Ultrafast, Programmable, and Electronics-Free Soft Robots Enabled by Snapping Metacaps

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Soft robots offer a myriad of potential because of their intrinsically compliant bodies, enabling safe interactions with humans and adaptability to unpredictable environments. However, most of them have limited actuation speeds, require complex control systems, and lack sensing capabilities. To address these challenges, herein, a class of metacaps is geometrically designed by introducing an array of ribs to a spherical cap with programmable bistabilities and snapping behaviors, enabling several unprecedented soft robotic functionalities. Specifically, a centimeter-sized, sensor-less metacap gripper is demonstrated that can grasp objects in 3.75 ms upon physical contact or pneumatic actuation with tunable behaviors that have little dependence on the rate of input. The grippers can be readily integrated into a robotic platform for practical applications. The metacap can further enable propelling of a swimming robot, exhibiting amplified swimming speed as well as untethered, electronics-free swimming with tunable speeds using an oscillating valve. The metacap designs provide new strategies to enable the next-generation soft robots to achieve high transient output energy and autonomous and electronics-free maneuvering.

1. Introduction

Over the last decades, there have been considerable developments in soft robots that attempt to bridge the gap between conventional machines with high performance and rigid components and biological organisms with remarkable versatility and adaptability.[1–8] The merits of soft robots are generally accomplished by deforming partial or all of the compliant robotic bodies via approaches such as pneumatic and hydraulic actuation,[9–11] thermal stimulation,[12,13] solvent swelling,[14,15] and application of magnetic and electric fields.[16–18] The deformation mechanisms of soft robots can be roughly classified into two types: one deforms with a rate monotonically related to the input energy, but the performance is limited by the power and capacity of the input. For instance, the actuation speed of most pneumatically driven actuators is monotonically related to the input air flow rate.[9,19] A pump with high power is required in order to realize high actuation speed. The other exploits mechanical bistability (or multistability) to decouple the output from input by gradually storing elastic energy before releasing it suddenly.[20–22] In this case, high-speed actuation can be realized even from the input of a small power, providing an ideal mechanism for applications that require high-rate motion and fast energy release.

Mechanical bistability exploited in soft robots typically results from geometrical frustrations induced by buckled beams,[28,29] mechanism-based rotating units,[30–32] and doubly curved shells.[33–35] These building blocks enable various structures, exhibiting two or more stable states that remain respective equilibrium configurations without the application of external forces. The principle of designing diverse systems with tunable bistability using buckled beams or mechanism-based rotating units has been broadly investigated and well understood.[16,17] However, guidelines for designing spherical shells with tunable bistability are still elusive and poorly explored.

Snap-through behaviors of spherical shells when tuned “inside-out” have been one of the most widely employed mechanisms for achieving rapid responses in robots.[38,39] However, the performance of these robotic systems is generally restricted by the intrinsic property of the caps. For instance, a simple spherical cap with uniform thickness and clamped border is typically monostable and extremely sensitive to imperfections when the
thickness-to-radius ratio is small, leading to asymmetric deformation and limited energy release upon snapping (see Figure 1a and the corresponding pressure–volume curve in Figure 1d). While increasing the thickness-to-radius ratio can enhance the cap robustness, it also compromises the snapping behavior (see Figure 1b and the corresponding pressure–volume curve in Figure 1d).

Mechanical metamaterials, whose properties go beyond those of the ingredient materials and are tailored by the architected geometries at the micro- and macroscales, offer a new paradigm to realize extraordinary snap-through behaviors and tunable stabilities by leveraging geometric frustrations. These properties enable metamaterials with great potential in applications of “smart” purposes, such as energy absorption,[36,40] biomedical devices,[41,42] and soft robotics.[43,44] Here, we introduce the metamaterial concept to the spherical cap by designing a class of metacaps, which can realize different robotic functions enabled by the nonlinear yet programmable snapping behaviors. The metacap comprises a spherical cap patterned with an array of ribs aligned in the circumferential and radial directions of the cap (Figure 1c). By rationally tailoring the dimensions and geometry of the ribs, we realize rich nonlinear mechanical properties of the caps, enabling a variety of soft robotic systems with unprecedented functionalities, including 1) a passive metacap gripper with mechanically embedded sensing capable of grasping objects in 3.75 ms upon contact; 2) a pneumatically actuated metacap gripper with tunable actuation speeds that are independent of the input rate but readily tunable by changing the volume of the chamber connected to the gripper; and 3) a swimming robot whose speed is amplified by the metacap, which can be actuated untethered and electronics-free. Distinguished from the existing bistable robotic systems, which show fast responses but lack tunability,[23,36,40] our study provides new strategies to realize spherical shells with programmable stabilities and robotic systems with fast yet tunable responses, paving the way for the next-generation soft robots that are ultrafast, programmable, autonomous, and electronics-free.

2. Design of the Metacap

To render the metacap with highly robust, bistable, and fast snapping behaviors, we introduce an array of ribs to a simple spherical cap of radius, $R$, thickness, $t$, and polar angle, $\phi$. The array contains eight radial ribs (green in color, with thickness, $t_r$, polar angle, $\theta_r$, and azimuthal angle, $\theta_c$, in Figure 1c) and one circumferential rib (red in color, with thickness, $t_c$, polar angle, $\phi_c$). As the ribs affect the bending stiffness of the cap locally, the mechanical response of the metacaps can be significantly different from that of the spherical caps of uniform thickness.

First, we conduct finite element (FE) analyses to investigate the response of caps with variable geometries upon pressurization. Figure 1d compares the pressure–volume curves of three representative caps, including the thin cap with $t_1/R = 0.075$, the thick cap with $t_2/R = 0.15$, and the metacap with $t/R = 0.075, \phi_0 = 5.0^\circ, \phi_c = 8.0^\circ, t_c/R = 0.133, \phi_c = 47.85^\circ, \theta_c = 35.0^\circ$, and $t_c/R = 0.267$. All have the same polar angle $\phi = 57.85^\circ$. Upon inflation, a sharp pressure drop inside the metacap is observed when the applied volume is larger than the critical volume, which occurs at the peak pressure, indicating a more pronounced snapping behavior than that of spherical

![Figure 1](https://www.advancedsciencenews.com)
caps of various thicknesses. Moreover, the metacap can achieve a new equilibrium state after snapping, which is highlighted by the black dot in Figure 1d. In contrast, conventional spherical caps with clamped boundaries are monostable upon inflation, regardless of the thickness and radius.\(^{[46]}\) Figure 1e plots the evolution of the strain energy as a function of the volume change for the three caps. The inflation and deflation curves of the thick cap are identical, which increase monotonically as the applied volume increases. Differently, the metacap and the thin cap show hysteresis between inflation and deflation curves due to the snapping-induced energy dissipation. The thin cap has a monotonically decreasing curve upon deflation, implying that the thin cap is monostable. In contrast, the deflation curve of the metacap has two local energy minima, indicating the bistability of the metacap, which is crucial for various robotic applications.

To shed light on how the geometry of the ribs affects the mechanical response of the metacap, we conduct a parametric study via FE simulations and report the landscape of the energy release, \(E_r\), when the metacap deforms from the everted state to the undeformed state, and the energy barrier, \(E_b\), which is required to trigger the transformation from the everted state to the undeformed state, in Figure 1f,g, respectively. Throughout the study, we consider \(R=30\,\text{mm}, \phi = 57.85^\circ, t/R = 0.075, \phi_0 = 5.0^\circ, \phi_f = 8.0^\circ, \phi_1 = 47.85^\circ, \text{and } \theta_0 = 35.0^\circ\) as fixed parameters and tune the response of the metacap by varying \(t_c/R \in [0 - 0.33]\) and \(t_t/R \in [0 - 0.33]\). Note that within this design space we can achieve metacaps with diverse nonlinear mechanical responses, and structures of other parameters can also be investigated using the same method. Details on the design principle of the metacap can be found in Section S3, Supporting Information. From Figure 1f we find that the metacap is always monostable when \(t_c/R \geq 0.2\) or \(t_t/R \leq 0.067\) (the gray region in Figure 1f). For a given \(t_c/R \geq 0.1\), as the thickness of the circumferential ribs \(t_c\) increases, \(E_b\) monotonically increases so that the released energy becomes larger and larger. While the effect of \(t_t\) on \(E_b\) is less pronounced, characterized by little variation of \(E_b\) when \(t_t\) is fixed (Figure S20, Supporting Information). In contrast, both \(t_c\) and \(t_t\) have a significant impact on the energy barrier \(E_b\); a smaller \(E_b\) can be achieved around the border between monostable and bistable regions, indicating that the metacaps from that region can be easily triggered to transform from the everted state to the undeformed state.

3. Ultrafast, Passive Metacap Grippers

The programmable bistabilities of the metacap allow us to design a passive gripper capable of grasping objects when a certain contact force is applied to the center of the metacap. The passive gripper comprises a bistable metacap, four fingers (3D printed from Acrylonitrile Butadiene Styrene, ABS) evenly glued on the radial ribs of the cap, and two acrylic plates fixed by four bolts to clamp the border of the metacap (see Figure 2a and Section S1.1, (a) Schematics of the passive gripper that closes upon applying a certain force at the center of the cap. The cap is fixed by two acrylic plates through four bolts, and four 3D-printed fingers (ABS) are glued on the ribs of the cap to catch the objects. b) The grippers can grasp objects of different shapes, moduli, and weights. c) The gripper is capable of realizing highly dynamic grasping tasks. A ball hits at the center of the cap with a speed of around 5.8 m s\(^{-1}\) and is caught by the gripper in 3.75 ms. d) Integration of the gripper into a baseball glove can facilitate the catching of baseballs. e,f) The metacap gripper is integrated into a robotic arm (Franka Emika Panda) and controlled by a linear actuator for opening, closing is fully passive. Scale bar: 30 mm.
When the gripper is integrated into a baseball glove, the simplicity of our metacap gripper makes it easy to be readily triggered without suffering the snapping response, parameters corresponding to small $E_0$ and large $E_c$ should be selected. The fingers of the Flex 80 gripper are coated with a thin layer of elastomer (Elite Double 22) to enhance friction for stable grasping. Although the fingers are printed from rigid ABS, the stiffness of the gripper and its response time is determined by the metacap instead of the fingers. While the majority of soft robotic grippers rely on complex sensing and control systems for successful grasping, our metacap gripper is a combination of sensor and effector by itself. To trigger the gripping function of our gripper, forces greater than 0.38 and 2.13 N for the grippers made of Elite Double 32 and Flex 80 are necessary (Figure S11, Supporting Information), implying that our gripper can sense the forces larger than the specific value and transfer this information to the effector to grasp objects. More grasping tests on different objects can be found in Figure S21, Supporting Information.

As the bistable metacap releases a large amount of elastic energy when the gripper deforms from the open to the closed state, the gripper is able to react rapidly and perform highly dynamic grasping tasks. Figure 2c shows experimental snapshots of the metacap gripper made of Flex 80, grasping a stress ball in 3.75 ms after it hits the center of the metacap at a speed of $\approx 5.8 \text{ m s}^{-1}$. When the gripper is integrated into a baseball glove, it facilitates catching without the need for fingers (Figure 2d), which can help with hand movement practice. This feature would be especially beneficial for people with hand disabilities to play baseball (see Movie S3, Supporting Information, and fabrication of the glove with the gripper in Figure S3, Supporting Information). Furthermore, the rapid response of the metacap gripper shows great potentials for locomotion tasks on thin, cantilevered beams. A real-life example is that of squirrels’ landing behavior when they leap from branch to branch (Figure S13, Supporting Information). Squirrels are known for their acrobatic maneuvers and capability of leaping through complex tree canopies to travel and avoid predators, which makes them exemplary models to emulate for high-mobility robots. Our metacap gripper can mimic the landing behavior of squirrels’ paws and facilitate the design of biomimetic robots with high agility.

Finally, our metacap gripper shows great potential in the docking system for safe space rendezvous, owing to its intrinsically compliant body and the passive and fast grasping mechanism.

The simplicity of our metacap gripper makes it easy to be integrated into an existing robotic platform for industrial applications. Toward this end, we clamp the gripper onto a 3D-printed frame and mount a linear actuator (USLICCX LA-T8) at the center of the frame (Figure 2e) to open the gripper by pushing the cap using the shaft of the linear actuator. As the gripper is passive, it can grasp the object automatically when in contact with the object above a certain force. As shown in Figure 2f, the objects can be grasped by the gripper when the robotic arm moves down and be released at the target position by pushing the metacap using the linear actuator (Movie S5, Supporting Information).

4. Pneumatically Actuated Grippers with Tunable Actuation Speeds

When the passive metacap gripper grasps objects rapidly, it also inflicts high impacts onto the objects, causing undesirable damage to soft and delicate objects such as fruits and eggs. To extend the capability and adaptiveness of our grippers, we design a pneumatic actuation mechanism (Figure 3a) where the actuation speed can be fine-tuned to allow for not only the rapid grasping for highly dynamic tasks but also the gentle manipulation of delicate objects. We clamp the metacap gripper to a chamber formed by an acrylic tube and a 3D-printed piston, whose volume can be adjusted by changing the position of the piston via twisting the translational screw that is connected to the piston (see Section S1.4, Supporting Information, about the fabrication of the pneumatically actuated gripper). By leveraging the compressibility of air and the bistability of the metacap, we achieve gentle actuation when the initial volume of the chamber $V_0$ is small (e.g., 10 mL in Figure 3b) while realizing rapid grasping when $V_0$ is large (e.g., 90 mL in Figure 3b). The metacap is made of Elite Double 32 with the geometry highlighted in Figure 1f,g. It takes 500 ms for the gripper with $V_0 = 10$ mL to snap open when inflated using a diaphragm pump (JSB1523006, TSC, China), but 6.75 ms to snap open when $V_0 = 90$ mL with the same input (Movie S6, Supporting Information).

To quantitatively understand the effect of $V_0$ on the actuation speed of the gripper under a constant pneumatic input, we develop a simple model to investigate the energy release during the opening and closing of the gripper. We denote the critical pressure and the critical volume change that the cap snaps as $P_c$ and $\Delta V_{cap}$, respectively, and the pressure and the volume change after the cap snaps as $P_x$ and $\Delta V_x$, respectively (Figure 3c). The actuation speed is determined by the amount of energy release during the snapping. We ignore the energy from the input because the snapping is fast and the input flow rate is relatively slow. Therefore, the total energy release contains the elastic energy change from the metacap $\Delta E_{cap}$ and the compressed air $\Delta E_{air}$ as

\[
\Delta E = \Delta E_{cap} + \Delta E_{air}
\]  

Note that both $\Delta E_{cap}$ and $\Delta E_{air}$ are affected by $V_0$ due to the compressibility of air. Here, we assume that the snapping is an isothermal process and the status of the cap after snapping can be determined via Boyle’s law

\[
P_c V_c = P_x V_x = P_0 V_t
\]

where $P_x = P_0 + P_s$ (with $s = c$ or $t$) is the absolute pressure with $P_0 = 101.3$ kPa as the standard atmospheric pressure, $V_x = V_0 + \Delta V_x$ is the total volume inside the chamber, and
Figure 3. Pneumatically actuated grippers with tunable speeds. a) An experimental snapshot of the actuator. The metacap gripper is clamped to an acrylic chamber whose volume is tunable by changing the position of the 3D-printed piston. b) Experimental snapshots of the opening process of grippers with different initial volumes. The one with $V_0 = 10$ mL takes 500 ms to deform from the closed state to the open state, while the one with $V_0 = 90$ mL needs 6.75 ms to snap open, indicating that the actuation speeds are affected by the initial volume of the chamber. c) Schematic of the pneumatically actuated gripper before and after snapping. $P_c$ and $\Delta V_c$ are the critical pressure and volume change inside the chamber before the metacap snaps. $P_t$ and $\Delta V_t$ represent the pressure and volume change after the metacap snaps. d) The energy release from compressed air during the snapping process can be calculated from the pressure–volume curve of the metacap via Boyle’s law. The pressure–volume curve is obtained from FE simulations. e) Evolution of the strain energy of the metacap as a function of volume change obtained from FE simulations. When the initial volume $V_0 = 10$ mL, the metacap releases 19.3 mJ during the snapping, while absorbing 10.3 mJ when $V_0 = 90$ mL. f) Evolution of the total energy release (calculated from Equation (1)) and the maximum speed of the gripper (measured from experiments) as a function of the initial volume $V_0$. g) Experimental snapshots of the metacap gripper with $V_0 = 10$ mL, taking 750 ms to grasp a strawberry gently. h) Experimental snapshots of the metacap gripper with $V_0 = 90$ mL, taking 8.3 ms to grab a plastic ball. i) Comparison of the actuation speed and dimensions from our metacap grippers versus those from the soft actuators reported in the literature based on pneumatic actuation,[19,24,50,51,60] swelling,[14] application of electric[61–63] and magnetic[64] fields, and thermal activation.[65,66] Our grippers exhibit the fastest actuation speed while still being tunable for multipurpose applications. Scale bar: 30 mm.
the subscripts c and t represent the states before and after the cap snaps, respectively.

According to Equation (2), one can predict the state of the snapped metacap from the initial state of the chamber. For instance, the metacap snaps from state a to state b (Figure 3d) when $V_0 = 10 \text{ mL}$, and the compressed air releases 97.6 mJ during the snapping process, which can be calculated by computing the green area shown in Figure 3d. When $V_0 = 90 \text{ mL}$, the metacap snaps from state a to state c, releasing 370.2 mJ from the compressed air, which is equal to the summed area of green and red regions. Moreover, the energy release from the metacap can be calculated from the elastic energy–volume change curve shown in Figure 3e, that is, 19.3 and $-10.3 \text{ mJ}$ for $V_0 = 10$ and $90 \text{ mL}$, respectively. The negative sign indicates that the metacap will absorb energy if $V_0$ is large enough. In light of Equation (1), the total energy release for $V_0 = 10$ and $90 \text{ mL}$ is 116.9 and 359.9 mJ, respectively. As expected, more energy can be released from larger $V_0$, which explains the faster actuation speed observed in Figure 3b when $V_0 = 90 \text{ mL}$.

In Figure 3f, we report the evolution of total energy release $\Delta E$ as a function of $V_0$, showing a monotonic relationship. Likewise, the maximum speed of the finger tips of the gripper shows a similar trend with $V_0$ as predicted by our model, i.e., larger initial volume results in higher snapping speed. To demonstrate the capability of adjusting the actuation speed for diverse objects, we integrate our gripper into a robotic arm and grasp soft objects (i.e., a strawberry) using a gentle actuation (750 ms, $V_0 = 10 \text{ mL}$) to avoid potential damage (Figure 3g), while using fast actuation speeds (8.3 ms, $V_0 = 90 \text{ mL}$) to grasp strong and rigid objects for highly dynamic tasks (Figure 3h). Moreover, the tunable actuation of our gripper can be utilized to classify objects by ejecting them to different locations using variable speeds (Figure S23, Supporting Information). Note that the closing process of the gripper is slower than the opening with the same $V_0$ and input flow rate because less energy is released during the closing process (Figure S22, Supporting Information). Although higher actuation speed can be achieved with larger $V_0$, longer pumping time is also expected to trigger the actuation. A hybrid actuation mechanism combining passive grasping and pneumatically controlled actuation could potentially improve the efficiency of our metacap gripper in practical applications. Specifically, one could use the passive mechanism to realize fast gripping with high efficiency and employ the pneumatically controlled mechanism to achieve slow and gentle actuation.

The motion of soft robots is mostly affected by the rate of deformation and elastic recovery of their compliant bodies—conventional soft actuators are either very slow when designed with large dimensions, or very small to acquire high actuation speed. Our passive grippers and pneumatically actuated grippers harness the extraordinary snapping behavior of metacaps and the compressibility of air, outperforming the conventional soft grippers in terms of actuation speed and tunability. In Figure 3i, we compare the actuation speed and dimensions between our grippers with a few representative soft actuators reported in the literature of different actuation mechanisms. Our grippers exhibit the fastest actuation speed compared with others with actuation time ranging from 12 ms to 20 s. Furthermore, our metacap grippers can benefit from the tunable actuation speeds, spanning a wide range of time scales (3.75–750 ms) for on-demand actuation, facilitating multipurpose grasping tasks with the same design. Importantly, the simple geometry and fabrication process make our metacap grippers ease of scaling up or down for applications at different length scales.

5. Swimming Robots

Besides gripping, our metacaps can be utilized to amplify the actuation speed of other actuators for applications that require high transient output power. We exemplify this by incorporating the metacap with a bending actuator (see details in Figure S5, S6, and S17, Supporting Information) and design a robot capable of swimming rapidly with a relatively slow pneumatic input (Figure 4a). We connect the metacap and the bending actuator via a 3D-printed robotic body (embedded with flow channels for air exchange, Figure 4b), providing buoyancy for the robot to float in water. Two fins are mounted at the ends of the bending actuator to generate propulsion for swimming. When supplied with a relatively slow pneumatic input, the bending actuator gradually deforms and opens the fins, while the metacap will not snap until the pressure inside the chamber reaches the critical pressure $P_c$. Once the cap snaps, the pressure inside the chamber decreases immediately, and the bending actuator quickly deforms back, driving the fins to generate a large propulsion for swimming. In contrast, if the metacap is replaced by an elastic membrane that cannot snap, the bending actuator deforms monotonically to the input flow rate, and the fins are not able to generate large enough propulsion for swimming.

To maximize the propulsion energy from the bending actuator, we use a simple model to quantify the energy release of the bending actuator during the metacap snapping. Specifically, we employ pressure–volume curves of the metacap and bending actuator (continuous lines in Figure 4c,d) to predict the behavior of the entire system when the metacap and the bending actuator are mechanically coupled through the flow channels (dashed lines in Figure 4c,d). Upon applying a slow pneumatic input, the metacap and the bending actuator first gradually deform to point I in Figure 4c,d. After snapping, the metacap and the bending actuator deform immediately to configurations that correspond to point II under the following constraints

\[
P_{\text{cap}}(\Delta V_{\text{cap}}) = P_{\text{actuator}}(\Delta V_{\text{actuator}}) \tag{3}
\]

\[
\Delta V_{\text{cap}} + \Delta V_{\text{actuator}} = \Delta V \tag{4}
\]

where $P_{\text{cap}}(\Delta V_{\text{cap}})$ and $P_{\text{actuator}}(\Delta V_{\text{actuator}})$ represent the pressure–volume relationships of the metacap and the bending actuator. $\Delta V_{\text{cap}}$ and $\Delta V_{\text{actuator}}$ are the volume change induced by the metacap and actuator upon pressurization, respectively. With this model, one can predict the energy release $\Delta E$ from the bending actuator by calculating the area of the blue region shown in Figure 4d. To identify the best design of the metacap that makes the robot swim rapidly, we systematically explore the parametric space of the metacap, and the energy release landscape of the bending actuator is shown in Figure 4e. The effect of $t_c$ on the energy release is more pronounced than that of $t_s$; when $t_c$ is large enough ($t_c \geq 6 \text{ mm}$), the energy release almost
stabilizes to a constant. However, the parameters above the dashed lines lead to undesired monostable metacaps because the residual pressure inside the chamber after metacap snaps prevents the bending actuator from closing completely, and the open fins give rise to large resistance during swimming.

For proof-of-principle, we test two robots with and without the metacap in a water tank (30 cm in width and 90 cm in length, Figure 4f). The metacap has $t_c = 8$ mm and $t_r = 4$ mm (highlighted in Figure 4e). By supplying with the same input (see the input profile in Figure 4g), the swimming robot with a nonsnapping membrane barely swims forward, while the one with the metacap can swim forward with a much faster speed after the cap snaps (Movie S7, Supporting Information). The lines in the figures represent the trajectories of the robots, and the colors of the lines indicate the instantaneous velocity of the robots. In Figure 4g, we compare the instantaneous velocity of these two robots, and it is clear that the robot with a metacap has a much faster speed (more than 10 times larger in maximum speed) characterized by two peaks as a result of the metacap snapping up and down.

6. Untethered, Electronics-Free Robots Enabled by Oscillating Valves

Although our metacap can accelerate the speed of the swimming robot significantly, the robot is regulated by a tethered electronic pump. Inspired by recent advances in simplifying robotic control,[52] we further design an oscillating valve and make the robot electronics-free and untethered by actuating it using a CO₂
The valve consists of a monostable metacap with an aperture (3 mm in diameter) at the center of the cap, which is covered by a thermoplastic elastomer (TPE) membrane (Figure 5b and S7, Supporting Information). When the pressure inside the chamber $P$ is smaller than $P_c$, the aperture remains sealed by the membrane. However, when $P$ is larger than $P_c$, the cap snaps, opening the valve. Thus, the air inside the chamber flows out through the aperture, leading to a dramatic pressure decrease inside the chamber. As the metacap is monostable, it will snap back when $P$ is lower than a certain value ($\approx 3.5$ kPa) and the aperture will be sealed by the membrane again. Hence, the valve exhibits an oscillating response when it is supplied with a constant pneumatic input.

To characterize the oscillating response of the valve, we mount a monostable metacap (with $t_c = 8$ mm, $t_r = 8$ mm, $\phi_c = 12^\circ$) and a TPE membrane (with $w = 7$ mm) to an acrylic chamber with a volume of 100 mL (Figure 5c) and monitor the evolution of the pressure inside the chamber using a pressure sensor (ELVH-015D, All Sensors, Figure S15, Supporting Information). By supplying the chamber with a constant pressure input, the metacap snaps up and down periodically, resulting in an oscillatory pressure profile inside the chamber, and the

![Diagram of the oscillating valve](image)

Figure 5. Oscillating valves enable untethered and electronics-free swimming robots. a) An experimental snapshot of the untethered and electronics-free swimming robot. b) Design and working mechanism of the oscillating valve. The valve comprises a monostable metacap with an aperture at the center of the cap and a TPE membrane. c) Experimental setup for characterizing the oscillating valve. d) Various pressure profiles are obtained by varying the input flow rate of the valve. e) Experimental comparison of the swimming speed for robots with different stroke frequencies. Scale bar: 10 cm. f) Experimental snapshots of the robot tested in a swimming pool. The backgrounds of the snapshots at 0 and 20 s are removed by Adobe Photoshop to show the capability of our swimming robot.
frequency of the valve can be readily tuned by varying the flow rate of the input. In Figure 5d, we show three pressure profiles of the same valve when supplied with a constant pressure ($\approx 50$ kPa) at low (the red curve), medium (the blue curve), and high (the green curve) rates, and the oscillatory frequency of the valve varies from 0.22 to 2.11 Hz. The maximum and minimum oscillating frequencies for each valve are determined by the geometry of the metacap and the membrane, as well as the cavity of the chamber. When fixing the geometry of the metacap and the chamber, but varying the width ($w$) of the membrane (Figure 5b), we obtain a wide range of oscillating frequencies $f \in [0.12, 4.25]$ when $w \in [3, 11]$ mm (Figure S16 and Movie S8, Supporting Information). Although a few oscillating valves have been reported,$^{[53-55]}$ ours outperforms the existing systems in three aspects: 1) it does not require a complex circuit to control oscillation; 2) it exhibits a sharp pressure drop in each cycle, which is beneficial for rapidly responsive robots; and 3) a wide range of oscillating frequencies can be achieved by simply tuning the input flow rate.

With the oscillating valve, our swimming robot can not only be untethered and electronics-free, but also have tunable swimming speed by varying the input flow rate from the CO$_2$ canister. Figure 5e shows that the robot can achieve stroke frequencies ranging from 0.7 to 2.0 Hz, capable of swimming 29 and 50 cm in 7 s, respectively. The lines in the figures represent the trajectories of the robots, and the colors of the lines indicate the instantaneous velocity of the robots. Furthermore, our swimming robot is highly efficient as it can work for more than 1 min at $\approx 1$ Hz when supplied with a 12 g CO$_2$ canister, and it can cross the diagonal of a swimming pool ($\approx 6 \times 6$ m$^2$) in 40 s (Figure 5f and Movie S9, Supporting Information).

7. Conclusions

We have developed a class of metacaps composed of a simple spherical cap and an array of ribs. Through finite element simulations, numerical modeling, and experimental demonstrations, we investigated the geometric effect of the metacap on its mechanical responses, the interaction between metacaps and compressible air, and the coupling between metacaps and conventional bending actuators. The rich nonlinear mechanical responses of the metacaps and the remarkable interactions between metacaps, air, and conventional actuators enable several robotic systems with ultrafast yet tunable actuation speed without the need for external sensors and complex control systems.

The passive grippers are capable of grasping diverse objects automatically upon application of a certain contact force. The fastest actuation speed (3.75 ms for grasping) is achieved in comparison to other soft grippers reported in the literature. We show that the passive grippers have great potential in sports equipment and industrial applications due to their remarkable adaptability and maneuverability, simple geometry, low cost, and ease of fabrication. The pneumatically controlled grippers uncouple the actuation speed from the input and realize tunable actuation speed by adjusting the initial volume of the chamber.

Finally, we demonstrated that our metacaps can be used to pneumatically regulate swimming robots for high transient energy output, exhibiting remarkably higher efficiency than those without the metacap. In turn, our study provides valuable insights into swimming and underwater robots for oceanic exploration. By varying the input flow rate, our oscillating valves exhibit a wide range of oscillating frequencies, providing a new design solution for untethered and electronics-free pneumatic robots, which are beneficial for applications that are sensitive to spark ignition (e.g., some rescue circumstances may be full of explosive gas).

The metacap has allowed us to infiltrate into the property space that was previously inaccessible for conventional metamaterials and has uncovered novel soft robots with unprecedented performances which are not achievable with simple spherical caps of uniform thickness. In particular, our metacaps hold promise for numerous applications that require high transient output energy in biomedical engineering and robotic systems, ranging from ventricular assist devices$^{[56,57]}$ and soft mechatrotherapy devices$^{[51]}$ to locomotive and jumping robots.$^{[58,59]}$ We envision that the concept of metacap demonstrated here would enrich the design palette of soft robots that are ultrafast, programmable, autonomous, and electronics-free.

Supporting Information

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

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Conflict of Interest

A provisional patent application has been filed on the metacap design and robotic demonstrations.

Author Contributions

S.Y. and L.J. conceived the research idea. L.J. designed the metacap, built the model, conducted the finite element simulations, and proposed the robotic demonstrations. L.J. and Y.Y. fabricated the prototypes. L.J., Y.Y., B.O.T.M., and N.F. conducted the experimental testing. S.D.L. and R.J.F. tested the squirrels’ behaviors. S.Y. supervised the research. L.J. and S.Y. wrote the manuscript. All authors contributed to the editing of the manuscript.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

bistability, electronics-free, mechanical metacaps, snap-through, ultrafast grippers
