High-Speed and Low-Energy Actuation for Pneumatic Soft Robots with Internal Exhaust Air Recirculation

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Multichamber soft pneumatic actuators (m-SPAs) are widely used in soft robotic systems to achieve versatile grasping and locomotion. However, existing m-SPAs have slow actuation speed and are either limited by a finite air supply or require energy-consuming hardware to continuously supply compressed air. Herein, these shortcomings by introducing an internal exhaust air recirculation (IEAR) mechanism for high-speed and low-energy actuation of m-SPAs are addressed. This mechanism recirculates the exhaust compressed air and recovers the energy by harnessing the rhythmic actuation of multiple chambers. A theoretical model to guide the analysis of the IEAR mechanism, which agrees well with the experimental results, is developed. Comparative experimental results of several sets of m-SPAs show that the IEAR mechanism significantly improves the actuation speed by more than 82.4% and reduces the energy consumption per cycle by more than 47.7% under typical conditions. The promising applications of the IEAR mechanism in various pneumatic soft machines and robots such as a robotic fin, fabric-based finger, and quadruped robot are further demonstrated. An interactive preprint version of the article can be found at: https://doi.org/10.22541/au.166428178.80668101/v1.

1. Introduction

Multichamber soft pneumatic actuators (m-SPAs) are promising in the applications of soft machines and robots, including rotators,[1] oscillators,[2] grippers,[3–5] robotic hands,[6,7] gloves,[8–10] snake-inspired robots,[11,12] bioinspired robotic fish,[13] multilegged robots,[14–18] and soft functional arrays.[19–21] Increasing the speed and reducing the energy consumption of m-SPAs could lead to more steady, reliable, and robust performance.[1,11,13,17,22–25] However, most existing architectures are designed with limited consideration of actuation speed and energy consumption and instead generally focus on other performance metrics related to versatile degree of freedoms,[26] larger working space,[27,28] higher force,[29,30] or smarter perception.[31–33]

To address these challenges, recent efforts have been dedicated to exploring variants of air pumps. These architectures can provide enhanced supplied air pressure and airflow by 1) connecting air pumps in series or parallel,[34] 2) introducing a double-piston[35] or a double-acting pneumatic cylinder[36] to compress more air in a compression cycle, or 3) using a phase-change medium (dry ice, liquid CO₂, dimethyl ether (DME), etc.) as a pneumatic source.[37,38] These pump variants indeed improve the actuation speed of m-SPAs, but they also introduce additional challenges related to complicated mechanical design and greater energy consumption.

Meanwhile, some low-power pumps have been developed as a promising alternative to reduce the energy consumption of m-SPAs. For example, based on charge-injection electrohydrodynamics[39] or dielectric fluid-amplified electrostatic zipping structure[40] stretchable electro-pneumatic pumps are reported to operate with a low pump power of fewer than 1 W. However, they suffer from supplying low pressures of less than 10 kPa[39,40] or small airflow (161 mL min⁻¹).[40] Alternatively, some chemical pumps that utilize fuel combustion or decomposition (CH₄, H₂O₂, etc.) have been designed to provide high pressure (≥50 kPa). However, the refueling process and low airflow (≤50 mL min⁻¹) make them unfeasible to build a compacted low-power system for practical applications.[16,41] Therefore, achieving high-speed and low-energy actuation of m-SPAs remains an open challenge (Table S1 and Figure S1a, Supporting Information).[13,14,18,22,34,42–47]

In tackling this challenge, it is important to note that most state-of-the-art m-SPAs utilize a “direct actuation” mechanism
in which compressed air enters the actuator directly through an inlet and leaves directly through an outlet to an ambient environment (termed DIDO, Figure 1a, S1b, and Movie S1, Supporting Information). As a result, the energy stored in the actuator for the DIDO mechanism cannot be recovered, and more input work is required. For higher energy efficiency, an optional method is to reduce the input work of the system by improving the inlet pressure of a pump. For example, an air pump can recompress the exhaust air with residual pressure to a target pressure through an external exhaust air recirculation (EEAR, Figure 1a) mechanism, where an extrapneumatic buffer (e.g., Re-Air valve) can be used to reduce severe pressure fluctuation. However, a key limitation is that this mechanism depends on the incorporation of pumps that typically have low electrical-to-mechanical energy conversion efficiency and, therefore, consume excess energy when recompressing the exhaust air. In addition, this mechanism lacks consideration of the actuation speed of m-SPAs (Figure S1b, Supporting Information). Based on the architecture of EEAR, some researchers also achieve impressive programmable output pressure by replacing the pneumatic buffer with a group of air regulators, while actuation speed or efficiency is not considered in applications.

In this work, we introduce an internal exhaust air recirculation (termed IEAR, Figure 1a) mechanism for high-speed and low-energy actuation of m-SPAs that overcomes these existing challenges. Through the rhythmic actuation of multiple chambers following a shortened energy path, our IEAR mechanism can recirculate the exhaust compressed air from one chamber to another through a specialized valve island. In contrast to other existing methods based on air recirculation, this approach avoids the need for pump-controlled air recompression. Moreover, we introduce a dynamic model of m-SPAs to guide the analysis of our IEAR mechanism, with theoretical predictions that reasonably agree with the experimental measurements. Building on previous studies that examined the dynamics of pneumatic actuators with a single chamber, our dynamic model is valid for actuators with multiple pneumatic chambers.

Characterization focuses on two exemplary embodiments of m-SPAs: an actuator with two chambers (Double Bellows) and an actuator with three chambers (Triple Bellows). These studies show that with IEAR, the actuation frequency for these two classes of m-SPAs can be improved by 82.4–91.2%, while the energy consumption per cycle is reduced by 47.7–51.2% under typical conditions. We further demonstrate the broad applications of

![Figure 1. Working Principle of IEAR.](https://example.com/figure1.png)

- **a)** The working principle of IEAR. (1) Inlet to inflate the chamber, (2) Outlet to deflate the chamber, (3) Branch for internal recirculation, (4) Branch to the atmosphere, (5) Closed branch for external recirculation. We have DIDO (1,2,4), IEAR (1,2,3,4), and EEAR (1,2,5). IEAR recirculates compressed air by a valve island. Compared with DIDO, IEAR recycles compressed air and recovers the energy of the system. Compared with EEAR, IEAR does not require an air buffer and air recompression by the pump. (b) The pressure–volume relationship (constant temperature, open system). In such a system, $\int p \, dV = W_{\text{load}} + W_{\text{material}} + W_{\text{dissipation}}$ plays a metric of the input work. With IEAR, exhaust air is directly transmitted and recirculated between chambers through a specialized valve island, thereby shortening the working cycle (the arrow path) and reducing the required input work. (c) Traditionally, compressed air actuates the chambers of m-SPAs with DIDO, leading to markedly energy loss and poor actuation performance (speed, energy efficiency, supplied pressure, system power, etc.).
the IEAR mechanism in various soft robotic systems, such as a robotic fin, fabric-based finger, and quadruped robot, for improving the actuation speed and reducing energy consumption. This work demonstrates that our IEAR mechanism plays a promising technology in the high-speed and low-energy actuation of m-SPAs for soft machines and robots.

2. Results

2.1. Working Principle of the IEAR Mechanism

The principle of our IEAR mechanism is illustrated in Figure 1. Unlike the traditional DIDO mechanism, the IEAR mechanism (Figure 1a) can recirculate the exhausted compressed air between the chambers. Taking a pair of chambers X and Y as an example, we can describe the actuation rhythms of our IEAR mechanism with the following steps (Figure 1b). 1) We begin by using compressed air stored in the tank to inflate X to a set working pressure $p_{\text{high}}$. 2) Next, we open the valve between X and Y to transmit the compressed air from X to Y. 3) When the pressure difference between X and Y is lower than a threshold $\Delta p$, we then close the valve. 4) The chamber X continues deflating to $p_{\text{low}}$, while the air tank takes over the inflating process to pressurize Y to the set working pressure $p_{\text{high}}$. By exchanging the roles of X and Y, we repeat the steps (1–4) to complete a working cycle. Since working cycles in practical applications can generally be approximated as an isothermal process (open system), the integral $\int p \, dV = W_{\text{fluid}} + W_{\text{material}} + W_{\text{dissipation}}$ can be used to determine the input work. In this sense, our IEAR mechanism essentially shortens the working cycle (i.e., the energy path), reduces the large requirement of input work (most becomes energy loss when deflating) observed in the traditional DIDO mechanism (Figure 1c), and leads to enhanced air supply, thus improving the actuation speed.

In our IEAR mechanism, the working state of the air pump is independent of these specific actuation processes (Figure 1a). When the pressure in the air tank $p_{\text{tank}}$ is less than a threshold $p_{\text{tank-low}}$, the air pump starts to work. Once $p_{\text{tank}}$ is more than $p_{\text{tank-high}}$, the air pump turns off. The difference between $p_{\text{tank-high}}$ and $p_{\text{tank-low}}$ is the pressure tolerance for pump resting. Notably, we generally set the gauge pressure $p_{\text{tank-low}}$ and $p_{\text{tank-high}}$ as 120 and 125 kPa, respectively.

To implement the IEAR mechanism, we develop an experimental platform (Figure S2a, Supporting Information) that mainly consists of an air pump and an air tank (1 L) to provide compressed air, a valve island fabricated by a set of solenoid valves to control the rhythmic actuation of m-SPAs, and a dSPACE controller (sampling frequency, 1 kHz) to operate the ON/OFF states of the solenoid valves. The detailed air passage network of a three-channel valve island is presented in Figure S2b, Supporting Information.

2.2. The Dynamic Model of m-SPAs

To guide the actuation performance analysis of the IEAR mechanism, we develop a dynamic model of m-SPAs based on the Clapeyron equation. (See Note S1 and Figure S3, Supporting Information).

For m-SPAs with $n$ chambers, we can express the dynamic model as

$$p = \xi \left[ \text{diag}(V) + \text{diag}(p) \frac{\partial V}{\partial p} \right]^{-1} Q$$

(1)

$$\xi = \rho RT M$$

(2)

where $p = [p_1 \ p_2 \ \cdots \ p_n]$, $V = [V_1 \ V_2 \ \cdots \ V_n]$, and $Q = [Q_1 \ Q_2 \ \cdots \ Q_n]$ represent the vectors of the pressure inside the chamber, chamber volume, and mass flow into each chamber, respectively. The parameters $\rho$, $R$, $T$, $M$ are the air density under the standard conditions (1.293 g L$^{-1}$, 0 °C, 101.325 kPa), the ideal gas constant (8.314 J mol$^{-1}$ K$^{-1}$), the absolute temperature, and the molar mass of air (28.9648 g mol$^{-1}$), respectively.

Due to the lightweight of most soft actuators,\cite{43,44,52} we ignore the actuator mass and hypothesize that the volume is a function of air pressures. In this manner, we can express $V_i$ as a function of the internal pressures

$$V_i = f_i(p)$$

(3)

Thus, we can use the Jacobian matrix of chamber volume $\frac{\partial V}{\partial p}$ to determine the effects of air pressure change on volume change and the interaction between the chambers.

The dynamic model of m-SPAs implies that a shortened energy path resulting in a reduced range of pressure to follow and an improved mass flow for a reinforced $p$ can increase the actuation speed of m-SPAs, unveiling our IEAR mechanism’s theoretical essence.

2.3. IEAR in m-SPAs with Two Chambers

To validate the use of the IEAR mechanism for pneumatic actuation, we first use the following exemplary architecture: m-SPAs with two chambers, which we term the Double Bellows (25.4 g, 150 mm). This validation study is used to verify the dynamic model and the ability of our IEAR mechanism to achieve high-speed and low-energy actuation (Figure 2; Movie S2 and S3, Supporting Information).

Here, the Double Bellows has a symmetric structure to produce bidirectional bending by alternatively inflating these two chambers (Figure 2a and S4, Supporting Information). According to Equation (1), we establish the dynamic model of the Double Bellows to obtain the theoretical pressures by analyzing its deformation geometry and the force equilibrium (Figure 2b,c; Note S2, Supporting Information).

The dynamic actuation of the Double Bellows with our IEAR mechanism has different ON/OFF timings of the solenoid valves compared with the working cycle with a conventional DIDO mechanism (Figure 2d,e; S2d, Supporting Information). Following the initial actuation cycles, the Double Bellows exhibit a rapid transition and enter a steady-state pressure response (Figure S5a,b, Supporting Information). Unlike DIDO, our IEAR mechanism prevents a sharp decrease in the supplied
air pressure $p_{\text{tank}}$ during the transition. The comparative results demonstrate that our dynamic model of the Double Bellows agrees well with the experimental results under both the DIDO and IEAR mechanisms (Figure 2f and S6, Supporting Information). Such agreement suggests that our model can facilitate analysis of the actuation performance, including actuation speed and energy consumption. (see Table 1 in Experimental Section)

We obtain the theoretical actuation frequency and energy consumption per cycle of the Double Bellows with $p_{\text{high}}$ ranging from 50 to 100 kPa and experimentally validate these results (Figure 2g,h). With the increase of $p_{\text{high}}$, both actuation frequencies with the DIDO and IEAR mechanisms decrease. However, the actuation frequency with our IEAR mechanism is markedly higher than that with DIDO for the full range of pressures $p_{\text{high}}$ from 50 to 100 kPa.

Table 1. Calculation of the actuation performance indicators.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Theoretical</th>
<th>$^\ast$ Experimental</th>
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<tbody>
<tr>
<td>Actuation frequency $f$</td>
<td>$f$</td>
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<tr>
<td>Air tank pressure $p_{\text{tank}}$</td>
<td>$p_{\text{tank}}$</td>
<td>$p_{\text{tank}}$</td>
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<tr>
<td>System power $P$</td>
<td>$P_{\text{valve}} + P_{\text{pump}}(p_{\text{tank}})$</td>
<td>$P_{\text{valve}} + P_{\text{pump}}$</td>
</tr>
<tr>
<td>Energy consumption per cycle $e$</td>
<td>$e_{\text{valve}} + e_{\text{pump}}(p_{\text{tank}})$</td>
<td>$e_{\text{valve}} + e_{\text{pump}}$</td>
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(Figure 2g). At the same time, the energy consumption per cycle with IEAR is far less than that with DIDO (Figure 2h). For example, when $p_{\text{high}} = 75$ kPa, the actuation frequency and energy consumption with DIDO are $0.49 \pm 0.01$ Hz and...
8.08 ± 0.15 mWh cycle⁻¹, respectively. Our IEAR mechanism improves the actuation frequency to 0.93 ± 0.02 Hz (91.2%) while reducing the energy consumption to 3.94 ± 0.09 mWh cycle⁻¹ (51.2%). In addition, we change Δp (5, 10, 15 kPa) to investigate its influence on the actuation performance (Figure S6, Supporting Information). It demonstrates that the IEAR mechanism is widely feasible in various working conditions to achieve high-speed and low-energy actuation. Also, the dynamic model of m-SPAs shows a satisfying capability of actuation performance analysis on the Double Bellows.

### 2.4. IEAR in m-SPAs with Three Chambers

To further verify the generalized feasibility of the dynamic model and our IEAR mechanism, we examine the operation in m-SPAs with three chambers—an architecture we term Triple Bellows (34.3 g, 150 mm; Figure 3; Movie S4 and S5, Supporting Information).

Compared with the Double Bellows, the Triple Bellows comprises three chambers arranged in an equilateral triangle, while other structural features remain the same (Figure 3a and S4, Supporting Information). These three chambers endow the Triple Bellows with two degrees of freedoms (DOFs): bending relative to the ground and rotation above the z-axis (Figure 3b). According to the force equilibrium on these two DOFs, we can establish the dynamic model (Figure 3c and Note S3 and S4, Supporting Information). For both the DIDO and IEAR mechanisms (Figure 3d,e), the comparative theoretical and experimental results show good agreement with the others (Figure 3f and S7, Supporting Information).

#### Figure 3. m-SPAs with three chambers: Triple Bellows.

- **a)** Structure of the Triple Bellows.
- **b)** Deformation geometry of the Triple Bellows with two DOFs: bending relative to the ground and rotation above the z-axis.
- **c)** Equivalent section force diagrams of the Triple Bellows.
- **d)** Working flow chart of DIDO. When the conditions along the arrows are satisfied, the actuator moves to the next stage.
- **e)** Working flow chart of IEAR.
- **f)** Experimental pressures and theoretical pressures of DIDO and IEAR in 0–3 s. \( p_{\text{low}} = 10 \text{kPa}, \Delta p = 10 \text{kPa} \).
- **g)** Steady-state actuation frequency with \( p_{\text{high}} \) from 50 to 100 kPa.
- **h)** Steady-state energy consumption per cycle with \( p_{\text{high}} \) from 50 to 100 kPa.
We further characterize the actuation frequency and energy consumption per cycle of the Triple Bellows with \( p_{\text{high}} \) from 50 to 100 kPa covered. According to Figure 3g,h, the Triple Bellows also achieve high-speed and low-energy actuation with IEAR. Taking \( p_{\text{high}} = 75 \text{ kPa} \) as an example, the actuation frequency and energy consumption of DIDO are 0.33 ± 0.01 Hz and 13.50 ± 0.50 mWh cycle \(^{-1}\), respectively. Through our IEAR mechanism, the actuation frequency is improved to 0.60 ± 0.02 Hz (82.4%) while the energy consumption is reduced to 7.06 ± 0.27 mWh cycle \(^{-1}\) (47.7%). The results from changing \( \Delta p \) (5, 10, 15 kPa) again verify the dynamic model of m-SPAs and the ability of our IEAR mechanism to improve actuation speed and reduce energy consumption in various working conditions (Figure S7, Supporting Information).

2.5. Applications of IEAR

2.5.1. Robotic Fin

We first design a robotic fin (89.2 g) composed of two Double Bellows and a polyvinyl chloride (PVC) sheet to verify our IEAR mechanism for applications in soft robotics (Figure 4a–f, Note S5, and Movie S6, Supporting Information). In an underwater experiment, the robotic fin swings and drags the PVC sheet to produce propulsion force, which fluctuates with different magnitudes and periods in real time (Figure 4c). Experimental results show that, compared with DIDO for the full range of \( p_{\text{high}} \), IEAR has a markedly higher swinging frequency and average propulsion force (Figure 4d, e), and the energy consumption with IEAR is significantly reduced (Figure 4f). For instance, when \( p_{\text{high}} = 75 \text{ kPa} \), the swinging frequency, average propulsion force, and energy consumption with DIDO are 0.41 ± 0.00 Hz, 0.19 ± 0.01 N, and 9.29 ± 0.08 mWh cycle \(^{-1}\), respectively. In contrast, the corresponding actuation performance with IEAR is 0.76 ± 0.01 Hz (85.4%), 0.32 ± 0.01 N (68.4%), and 4.77 ± 0.04 mWh cycle \(^{-1}\) (48.7%). These results mean the robotic fin can produce higher swimming velocity with energy-efficient IEAR when actuating underwater vehicles.\(^{[53]}\)

Moreover, we observe an extra beneficial effect of IEAR that the supplied air pressure \( p_{\text{tank}} \) is improved, and the system power is reduced simultaneously, which produces conducive factors in high-speed and high-efficiency actuation (Figure S8a–c, Supporting Information).

2.5.2. Fabric-Based Finger

We further fabricate a soft fabric-based pneumatic actuator\(^{[8,54]}\) for use in rehabilitation and assistive exoskeletons to examine the broad potential of IEAR for different materials and actuator types (Figure 4g–i, Note S6, and Movie S7, Supporting Information). This fabric-based actuator (10.2 g) comprises a flexing chamber and an extending chamber, and it is worn on a silicone hand to assist the finger motion. Experimental results show that the actuation frequency with our IEAR mechanism is nearly 2 \( \times \) that with DIDO for the full range of pressures, while the energy consumption per cycle only takes about half that with DIDO (Figure 4h,i). For example, when \( p_{\text{high}} = 75 \text{ kPa} \), the actuation frequency and energy consumption with DIDO are 0.33 ± 0.01 Hz and 11.70 ± 0.28 mWh cycle \(^{-1}\). However, the corresponding actuation performances with IEAR are 0.62 ± 0.02 Hz (87.9%) and 5.99 ± 0.20 mWh cycle \(^{-1}\) (48.8%). In hand rehabilitation, especially assistance, an actuation speed of faster than 0.5 Hz is important for activities of daily living (ADLs),\(^{[53]}\) such as grasping an apple, operating a ball, or drinking water. In addition, the comparisons of the supplied air pressure \( p_{\text{tank}} \) and the system power also demonstrate the advantages of our IEAR over the traditional DIDO (Figure S8d–f, Supporting Information). Except for the fabric-based finger, an extensive application on a fiber-reinforced silicone actuator also verifies the effectiveness of IEAR in improving actuation speed and energy efficiency (Figure S9a–c and Note S7, Supporting Information).

2.5.3. Quadruped Robot

To verify the potential application of the Triple Bellows, we adopt an electronics-free soft-legged design\(^{[14]}\) and fabricate a quadruped robot (Figure 5, Note S8, and Movie S8, Supporting Information). The quadruped robot (244.1 g with a body length of 220 mm) constitutes four Triple Bellows, whose chambers are connected to form three groups numbered in color (Figure 5a,b). By sequentially actuating these chambers, we let the robot walk on a 900 mm floorboard and record the walking performance (Figure 5c). According to the results in Figure 5d–f, both the step frequency and walking velocity with our IEAR mechanism are markedly more than that with DIDO for the full range of pressures, while IEAR consumes much less energy per step than DIDO. Typically when \( p_{\text{high}} = 75 \text{ kPa} \), the walking time with IEAR (64.5 ± 2.3 s) is 30.6 ± 4.4 s shorter than that with DIDO (95.1 ± 3.7 s), and the energy consumption per step with IEAR (16.53 ± 0.82 mWh step \(^{-1}\)) is 39.4% less than that with DIDO (27.27 ± 1.42 mWh step \(^{-1}\)). Moreover, the step length with DIDO is smaller than that with IEAR, which reflects the smaller air supply with the DIDO mechanism (Figure 5f). For the quadruped robot, the supplied air pressure \( p_{\text{tank}} \) and system power are also slightly ameliorated (Figure S8g–i, Supporting Information). Compared with the robotic fin and fabric-based glove, the large air consumption of the quadruped robot might reduce the extra improvement of \( p_{\text{tank}} \) and system power.

3. Discussion

We present the IEAR mechanism to achieve high-speed and low-energy actuation of m-SPAs in various pneumatic soft machines and robots. A dynamic model of m-SPAs is developed to guide the analysis of the actuation mechanism, which agrees well with the experiments on the exemplary m-SPAs, the Double Bellows and the Triple Bellows. These experiments also demonstrate the ability of IEAR to improve actuation speed and reduce energy consumption. Moreover, we observe an improvement in the supplied air pressure \( p_{\text{tank}} \) and a decrease in the system power, which may result from the enhanced performance of the air supply and the reduction of required energy input to the IEAR-assisted system, respectively. Finally, we demonstrate the practical feasibility and broad potential of IEAR with applications on a robotic fin, fabric-based finger, and quadruped robot.
Figure 4. Verification on a robotic fin and a fabric-based finger. a) The robotic fin swings in water to produce propulsion force where $p_{\text{low}} = 10$ kPa and $\Delta p = 10$ kPa. b) The robotic fin comprises two Double Bellows and a PVC sheet with a thickness of 0.5 mm. c) Propulsion force in real time when $p_{\text{high}} = 50, 75, 100$ kPa, respectively. d) Swinging frequency of the robotic fin. e) Average propulsion force produced by the robotic fin. f) Energy consumption per cycle of the robotic fin. g) The fabric-based actuator is composed of a flexing chamber and an extending chamber. The actuator is worn on a silicone model hand to assist the finger. h) Steady-state actuation frequency of the actuator. i) Steady-state energy consumption per cycle of the actuator.
As demonstrated in our experiments, the dynamic model of m-SPAs can give accurate pressure and actuation frequency. Although there are some errors, it is not easy for the dynamic pressure modeling of soft robots, especially for these m-SPAs with coupled interaction between chambers. These errors mainly come from the ignorance of actuator mass, the inaccuracy of actuator volume modeling, and the inconsistency of commercial solenoid valves. Indeed, this model is generally applicable to both rigid and soft multichamber actuators, as long as the volume-pressure function Equation (3) can be established. Based on our dynamic model of m-SPAs and some practical models for mass flow,[43,51,56–61] a reverse design for air passage and actuation could be feasible and may lead to higher-performing soft machines and robots.

In this study, we present a group of comparative experiments with EEAR, where we find that IEAR performs better in improving actuation speed and energy efficiency, and the combination of IEAR and EEAR can greatly reinforce the performance of EEAR under high working pressure (Figure S9g–k and Note S9, Supporting Information). These experiments verify the ability of IEAR to achieve high-speed and low-energy actuation of m-SPAs. However, since the air in this study flows only between a pair of chambers at each step, further investigation is required to study simultaneous flow among a network of chambers. For a more lightweight system with IEAR, soft circuits supporting onboard control should also be investigated as a replacement for the rigid valve island by adopting soft pumps, microfluidic-activated valves, and smart fluids.[62] Thus, a wider range of soft machines and robots, including fully untethered robotic systems,[63] might benefit from our IEAR mechanism.

4. Experimental Section

Materials of the Pneumatic Control System: The components of the pneumatic system included a micro air pump (KZP-PE, Kamoer Fluid Tech Co., Ltd., China, Note S10, Supporting Information), a 3D-printed...
air tank and a valve island (DSM IMAGE8200, WeNext Technology Co., Ltd., China), 12 solenoid valves (0520D, Foshan Weizi Electronic Technology Co., Ltd., China), two current sensors (Huabei Vidius Electronic Technology Co., Ltd., China), a temperature sensor (Quanzhou Guanhangda Electronic Technology Co., Ltd., China), four pressure sensors (MPX4250DP, Freescale Semiconductor, USA), a relay (Risym, China) for the air pump, two solid-state relay panels (customized) for solenoid valves, two high-precision programmable linear power supplies (SS-L303SPV, Dong Guan Great Electronics Co., Ltd., China), and a controller (microLabBox 1202, dSPACE, Germany).

The electrical current data were used for power measurement, and the temperature sensor was inserted into the air tank to record the temperature of compressed air. In this study, the actual temperature of compressed air was generally 17–24 °C, and we approximate the temperature as a constant 20 °C for simplification, which had little influence on the results under the thermodynamic scale of temperature. For the pressure sensors, one measured \( \rho_{\text{tank}} \), and the other three were assigned to \( p_1 \), \( p_2 \), and \( p_3 \). All the pneumatic components and actuators were connected by silicone tubes (Daoguan, China) with an inner diameter of 2 mm and an outer diameter of 4 mm. When the output pressure of the pump changed, the pump power varied following the experimentally obtained law (Figure S2c, Supporting Information), and we hypothesized that the tube was linearly elastic and experimentally obtained the stiffness using the universal testing machine (685C-2, Instron, USA).

The Double Bellows was primarily composed of two commercial bellows-shaped PVC tubes (Figure 2a and S4, Supporting Information) with air tightness at two ends. A pair of steel wires were introduced in the middle of the Double Bellows to keep the length of the central axis constant, which made more length change of PVC tube convert to actuator bending. To avoid mechanical instability of the PVC tube when inflated, a group of constraint rings was inserted along the actuator body to bundle these PVC tubes and steel wires. Compared with the Double Bellows, the Triple Bellows comprised three PVC tubes arranged in an equilateral triangle (Figure 3a and S4, Supporting Information). Other structural features of the Triple Bellows were the same as that of the Double Bellows. The tube length of both the Double Bellows and the Triple Bellows was 150 mm (To improve structure stiffness, the length in the applications was 100 mm).

The fabrication of these exemplary m-SPAs contained six steps: 1) cutting PVC tubes; 2) bundling the tube with the constraint rings; 3) fabricating the end caps and sealing the tubes with AB glue; 4) inserting and fixing the steel wires; 5) waiting for the glue to cure; and 6) examining the air-tightness of the actuator.

Numerical Analysis of the Theoretical Model: The dynamic model of m-SPAs Equation (1) is a first-order matrix partial differential equation, which generally has no analytical but numerical solutions. We analyzed the dynamic pressures by MATLAB and SIMULINK (The MathWorks, Inc., USA). MATLAB was used to adjust stimulation parameters and control the simulation process. SIMULINK took charge of numerical solutions by the fixed-step solver ode14x (extrapolation) with a step size of 0.001 s. The numerical solutions included \( \rho_{\text{tank}}, p_1, p_2, \) and \( p_3 \). The actuation frequency \( f_i \), air tank pressure \( \rho_{\text{tank}} \) (supplied air pressure), system power \( P \), and energy consumption per cycle \( e \). The calculation methods are presented in Table 1 (See Note S13, Supporting Information), where the average was obtained from a time interval after transition into steady-state actuation and \( N \) is the equivalent weighted average number of solenoid valves in use for a working-cycle (Figure S2d, Supporting Information). All the experimental results in this work were obtained from seven repetitive measurements.

Materials and Fabrication of the Robots in Applications: The robotic fin (Figure 4b) comprised two Double Bellows and a PVC sheet (160 mm × 75 mm × 0.5 mm). All the frames and connectors in this application were 3D printed (DSM IMAGE8200, WeNext Technology Co., Ltd., China), including the mounting base of the force sensor (LSB201, FUTEK Advanced Sensor Technology, Inc., USA). The robotic fin, the force sensor, and the sensor mounting base were fabricated and fixed on the 6-DOF manipulator (JAKA Zu7, JAKA Robotics, China) to adjust and stabilize the position conveniently. Then, we immersed the robotic fin in the water tank (600 mm × 400 mm × 450 mm, water depth 300 mm) to investigate the actuation performance (Figure S8a, Supporting Information).

The fabric-based soft finger (Figure 5d, Supporting Information) was fabricated by 3D rib weft-knitted polyester fabric coated with 0.2 mm TPU (Jiaying Yingcheng Textile Co., Ltd., China). A laser cutter (VLS 3.50, Universal Laser Systems, USA) trimmed the fabric to the target computer-aided design (CAD) pattern, and then a heat-sealing machine (customized) manually sealed the fabric pieces into actuators. Specific methods are referred to the work of Feng et al. for the extensive application, Ecoflex 0030 (Smooth On, USA) and M 4601 (Wacker, Germany) were mixed 1:1 (mass) to cast the fiber-reinforced silicone actuator (62.1 g).

For the quadruped robot (244.1 g), a body frame connected four Triple Bellows, shown in Figure S8g, Supporting Information. The body length of the quadruped robot was 220 mm, and each foot was 100 mm long (Figure 5b). Silicone feet (Sujie, China) were stuck on the caps of the Triple Bellows to prevent slipping.

Supporting Information

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

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Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
M.F.: conceived the idea and contributed to experiments, modeling, data processing, and writing; D.Y.: assisted in experiments and writing; G.G. and C.M.: supervised the project and contributed to the design of experiments and writing. All the authors provided feedback and agree with the final version of the manuscript.

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

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