A soft robot that adapts to environments through shape change

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Many organisms, including various species of spiders and caterpillars, change their shape to switch gaits and adapt to different environments. Recent technological advances, ranging from stretchable circuits to highly deformable soft robots, have begun to make shape-changing robots a possibility. However, it is currently unclear how and when shape change should occur, and what capabilities could be gained, leading to a wide range of unsolved design and control problems. To begin addressing these questions, here we simulate, design and build a soft robot that utilizes shape change to achieve locomotion over both a flat and inclined surface. Modelling this robot in simulation, we explore its capabilities in two environments and demonstrate the automated discovery of environment-specific shapes and gaits that successfully transfer to the physical hardware. We found that the shape-changing robot traverses these environments better than an equivalent but non-morphing robot, in simulation and reality.

Nature provides several examples of organisms that utilize shape change as a means of operating in challenging, dynamic environments. For example, the spider Araneus rechenbergi30 and the caterpillar of the mother-of-pearl moth (Pleurotya ruralis)31 transition from walking gaits to rolling in an attempt to escape predation. Across larger timescales, caterpillar-to-butterfly metamorphosis enables land-to-air transitions, while mobile sessile metamorphosis, as observed in sea squirts, is accompanied by radical morphological change. Inspired by such change, engineers have created caterpillar-like rolling4, modular5–7, tensegrity8,9, robot5,6 and origami11,12 robots that are capable of some degree of shape change. However, progress towards robots that dynamically adapt their resting shape to attain different modes of locomotion is still limited. Further, design of such robots and their controllers is still a manually intensive process.

Despite the growing recognition of the importance of morphology and embodiment on enabling intelligent behaviour in robots15, most previous studies have approached the challenge of operating in multiple environments primarily through the design of appropriate control strategies. For example, engineers have created robots that can adapt their gaits to locomote over different types of terrain16–18, transition from water to land19,20 and transition from air to ground19–21. Other research has considered how control policies should change in response to changing loading conditions22,23, or where the robot’s body was damaged24–26. Algorithms have also been proposed to exploit gait changes that result from changing the relative location of modules and actuators27, or tuning mechanical parameters, such as stiffness28. In such approaches, the resting dimensions of the robot’s components remained constant. These robots could not, for instance, actively switch their body shape between a quadrupedal form and a rolling-optimized shape.

The emerging field of soft robotics holds promise for building shape-changing machines29. For example, one robot switched between spherical and cylindrical shapes using an external magnetic field, which could potentially be useful for navigating internal organs such as the oesophagus and stomach30. Robotic skins wrapped around sculptable materials were shown to morph between radially symmetric shapes such as cylinders and dumbbells to use shape change as a way to avoid obstacles31. Lee et al. proposed a hybrid soft–hard robot that could enlarge its wheels and climb onto step-like platforms32. A simulated soft robot was evolved to automatically regain locomotion capability after unanticipated damage, by deforming the shape of its remnant structure33. With the exception of the study by Kriegman et al.33, control strategies and metamorphosis were manually programmed into the robots, thereby limiting such robots to shapes and controllers that human intuition is capable of designing. However, there may exist non-intuitive shape–behaviour pairings that yield improved task performance in a given environment. Furthermore, manufacturing physical robots is time consuming and expensive relative to robot simulators such as VoxCad34, yet discovering viable shape–behaviour pairs and transferring simulated robots to functioning physical hardware remains a challenge. Although many simulation-to-reality (‘sim2real’) methods have been reported35–43, none have documented the transfer from simulation to reality of shape-changing robots.

To test whether situations exist where shape change improves a robot’s overall average locomotion speed within a set of environments more effectively than control adaptations, here we present a robot that actively controls its shape to locomote in two different environments: flat and inclined surfaces (Fig. 1). The robot had an internal bladder, which it could inflate/deflate to change shape, and a single set of external inflatable bladders that could be used for locomotion. Depending on the core’s shape, the actuators created different motions, which could allow the robot to develop new gaits and gain access to additional environments. Within a soft multi-material simulator, an iterative ‘hill-climbing’ algorithm36 generated multiple shapes and controllers for the robot, then automatically modified the robots’ shapes and controllers to discover new locomotion strategies. No shape–controller pairs were found that could locomote efficiently in both environments. However, even relatively small changes in shape could be paired with control policy adaptations to achieve locomotion within the two environments. In flat and even
slightly inclined environments, the robot’s fastest strategy was to inflate and roll. At slopes above a critical transition angle, the robot could increase its speed by flattening to exhibit an inchworm gait. A physical robot was then designed and manufactured to achieve similar shape-changing ability and gaits (Fig. 2). When placed in real-world analogues of the two simulated environments, the physical robot was able to change shape to locomote with two distinct environmentally effective gaits, demonstrating that shape change is a physically realistic adaptation strategy for robots.

Results

The simulated robot. We initially sought to automate search for efficient robot shapes and control policies in simulation, to test our hypothesis that shape and controller adaptation can improve locomotion speeds across changing environments more effectively when given a fixed amount of computational resources, compared with controller adaption only. To verify that multiple locomotion gaits were possible with the proposed robot design, we first used our intuition to create two hand-designed shape and control policies: one for rolling while inflated in a cylindrical shape (Fig. 1a), and the other for inchworm motion while flattened (Fig. 1d). Briefly, the rolling gait consisted of inflating the trailing-edge bladder to tip the robot forward, then inflating one actuator at a time in sequence. The hand-designed ‘inchworm’ gait consisted of inflating the four upward-facing bladders simultaneously to smooth the robot in an arc. We then performed three pairs of experiments in simulation. Within each pair, the first experiment automatically sought robot parameters for flat ground; the second experiment sought parameters for the inclined plane. Each successive pair of experiments allowed the optimization routine to control an additional set of the robot’s parameters, allowing us to measure the marginal benefit of adapting each parameter set when given identical computational resources (summarized in Table 1 and Fig. 3). The three free parameter sets of our shape-changing robot are shape, orientation relative to the contour (equal elevation) lines of the environment, and control policy (Fig. 3a). This sequence of experiments sought to determine whether optimization could find successful parameter sets in a high-dimensional search space, while also attempting to determine to what degree shape change was necessary and beneficial.

In all experiments, fitness was defined as the average speed the robot (measured in body lengths per second (BLs⁻¹)) attained over flat ground or uphill, depending on the current environment of interest, during a fixed period of time. Parameters for the simulation were initialized based on observations of previous robots and adjusted to reduce the simulation-to-reality gap after preliminary tests with physical hardware (see Methods for additional details). The results reported here are for the final simulations that led to the functional physically realized robot and gaits.

In the first pair of experiments, we sought to discover whether optimization could find any viable controllers within a constrained optimization space, which was known to contain the viable hand-designed controllers. Solving this initial challenge served to test the pipeline before attempting to search in the full search space, which has the potential to have more local minima. The shape and orientation were fixed (flat and oriented length-wise, \( \theta = 90^\circ \), for the inclined surface, cylindrical and oriented width-wise, \( \theta = 0^\circ \) for

Fig. 1 | Shape change can result in faster locomotion speeds than control adaptation, when a robot must operate in multiple environments. a. Using inflatable external bladders, rolling was the most effective gait on flat ground. b. Rolling was ineffective on the inclined surface. c,d. Search discovered a flat shape (achieved by deflating the inner bladder) and crawling gait (d) that allowed the robot to succeed in this environment. e,f. After discovering these strategies in simulation, we transferred learned strategies for rolling (e) and inchworm motion (f) to real hardware. Scale bars, 5cm.
the flat surface). In the second pair of experiments, the algorithm was allowed to simultaneously search for an optimal shape and controller pair. Finally, in the third pair of experiments, all three parameter sets were open to optimization in both environments, allowing optimization the maximum freedom to produce novel shapes, orientations and controllers for locomoting in the two different environments. For each experiment, we ran 60 independent ‘hill climbers’ (instantiations of the hill-climbing search algorithm\(^1\), not to be confused with a robot that climbs a hill) for 200 iterations, thus resulting in identical resource allocation for each experiment (Fig. 3b,c). In addition, we ran a control experiment in which we fixed the shape of the robot to be fully inflated and oriented width-wise (\(\theta=0^\circ\)) for the inclined surface, to determine whether shape change was necessary. The best the robot could do was prevent itself from rolling backward, and it attained a fitness value of \(-0.001 \text{ BL s}^{-1}\).

When shape and orientation were set as fixed parameters, optimization found a control policy that had a similar behaviour to those that were hand-designed. Thus, even though optimization did not hinder the search process, allowing the algorithm to discover efficient solutions without any priori knowledge of the viability of the attainable shape–controller pairs.

In the last pair of experiments (all parameters open), the algorithm again discovered that cylindrical rolling robots were the most effective over a flat surface. However, over the inclined surface, the optimization algorithm found better designs with a semi-inflated shape capable of shuffling up the hill when oriented at an angle (maximum fitness 0.042 BL s\(^{-1}\)). Using this strategy, the robot achieved combined locomotion of 0.136 BL s\(^{-1}\), outperforming the hand-designed strategy of using crawling on inclines and rolling on flat ground. The deflated shape increased the surface area of the robot in contact with the ground, increasing friction between the robot and the ground, while the non-standard orientation reduced the amount of gravitational force opposing the direction of motion, thereby requiring less propulsive force and reducing the likelihood of the robot rolling back down the hill. However, when we attempted to replicate this behaviour in physical hardware, the robot could not shuffle, and rather rocked in place. Thus, the best transferable strategy for moving up the incline was to attain the flattened shape and traverse the hill using an inchworm-like gait. In all the experiments, the policies found were less finely tuned than those that were hand-designed. Thus, even though optimization produced similar overall behaviours and performance (inching and rolling), these behaviours also included occasional counterproductive or superfluous actuations (Supplementary Video 1). Such unhelpful motions could probably be overcome via further optimization and by adding a fitness penalty for the number of actuators used per time step.
better, experiment. The optimized solutions were found to be significantly previous pairs of experiments against the transferable solutions in this comparing the solutions found through optimization during the three experiments. More sophisticated optimization algorithms that can operate in an exponentially growing search space. When designing robots with increased degrees of freedom, using the algorithm’s design freedom would be even more important. We hypothesize that maximizing the performance compared with the control-only experiments (Fig. 3). Here we show an example controller for the eight main bladders, with green shaded squares illustrating inflation and white squares showing deflation. Results on a flat surface (b) and on an inclined surface (c). Shaded regions represent 1 s.d. about the mean (solid line) and dashed lines represent maximum fitness. The legend indicates which parameters were to open to optimization, the others being held constant.

Our control experiment, where the robot was constrained to be oriented width-wise against the inclined surface and fully inflated, tested whether optimization found intuitive shapes and behaviours for the given environments (rolling on flat ground, inching on moderate inclines), we further sought to discover optimal shape–behaviour pairs in very slightly inclined environments, where it was not obvious whether the robot would benefit from being able to detect sudden decreases in performance to allow them to respond by transitioning to a different, more appropriate shape–policy strategy. We further note that the exact critical incline angle, or transition angle, is dependent on the friction between the robot and the surface it is traversing. While optimization found intuitive shapes and behaviours for the given environments (rolling on flat ground, inching on moderate inclines), we further sought to discover optimal shape–behaviour pairs in very slightly inclined environments, where it was not obvious whether the robot would benefit from being able to detect sudden decreases in performance to allow them to respond by transitioning to a different, more appropriate shape–policy strategy. We further note that the exact critical incline angle, or transition angle, is dependent on the friction between the robot and the surface it is traversing.

Overall, this sequence of experiments showed that automated search could discover physically realistic shapes and controllers for our shape-changing robot in a given environment (a prescribed ground incline). In addition, when faced with an incline sweep, evolutionary algorithms could discover the transition point where shape change is necessary. Although the hand-designed controllers each performed comparably to the best discovered controllers.
in a single environment, by changing shape, the robot had a better combined average speed in both environments. Concretely, the best shape–controller pair found by hill climbing locomoted at a speed of 0.229 BL s$^{-1}$ on flat ground and 0.042 BL s$^{-1}$ on incline, resulting in an average speed across the two environments of 0.136 BL s$^{-1}$, compared with the average speed of $-0.198$ BL s$^{-1}$ for the round shape with a rolling gait and 0.079 BL s$^{-1}$ for the flat shape with an inchworm gait (Table 1).

Transferring to a physical robot. Transferring simulated robots to reality introduces many challenges. For perfect transferal, the simulation and hardware need to have matching characteristics, including: material properties, friction modelling, actuation mechanisms, shape, geometric constraints and range of motion. In practice, hardware and software limitations preclude perfect transferal, so domain knowledge must be used to achieve a compromise between competing discrepancies. Here we sought to maximize the transferal of useful behaviour, rather than strictly transferring all parameters. In simulation, we found that the same actuators could be used to create different locomotion gaits. When restricted to the cylindrical shape, successful controllers typically used sequential inflation of the bladders to induce rolling. The flatter robots employed their actuators to locomote with inchworm motion. To transfer such shape change and gaits to a physical robot, we created a robot that had an inflatable core, eight pneumatic surface-based actuators for generating motion and variable-friction feet on each edge to selectively grip the ground. When the balloon was inflated (50 kPa), it pushed the silicone lamina outward and created a higher-friction contact with the ground. When the balloon was uninflated (0 kPa), the silicone lamina was pulled into its fabric sheath, thus the fabric was the primary contact with the ground. Thus, flatter robots should bend to higher curvatures for a given pressure. However, even for the flattest shape, bending was insufficient to produce locomotion: on prototypes with unbiased frictional properties, bending made the robot curl and flatten in place.

Variable-friction ‘feet’ were integrated onto both ends of the robot and actuated one at a time to alternate between gripping in front of the robot and at its back, allowing the robot to inch forward (average speed of 0.01 BL s$^{-1}$ on flat wood). The feet consisted of a latex balloon inside unidirectionally stretchable silicone lamina, wrapped with cotton broadcloth. When the inner latex balloon was inflated (~80 kPa), the silicone lamina was pulled into its fabric sheath, thus the fabric was the primary contact with the ground. When the balloon was inflated (50 kPa), it pushed the silicone lamina outward and created a higher-friction contact with the ground (Fig. 6a). To derive coefficients of static friction ($\mu_s$) for both the uninflated ($\mu_u$) and the inflated ($\mu_i$) cases, we slid the robot over various surfaces including acrylic, wood and gravel. As the robot slid over a surface, it would typically exhibit an initial linear regime corresponding to pre-slip deformation of the feet, followed by slip and a second linear kinetic friction regime (Fig. 6b). From the pre-slip regime, we infer that on a wood surface $\mu_u = 0.56$ and $\mu_i = 0.70$—an increase of ~25% (Fig. 6c). On acrylic, $\mu_u = 0.38$ and $\mu_i = 0.51$, which is an increase of 35%, yielding an inching speed of 0.007 BL s$^{-1}$. When the difference in friction ($\Delta \mu = \mu_i - \mu_u$) for the variable-friction feet was too low (such as on gravel), inchworm motion was ineffective, as predicted by simulation (Fig. 6d). Similarly, when the average friction ($\mu_{\text{ave}} = (\mu_u + \mu_i)/2$) was too high, it would overpower the actuators and lead to negligible motion (Fig. 6e). On wood, the inchworm gait was effective on inclines up to ~14°, at a speed of 0.008 BL s$^{-1}$ (Fig. 5 and the Supplementary Video 1). Thus, the robot could quickly roll over flat terrain (0.05 BL s$^{-1}$) then flatten to ascend moderate inclines, attaining its goal of maximizing total travelled distance.

Discussion

In this study, we tested the hypothesis that adapting the shape of a robot, as well as its control policy, can yield faster locomotion across environmental transitions than adapting only the control policy of a single-shape robot. In simulation, we found that a shape-changing robot traversed two test environments faster than an equivalent but
non-morphing robot. Then, we designed a physical robot to utilize the design insights discovered through the simulation, and found that shape change was a viable and physically realizable strategy for increasing the robot’s locomotion speed. We have also shown progress towards an automated sim2real framework for realizing metamorphosing soft robots capable of operating in different environments. In such a pipeline, simulated shape-changing robots would be designed to achieve a desired function in multiple environments, then transferred to physical robots that could attain similar shapes and behaviours. We demonstrated each component of the pipeline on a representative task and set of environments: locomotion over flat ground and an incline. Starting with an initial robot design, the search method sought valid shapes and control policies that could succeed in each environment. The effective shapes and gaits were then transferred to physical hardware. However, the simulation was able to generate some non-transferable behaviour by exploiting inaccuracies of some simulation parameters. For example, when the friction coefficient was too low, the robot would make unrealistic motions such as sliding over the ground. Other parameters, such as modulus, timescale, maximum inner bladder pressure, resolution of the voxel simulation (that is, the number of simulated voxels per bladder) and material density, could be adjusted without causing drastic changes in behaviour. Developing a unified framework for predicting the sim2real transferability of multiple shapes and behaviours to a single robot remains an unsolved problem.

Insights from early physical prototypes were used to improve the simulator’s hyperparameters (such as physical constants), resulting in more effective sim2real transfers. Pairing hardware advances with multiple cycles through the sim2real pipeline, we plan to systematically close the loop such that data generated by the physical robot can be used to train a more accurate simulator, after which a new round of sim2real transfers can be attempted. This iterative process will be used to reduce the gap between simulation and reality in future experiments.

With advances such as increased control of the physical robots’ shape and more efficient, parallelized soft-robot simulators, the pipeline should be able to solve increasingly challenging robot design problems and discover more complicated shape–controller pairs. While the sim2real transfer reported in this manuscript primarily tested intermediate shapes between two extremal shapes—a fully inflated cylinder and a flattened sheet—future robots may be able to morph between shapes embedded within a richer, but perhaps less intuitive morphospace. For example, robots could be automatically designed with a set $C$ of $N_c$ inflatable cores and corresponding constraining fabric outer layers. To transition between shapes, a different subset $C$ could be inflated, yielding $2^{N_c}$ distinct robot morphologies. Designing more sophisticated arrangements of actuators and inflatable cores could be achieved using a multilayer evolutionary algorithm, where the material properties of robots are designed along with their physical structure and control policies.$^{51}$
Robots potentially could metamorphose to attain multiple grasping to expand their competencies. By leveraging soft materials, such shape-changing amphibious robots remains largely unstudied.

In addition, it is unclear how to properly embed sensors into the physical robot to measure its shape, actuator state and environment. Although some progress has been made towards intrinsically sensing the shape of soft robots and environmental sensing, it remains an open challenge for a robot to detect that it as encountered an unforeseen environment and edit its body morphology and behavioural control policy accordingly.

Future advances in hardware and search algorithms could be used to design shape-changing robots that can operate across more challenging environmental changes. For example, swimming or amphibious robots could be automatically designed using underwater soft-robot simulation frameworks, and changing shape within each gait cycle might allow robots to avoid obstacles or adapt to environmental transitions. We have begun extending our framework to include underwater locomotion, where locomoting between terrestrial and aquatic environments represents a more extreme environmental transition than flat-to-inclined surface environments. Our preliminary results suggest that multiple swimming shape–gait pairs can be evolved using the same pipeline and robot presented herein (Supplementary Information). While recent work has shown the potential advantages of adapting robot limb shape and gait for amphibious locomotion, closing the sim2real gap on shape-changing amphibious robots remains largely unstudied.

Collectively, this work represents a step towards the closed-loop automated design of robots that dynamically adjust their shape to expand their competencies. By leveraging soft materials, such robots potentially could metamorphose to attain multiple grasping modalities, adapt their dynamics to intelligently interact with their environment and change gaits to continue operation in widely different environments.

Methods

Simulation environment. The robots were simulated with the multi-material soft-robot simulator Voxelize, which represents robots as a collection of cubic elements called voxels. A robot can be made to move via external forces or through expansion of a voxel along one or more of its three dimensions. V Voxels were instantiated as a lattice of Euler–Bernoulli beams (Supplementary Fig. 1a). Thus, adjacent voxels were represented as points connected by beams (Supplementary Fig. 1b). Each beam had length $l = 0.01$ m, elastic modulus $E = 400$ kPa, density $\rho = 3,000$ kg m$^{-3}$, coefficient of friction $\mu = 0.5$ and damping coefficient $\zeta = 1.0$ (critically damped). For comparison, silicone typically has a modulus of $-100$–$600$ kPa and density of $-1,000$ kg m$^{-3}$. These parameters were initially set to $E = 100$ kPa and $\rho = 1,000$ kg m$^{-3}$, but were iteratively changed to increase the speed and stability of the simulation while maintaining physically realistic behaviour. We simulated gravity as an external acceleration ($g = 9.80665$ m s$^{-2}$) acting on each voxel. For the flat environment, gravity was in the simulation’s negative $z$ direction. Since changing the direction of gravity is physically equivalent to and computationally simpler than rotating the floor plane, we simulated the slope by changing the direction of gravity. The robot could change shape by varying the force pushing outward, along to the interior voxels’ surface normals, representing a discrete approximation of pressure (Supplementary Fig. 1c). The maximum pressure was set at 14 kPa (1.4 N per voxel) after comparison with previous results (for example, the robotic skins introduced by Shah et al. inflated their pneumatic bladders to under 20 kPa (ref. 31)) and after initial experiments with hardware revealed only 10–35 kPa was necessary. The robots’ external bladders were simulated via voxel expansion such that a voxel expanded along the $z$-dimension of its local coordinate space at $3 \times 10^{-4}$ m per simulation step and $1.5 \times 10^{-2}$ m along the $x$ dimension. Expansion in the $y$ dimension created a bending force on the underlying skin voxels. This value was changed on a sliding scale from $1.76 \times 10^{-4}$ m to $3 \times 10^{-4}$ m based on the pressure of the robots’ core, such that bladder expansion created minimal bending force.
when the robot was inflated, simulating the expansion of physically realizable soft robots. Concretely, the $y$-dimension expansion was computing using a normalizing equation $(\varphi - \varphi_{\text{min}}(P_{\text{air}} - P_{\text{air}}))(\varphi_{\text{max}} - \varphi_{\text{min}})) + \varphi_{\text{min}}$, where $\varphi = 1.70, \varphi_{\text{max}} = 5.0$, $P_{\text{air}}$ is the maximum outward force per voxel (N), $P_{\text{air}}$ is the minimum outward force per voxel (N) and $P$ is the current outward force per voxel. These values were adjusted iteratively, until simulated and physical robots with the same controllers exhibited similar behaviour in both the inclined and flat environments. Lastly, to prevent the robot from slipping down the hill, and to enable other non-rolling gaits, the robot was allowed to change the static and kinetic friction of its outer voxels between a low value ($\mu = 1 \times 10^{-5}$) when inactive and high value ($\mu = 2.0$) when active.

Optimization. The optimization algorithm searched over three adjustable aspects of the robots: shape (parameterized as inner bladder pressure), orientation of the robots relative to incline plane and actuation sequence process over a single number $p \in [0, 1.4]$ (N per voxel) for shape and $\theta \in [0°, 90°]$ for orientation (see Supplementary Fig. 3a for illustrations of each parameter). The robot's actuation sequence $S$ over $T$ actuation steps was represented by a binary $10 \times T$ matrix where $1$ corresponds to bladder expansion and $0$ corresponds to bladder deflation. Each of the first eight rows corresponded to one of the inflatable bladders, and the last two rows controlled the variable-friction feet. Each column represented the actuation to occur during a discrete amount of simulation timesteps $t$, resulting in a total simulation length of $t \times T$. It was set such that an actuation achieved full inflation, followed by a pause for the elastic material to settle. Actuating in the inner minimizes the effects of the complex dynamics of soft materials, reducing the likelihood of the robots exploiting idiosyncrasies of the simulation environment. In this study, we used $t = 11,000$ timesteps of 0.0001s each and $T = 16$ for all simulations, for a total simulation time of 17.6s. To populate $S$, the algorithm searched over a set of parameters (frequency $f$ and offset $\phi$) for each of the ten actuators. Both of these parameters were kept in the range $0$–$7$ where $f = 2$ for our case $T = 16$, $\phi$ determined the oriented of the actuator to contact the environment, leading to a low-friction interaction. When the feet were inflated, the silicone would contact the environment, allowing the feet to increase their friction.

Finally, the robot was assembled by attaching the feet to the main robot body using Sil-Poxy; and the robot was folded to bond the inner bladder to the bladderless half, using DS10 (Supplementary Fig. 2d).

Experiments with the physical robot. To test the robot's locomotion capabilities, we ran the physical robots through several tests on flat and inclined ground. The pressure in the robots' bladders was controlled using pneumatic pressure regulators (9). The robots were operated primarily on wood (flat and tipped to angles up to $-15°$), with additional experiments carried out on a flat acrylic surface and a flat gravel surface (Fig. 5 and Supplementary Video 1).

The variable-friction feet were assessed by pulling the robot across three materials (acrylic, wood, gravel) using a materials testing machine (Instron 3343). The robot was placed on a candidate material and dragged across the surface at $100$ mm min$^{-1}$ for $130$ mm at atmospheric conditions ($23°C, 1$ atm). This process was repeated ten times for each material, at two feet inflation pressures: vacuum ($-80$ kPa) and inflated ($50$ kPa). The static coefficient of friction, $\mu_s$, was calculated by dividing the force at the upper end of the linear regime by the weight of the robot.

The robot's shape-changing speed was assessed by manually inflating and deflating the robot's inner core for $20$ cycles. For each cycle, the robot body was inflated to a cylindrical shape with a line pressure of $50$ kPa, and the time required to attain a diameter of $-7$ cm was recorded. The body was then deflated with a line pressure of $-80$ kPa, and the time required to flatten to a height of $-1.2$ cm was recorded.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

A public repository at https://doi.org/10.5281/zenodo.4067077 contains the code necessary to reproduce the soft-robot simulations.

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Author contributions

J.R., R.K.-B., S.K., D.S.S. and J.P.P. conceived the project and planned the experiments. J.P.P. coded the simulation and ran the evolutionary algorithm experiments. D.S.S. and L.G.T. manufactured the robot and performed the hardware experiments. D.S.S., J.P.P., L.G.T., S.K., J.B., R.K.-B. and J.P.P. drafted and edited the manuscript. All authors contributed to, and agree with, the content of the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s42256-020-00263-1.
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For the soft robot simulations, we utilized custom scripts that used the open source physics simulator Voxelz and publicly-available Julia packages: Cxx, Libdl, Makie, LinearAlgebra, StatsBase, Colors, Random. Our code has been published for public access at https://doi.org/10.5281/zenodo.4067077

Data analysis

Data analysis of the physical robot was performed using standard functions in MATLAB 2019b, and simulated robots were analyzed using publicly-available Julia package HypothesisTests, and using gnuplot [www.gnuplot.info].

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Describe the antibodies used for the ChIP-seq experiments; as applicable, provide supplier name, catalog number, clone name, and lot number.

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Flow Cytometry

Plots

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Methodology

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Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.

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- [ ] Graph analysis
- [ ] Multivariate modeling or predictive analysis

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