig. 4), it is evident that the beam stiffens upon heating.

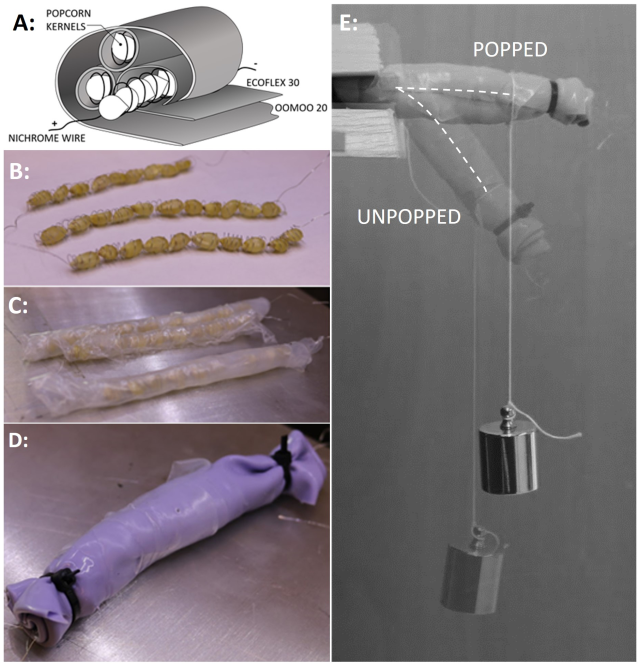


Fig. 4. Sketch (A) and photos (B-D) of how to compose a silicone-popcorn actuator. First, a coil is made by wrapping Nichrome wire around a rod; then kernels are inserted; next individual coils are wrapped in low modulus silicone to prevent short circuits; finally, a higher modulus membrane is used to combine three silicone tubes. When current is applied to the wire, the kernels are popped and jam against each other creating a relatively rigid rod. Figure E shows beam deflection before and after heating, with a 100g weight.

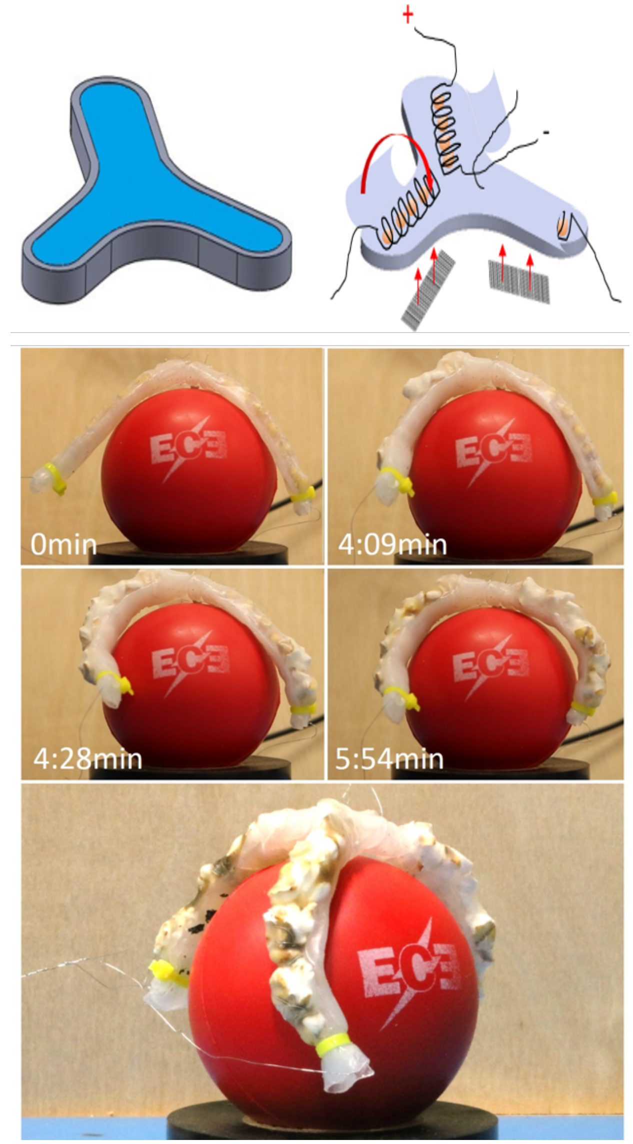


Fig. 5. Fiber-reinforced elastomer actuator powered using popcorn wrapped in Nichrome 60 wire. The top row shows the fabrication process for the actuator. Eco-Flex 00-30 is poured into a mold and wrapped around the wire and kernels and a strain-limiting layer is attached to the bottom side to create bending in the appropriate direction. The second and third rows show an image sequence of the actuation; the lower photo shows the finished result. We encourage the reader to also watch the video attachment of this experiment.

## IV. Popcorn-Driven Elastomer Actuator

Next, we demonstrate a three-fingered soft gripper powered by popcorn expansion (Fig. 5). To fabricate the gripper, the procedure is as follows: 1) The lower surface of the hand is molded using Ecoflex 00-30 embedded with an inextensible porous fabric. Note that the popping temperature of the popcorn is around 200 $^{o}$C (Table I), and Ecoflex is rated to a maximum temperature of 232 $^{o}$C. 2) Next, 60 mm long coils of Nichrome wire and popcorn were added to each of three fingers. Each coil was produced using 40 cm 34AWG Nichrome 60 wire. 10 cm of wire at each end was used for leads, the rest was coiled around a 3.8 mm rod (18 turns). 7 kernels were added to each coil. 3) Finally, a layer of Ecoflex 00-30 was wrapped tightly around each finger, and zip-tied as shown in Fig. 5.

To actuate the gripper, we applied voltage as described in Sec. III. When the kernels pop, their expansion exerts pressure against the outer walls; because the lower surface is inextensible, the fingers curl.

## V. Popcorn-driven Origami Actuators

To demonstrate the use of popcorn actuators in flexible mechanisms, we integrate popcorn into shape-programmable origami actuators. To fabricate these, we use recycled Newmans Organic Popcorn bags folded into bellow structures (Fig. 6.A) and seal them using microwave-safe silicone glue (Dap 00688 All-Purpose Adhesive Sealant). Activation occur via a microwave oven.

Fig. 6.B shows an example of a bellow structure in which one side of the folds were constrained such that it unfolds into a circular structure of radius 50 mm and height 50mm (corresponding to an internal volume, $V$, of $\sim$785 cm$^3$). We fill this with 80 g of kernels, as predicted by the density and expansion ratio found in Sec. II-A: $m = V/\epsilon \times \delta$ = 79.5 g.

Finally, Fig. 6.C shows an example of a three-fingered gripper holding a 9 lbs kettlebell to illustrate the compression strength of the popped kernels when constrained to a fixed space inside the paper bag. Although heating methods based

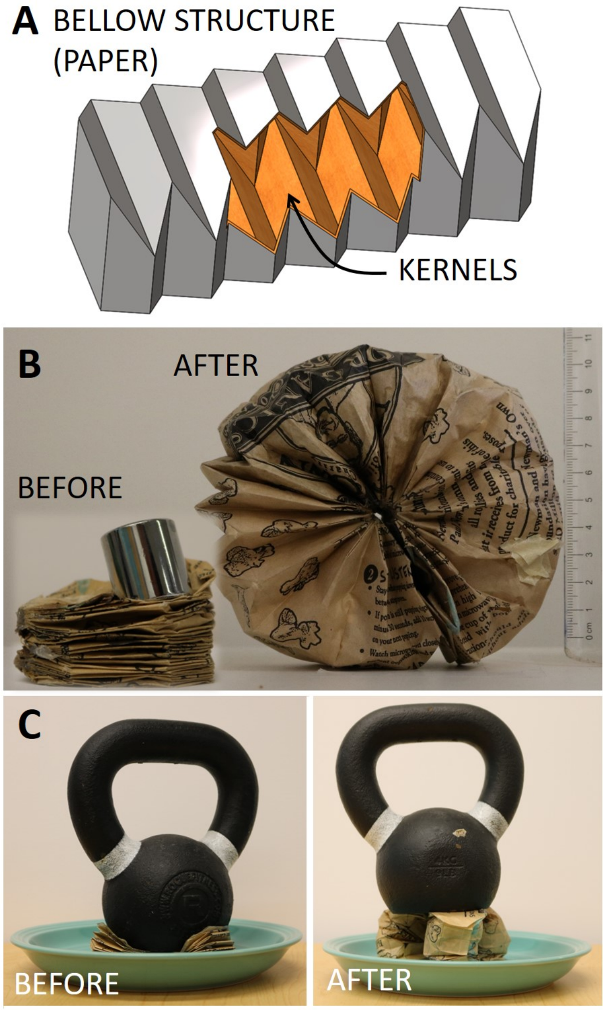


Fig. 6. Origami structures transitioning from compliant to expanded rigid structures. A: Sketch showing how bellow structures are folded out of popcorn paper bags. Expansion is achieved via a microwave oven. B) Example of a folded structure, mechanically programmed to expand into a circle. 80 g of kernels were used for actuation. C) Three-fingered gripper holding a 9 lbs kettlebell to illustrate the compression strength of expanded kernels. Each finger holds 7 g of popcorn.

on microwaves are less amenable to robotics, they serve to illustrate the use of popcorn with compliant mechanisms.

## VI. Popcorn-Driven Gripper With Rigid Links

Finally, we illustrate the use of popcorn to actuate a rigid link gripper using hot air to pop the kernels. The rigid links were 3D printed in ABS with a melting temperature of 230 $^{o}$C, and combined with tendons made from Kevlar fiber with a decomposition temperature above 400 $^{o}$C. The base of the gripper is composed of two parallel wooden plates surrounding 15 g of popcorn kernels. A metal grading on the outer plate allows access of hot air from a hot air gun. The tendons were attached to the upper plate. When kernels pop they force the plate upwards, contracting the tendons, and in turn curling the fingers (Fig. 7).

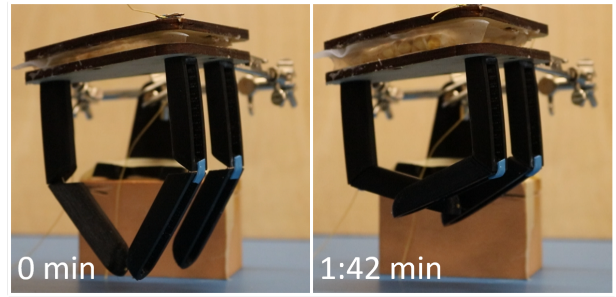


Fig. 7. Three-fingered gripper with rigid links and popcorn-driven tendons. The kernels are embedded between the two wooden plates; the upper plate has a metal grating through which hot air can heat the kernels. When the kernels pop they lift the wooden plates apart, contracting the tendons, and curling the fingers. We encourage the reader to also watch the video attachment of this experiment.

## VII. Conclusion

In summary, many robotic applications may benefit from the use of these multi-functional kernels. Besides the fact that they are inexpensive, edible, and readily available, we have shown that when heated they pop with high force (38.0$\pm$0.9 mN); expand in volume by 9.7$\pm$4.8 times; change viscosity by almost an order of magnitude; exhibit inter-kernel jamming capability; and become more susceptible to bio-degradability.

We have shown that popping can be induced using hot oil and air, microwaves, and direct contact with Nichrome wire. Each heating method has trade-offs. Nichrome wire is inexpensive and flexible, has a compact form factor, and is simple to actuate; as such it is likely the most feasible of all the demonstrated heating methods to work on stand-alone robots. Hot air requires more driving circuitry, but pops kernels faster than Nichrome wire ($\sim$ 1-2 min versus $\sim$ 4-5 min in our experiments). Microwaves are less feasible for stand-alone robots, but do produce the highest expansion ratios.

Finally, we have developed and demonstrated proof-of-concept methods for popcorn-driven elastomers, origami structures, and rigid-member gripping mechanisms, first of their kind. In the near future, we aim to design the infrastructure necessary for stand-alone popcorn-driven robots. This will require an embedded system capable of heating the kernels, and a pump capable of moving the kernels. Long term, the work on multi-functional granular fluids presented in this paper may help pave the way for a wide range of applications spanning the fields of rigid, compliant, and soft robots.

## References

[1] R. F. Shepherd, A. A. Stokes, J. Freake, J. Barber, P. W. Snyder, A. D. Mazzeo, L. Cademartiri, S. A. Morin, and G. M. Whitesides, "Using explosions to power a soft robot," *Angewandte Chemie International Edition*, vol. 52, no. 10, pp. 2892–2896, 2013.

[2] P. Polygerinos, N. Correll, S. A. Morin, B. Mosadegh, C. D. Onal, K. Petersen, M. Cianchetti, M. T. Tolley, and R. F. Shepherd, "Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot

Interaction," *Advanced Engineering Materials*, pp. 1 700 016—-n/a. [Online]. Available: http://dx.doi.org/10.1002/adem.201700016

[3] K. Petersen and R. Nagpal, "Complex Design by Simple Robots," *Architectural Design*, pp. 44–49, 2017.

[4] J. Shintake, H. Sonar, E. Piskarev, J. Paik, and D. Floreano, "Soft Pneumatic Gelatin Actuator for Edible Robotics," pp. 3–8, 2017. [Online]. Available: http://arxiv.org/abs/1703.01423

[5] R. C. Hoseney, K. Zeleznak, and A. Abdelrahman, "Mechanism of popcorn popping," *Journal of cereal Science*, vol. 1, no. 1, pp. 43–52, 1983.

[6] E. Virot and A. Ponomarenko, "Popcorn: critical temperature, jump and sound," *Journal of The Royal Society Interface*, vol. 12, no. 104, p. 20141247, 2015.

[7] E. Karababa, "Physical properties of popcorn kernels," *Journal of Food Engineering*, vol. 72, no. 1, pp. 100–107, 2006.

[8] K. C. Galloway, P. Polygerinos, C. J. Walsh, and R. J. Wood, "Mechanically programmable bend radius for fiber-reinforced soft actuators," in *Advanced Robotics (ICAR), 2013 16th International Conference on*. IEEE, 2013, pp. 1–6.

[9] R. V. Martinez, C. R. Fish, X. Chen, and G. M. Whitesides, "Elastomeric origami: programmable paper-elastomer composites as pneumatic actuators," *Advanced functional materials*, vol. 22, no. 7, pp. 1376–1384, 2012.

[10] L. U. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, "A compliant, underactuated hand for robust manipulation," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, 2014.

[11] E. Steltz, A. Mozeika, J. Rembisz, N. Corson, and H. M. Jaeger, "Jamming as an enabling technology for soft robotics," in *SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring*. International Society for Optics and Photonics, 2010, p. 764225.

[12] M. Cianchetti, T. Ranzani, G. Gerboni, T. Nanayakkara, K. Althoefer, P. Dasgupta, and A. Menciassi, "Soft robotics technologies to address shortcomings in today's minimally invasive surgery: the STIFF-FLOP approach," *Soft Robotics*, vol. 1, no. 2, pp. 122–131, 2014.

[13] N. G. Cheng, A. Gopinath, L. Wang, K. Iagnemma, and A. E. Hosoi, "Thermally Tunable, Self-Healing Composites for Soft Robotic Applications," *Macromolecular Materials and Engineering*, vol. 299, no. 11, pp. 1279–1284, 2014.

[14] W. Shan, S. Diller, A. Tutcuoglu, and C. Majidi, "Rigidity-tuning conductive elastomer," *Smart Materials and Structures*, vol. 24, no. 6, p. 65001, 2015.

[15] J. Shintake, B. Schubert, S. Rosset, H. Shea, and D. Floreano, "Variable stiffness actuator for soft robotics using dielectric elastomer and low-melting-point alloy," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*. IEEE, 2015, pp. 1097–1102.

[16] Y. Forterre and O. Pouliquen, "Flows of dense granular media," *Annu. Rev. Fluid Mech.*, vol. 40, pp. 1–24, 2008.

[17] L. Hines, K. Petersen, and M. Sitti, "Inflated Soft Actuators with Reversible Stable Deformations," *Advanced Materials*, vol. 28, no. 19, pp. 3690–3696, 2016.

[18] N. Napp and R. Nagpal, "Distributed amorphous ramp construction in unstructured environments," *Robotica*, vol. 32, no. 02, pp. 279–290, 2014.