Soft Electromagnetic Artificial Muscles Using High-Density Liquid-Metal Solenoid Coils and Bistable Stretchable Magnetic Housings

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Soft electromagnetic artificial muscles (SEAMs) that use electric currents are reported as their power sources. The proposed actuator consists of fully soft components: microfluidic coils, stretchable magnets, ferromagnetic silicone, and stretchable housings. The soft coils are fabricated by directly printing room-temperature liquid metal on a stretchable substrate, enabling the generation of high-density electromagnetic fields. Based on design optimization through modeling and simulation, the proposed actuators have a characteristic of bistability following the relationships of the forces acting on the components. Depending on the design configurations, the proposed actuators generate contraction and expansion motions as well as vibrations in a bidirectional manner, enabled by electromagnetic actuation. The main advantages of the proposed actuators are fully compliant structures, compact form factors, and short response times, which have not been observed in existing polymer-based artificial muscles. Another advantage is the self-detection of the actuation states by measuring the inductance change in the coils. Last, the modular design fully packaged with a coil and magnets in a soft housing makes it possible to easily resize and reconfigure the robotic systems with multiple actuator modules for different applications. Examples of applications demonstrated are a modular crawling robot, energy-efficient grippers, a multi-degrees of freedom (DOF) soft manipulator, and a high-frequency swimming robot.

1. Introduction

Soft actuators have potential in applications where the physical compliance of the actuator ensures safe and reliable interactions with neighboring humans and machines in a broad spectrum of unstructured and dynamic environments.[1–9] While researchers have been exploring various driving mechanisms for soft actuators, implementation of electromagnetic force (EMF)-based actuation into compliant architectures has been of specific interest due to the proven advantages of the mechanism in the form of conventional electric motors and voice coil actuators in many robotic applications. Unlike pneumatic artificial muscles (PAMs), for example, EMF-based soft actuators do not require bulky pneumatic peripherals, which significantly undermine the actuators’ portability.[10–15] EMF-based soft actuators also achieve significantly faster responses to input signals than shape memory alloys (SMAs) with the retarding heating and cooling process.[16–21] Furthermore, the relatively
In this work, we present a design and manufacturing strategy to develop EMF-based soft actuators to address the fundamental challenges mentioned above. We first design a bistable mechanism that maintains the deformed state of the actuator without the need for consistent application of electric currents that usually cause Joule heating. The bistable mechanism provides two different states with stability by changing the distance between two stretchable magnets using the electromagnetic force of the liquid-metal coil. Unlike conventional mechanisms for bistability that rely on the buckling of rigid materials, the proposed mechanism uses elastomers as structural materials to fabricate fully soft EMF-based actuators. We also exploited the technique of direct printing to manufacture a soft coil to achieve a high electromagnetic force with high consistency. With the proposed bistable mechanism and manufacturing method, we introduce two types of soft electromagnetic artificial muscle (SEAM) actuators (Figure 1A, and Movie S1, Supporting Information). Based on the principle of electromagnetic actuation, actuators operate rapidly and can easily be integrated with robotic systems. Both actuators have high resilience to external impacts due to their completely soft components and structures (Figure 1B, Section S1.1, Movie S2, Supporting Information). Furthermore, they are able to innately operate underwater since the components are fully sealed with an elastomer housing (Section S1.2 and Movie S3, Supporting Information). Furthermore, they are able to innately operate underwater since the components are fully sealed with an elastomer housing (Section S1.2 and Movie S3, Supporting Information). By utilizing custom-built stretchable magnets on the sides of the actuators, the SEAMs in this work can be used as modular actuators to form various actuation systems with different sizes and shapes depending on the applications, creating a wide variety of functional soft robotic platforms, including grippers and mobile robots in various real-world environments, as demonstrated in Figure 1C.

In the following section, we first discuss the device concept and the working principle of the SEAM actuators, followed by discussions on the analytic modeling of the force characteristics of the four components: a soft microfluidic coil, a stretchable magnet, ferromagnetic silicone, and a stretchable housing. We then evaluate the mechanical performances of both actuators: force, response time, and frequency response. With the features of the
2. Results

2.1. Device Concept and Working Principle

The entirely soft SEAM actuators consist of a liquid–metal printed coil layer coated with either a ferromagnetic or a nonmagnetic material between two stretchable magnets that are placed on the side of a highly deformable elastomer housing. The structure of the two magnets with the same orientation of magnetization generates an attractive force, while the opposite orientation exerts a repulsive force. A ferromagnetic material is attracted by the magnet regardless of the orientation of the magnetization of the magnet. Utilizing these magnetic properties with the spring force of the elastomer housing to restore its initial shape, bistability is achieved simply based on the relation of those forces. With bistability, SEAM-I contracts and expands by moving the two magnets in opposite directions, while SEAM-II creates vibrating motions by moving both of the magnets either to the left or to the right simultaneously. To minimize the effect of gravity, both actuators were designed to operate in the horizontal direction.

2.1.1. SEAM-I

In SEAM-I, the poles of the magnets are oriented in the same direction, which generates an attractive force between the magnets, and the silicone housing generates a spring force keeping the two magnets away from each other under deformation (Figure 2A). In the expanded state, the spring force of the silicone housing keeps the two magnets away as long as it is larger than the attractive force by the magnets (Figure 2B-a). When an electric current is applied to the coil for magnetization in the same pole orientation as the magnets, the coil attracts both magnets (Figure 2B-b). As the magnets approach each other by the EM force, the attractive force exponentially increases and overcomes the spring force of the housing since the spring force shows a smaller increment than the magnetic force with the displacement. As the distance between the two magnets decreases to the bistable threshold, the attractive EM force becomes larger than the spring force of the silicone housing; the two magnets remain in contraction even after the applied electric current on the coil is removed (Figure 2B-c). On the other hand, the electric current in the opposite direction creates a repulsive EM force that separates the two stretchable magnets (Figure 2B-d). As the distance between the two magnets exceeds the threshold, SEAM-I remains in the expanded state even after the current is removed (Figure 2B-e).

To realize the above actuation procedure, the forces acting on SEAM-I must satisfy certain conditions. Three types of forces exist during the actuation of SEAM-I: the attractive force between the two magnets $f_{\text{magnet}}$, the spring force of the stretchable housing $f_{\text{spring}}$, and the EM force between the coil and the magnets $f_{\text{coil}}$ (Figure 2C). $f_{\text{coil}}$ is either attractive or repulsive depending on the direction of the current applied to the coil, and its magnitude can be controlled by the amount of applied current. The above three forces vary with the distance between the magnet and the coil. If we define $x$ to be the position of a magnet relative to the coil surface, then $x_i$ is the position where the magnetic
force equals the spring force. If the following three conditions are satisfied, then the bistable mechanism can be developed without requiring a specific configuration:

i) To maintain the contracted state, the magnetic force must be greater than the spring force in the contracted position ($f_{\text{magnet}} > f_{\text{spring}}$ when $x = 0$).

ii) To maintain the expanded state, there must exist two points where the magnetic force is equal to the spring force in the entire travel range (i.e., $x_2$ and $x_3$ exist.).

iii) For state transition, the coil must generate an EM force greater than the EM force required to overcome the energy gap $S_1$ and $S_2$. ($S_1$ and $S_2$ are the areal differences between $f_{\text{magnet}}$ and $f_{\text{spring}}$ in Figure 2C).

If all the conditions above are met, then the actuator has an inherent bistable characteristic with a stable point at $x = 0$ and $x_2$.

### 2.1.2. SEAM-II

SEAM-II creates vibrational motions in both directions of the magnets based on a bistable principle different from SEAM-I. Compared to the SEAM-I design, SEAM-II has a magnetic orientation in which the two magnets are aligned against each other exerting a repulsive force all the time. Another key difference in the design of SEAM-II is that the middle structure with a liquid-metal coil has additional ferromagnetic silicone layers coated on both sides to create an attractive force with respect to the magnets (Figure 3A). Figure 3B shows the actuation states of SEAM-II. Initially, the actuator is in a state where only one magnet is in contact with the middle structure with a coil (Figure 3B-a). When an electric current creates a magnetic orientation on the coil that is opposite to that of the attached stretchable magnet, a repulsive force pushes the attached magnet away, while the other magnet with the same magnetic orientation as the coil adheres to the coil structure due to magnetic attraction (Figure 3B-b). These forces then cause the attached magnet to detach from the coil and the detached magnet to attach. Even if the current is no longer applied, the actuator remains in its transformed shape due to the symmetry of the structure (Figure 3B-c). This operation is reversible if the current is applied to the coil in the opposite direction (Figure 3B-d,e).

Unlike SEAM-I, SEAM-II actuates based on the force balances of four types of forces: the attractive magnetic force to the middle coil structure with ferromagnetic silicone coatings $f_{\text{ferro}}$, the repulsive force between the magnets $f_{\text{magnet}}$, the spring force of the stretchable housing $f_{\text{spring}}$, and the electromagnetic force of the coil $f_{\text{coil}}$ (Figure 3C). We define the sum of the forces acting on the magnet as $f = f_{\text{spring}} + f_{\text{magnet}} - f_{\text{ferro}}$. When the sign of $f$ is positive, the magnet moves away from the coil, and when the sign of $f$ is negative, the magnet moves closer to the coil. For the actuator to have a bistable structure, the following three conditions (i–iii) must be satisfied.

i) The magnet attached to the ferromagnetic silicone layer is fixed regardless of the position of the other magnet, and when we locate the other magnet on the ferromagnetic silicone, the sign of $f$ must be positive.

ii) When we locate the detached magnet at the position where the detached magnet meets the force equilibrium, the sign of $f$ must be negative.

iii) For a state transition, the coil must generate an electromagnetic force that makes magnets move.

If conditions (i) and (ii) are not satisfied, then both magnets are attached to or separated from the coil structure with ferromagnetic silicone coatings, respectively. When conditions (i) and (ii) are satisfied, both magnets can be neither attached to nor
2.2. Design Principle

To realize the aforementioned bistable mechanisms, all types of forces produced by the actuator components should be thoroughly analyzed first (Figure 4A). We conducted a study on the parameters that affected the component forces through theoretical modeling, finite element analysis (FEA) simulations, and experiments. Based on these results, we determined the dimensions and the material compositions of the components in the order of stretchable magnet, soft coil, ferromagnetic silicone, and stretchable housing to satisfy the bistable conditions. While most of the existing bistable devices rely on nonuniform energy distribution of the structures, such as buckling or anisotropy in

Figure 4. Actuator components. A) Images of the main actuator components. B) Remanence of stretchable magnets with different weight percentages of magnetic particles. C) Force between two magnets as a function of radius and height. Both magnets are mixed with 400% magnetic particles and 3.5 mm apart. D) Modeling and experimental results of the electromagnetic force with respect to the amount of the input current. Blue dots and dashed lines represent the experimental and modeling results when the distance between the coil and the magnets is 0 mm, and the red lines represent the results when the distance is 6 mm. E) Relative permeability of ferromagnetic silicone with different weight percentages of ferromagnetic particles. F) Force between the ferromagnetic silicone and 400% magnetic particles mixed magnet at a distance of 3.5 mm as a function of weight percentage and height. G) Magnetic field measurement of the center of the soft microfluidic coil surface with a magnified top view of the soft microfluidic coil. Simulation results of the SEAM-I (left) and SEAM-II (right) spring forces with distance according to the mixture ratio of silicone composite. Legends in (G) represent the weight ratio in the order of EcoFlex 00–30 and Dragon Skin 10.

separated from the coil structure at the same time. Then, the actuator is in a stable state where one magnet is attached to the coil, and the other magnet is away from the coil.
materials, the proposed mechanism takes advantage of the relationships of different types of forces acting on or generated by the actuator. Therefore, the performance of bistability in our devices can be easily tuned only by adjusting those forces depending on the applications.

2.2.1. Stretchable Magnet

Stretchable magnets are made of a mixture of silicone elastomer and magnetic particles magnetized during the curing process.\(^{[57,58]}\) The magnetic force of the magnet increases in proportion to its remanence and is determined by the shape parameter.\(^{[56]}\) Remanence is an intrinsic characteristic of the magnet, which is determined by the degree of the external magnetic field during curing (0.6 T in this research) and by the mixed ratio of the magnetic particle. We first evaluated the remanence of the magnets with various magnetic particle ratios. The magnetic particles were mixed up to 400% of the silicone in weight since it was difficult to mold the mixture exceeding this percentage into a desired shape. The remanence of the fabricated magnets increases as the proportion of the magnetic particles increases (Figure 4B). Based on the obtained remanence, we performed simulations of the magnetic force based on the shape parameter of the magnet. We limited the shape of the magnet to a cylinder, and the magnetic force according to the radius and the height were calculated (Figure 4C and Figure S1A–C, Supporting Information). The magnetic force tended to increase as the size of the magnet increased. Among different combinations of the parameters, we chose the percentage of the magnetic particles, the radius, and the height to be 400%, 6 mm, and 6 mm, respectively. In the prescribed mixed ratio and configuration, we mixed neodymium iron boron (NdFeB) particles (Sinopro), which are widely used in magnetic applications,\(^{[59,60]}\) with EcoFlex 00–30 (Smooth-on) and silicone oil (Sigma–Aldrich). Silicone oil was used as an additive to increase the softness of the stretchable magnet. The custom-made stretchable magnets provide enough force for bistability along with a fully soft structure.

2.2.2. Soft Microfluidic Coil

A liquid–metal coil made by direct printing of eutectic gallium–indium (eGaIn)\(^{[61,62]}\) was fabricated in a double-layer structure to increase the electromagnetic force and facilitate wiring. Compared with conventional injection methods, the direct printing method enabled the fabrication of a much thinner liquid-metal trace for the coil, which significantly increased the coil density. Furthermore, the small manufacturing tolerance in the thickness and the width of the trace made the wiring process easy since the fabrication process required little human intervention. The coil was designed to have a width of 350 μm, a pitch of 480 μm, and a diameter of 24 mm, and each coil layer had 21 turns. The diameter and thickness of the entire soft coil structure with two coil layers were set to 32 and 3.5 mm, respectively. The electromagnetic force with the distance between the fabricated magnet and the coil was evaluated according to the amount of the current applied to the coil (Figure 4D). Figure 4D shows that the electromagnetic force has a linear relationship with the input current, in agreement with the analytical prediction. The liquid–metal coil is highly deformable compared to a regular copper coil but suffers from Joule heating due to the considerably low electrical conductivity of eGaIn (3.4 × 10^6 S m⁻¹) relative to that of copper (6 × 10^7 S m⁻¹). To investigate the effect of Joule heating, we measured the change in the temperature of the coil caused by the applied current (Figure S2, Supporting Information). At a current of 6 A, the coil temperature rose to 100 °C within 2 s.

2.2.3. Ferromagnetic Silicone

Ferromagnetic silicone was prepared by mixing ferromagnetic particles (Carbonyl iron powder) with uncured silicone. The strength of ferromagnetic silicone is affected by its shape and increases in proportion to its relative permeability, which is determined by the mixed ratio of ferromagnetic particles. First, we conducted an experiment to determine the relationship between the relative permeability and the mixing ratio. The ferromagnetic particles were mixed up to 500% which was the maximum percentage to allow molding into a desired shape. Figure 4E shows that the relative permeability increases as the mixed ratio increases. The diameter of the ferromagnetic silicone layer was set to be equal to that of the soft coil to fully cover the coil surface. With the relative permeability we obtained and the determined diameter, simulation for the magnetic force between the fabricated magnets based on the height of the ferromagnetic silicone layers were conducted (Figure 4F and Figure S1D, Supporting Information). In consideration of the bistable conditions, we set the mixed ferromagnetic particles, the diameter, and the height of the ferromagnetic silicone layer to 500%, 32 mm, and 0.6 mm, respectively.

2.2.4. Stretchable Silicone Housing

To facilitate the motions of the magnets during actuation, we designed a housing to connect the magnets and the coil structure with pillars instead of a single membrane, making multiple holes between the pillars. In this way, the air was able to easily move in and out of the gap between the magnets and the coil structure during the expansion and contraction of the actuator, respectively. There are several parameters that determine the spring force of the silicone housing: the shape of the housing, the geometry of the pillars, the modulus of the material, and the thickness of the silicone layer. Due to the various shape parameters of the silicone housing and the nonlinear properties of the materials, it was challenging to model the equation for the spring force, unlike the magnetic force. To find the spring force that satisfies the bistable conditions, we performed simulations with the above parameters. We first simulated the spring force with the height, tilted angle, and number of pillars. Using the simulation results, we then determined the shape of the housing for each actuator. The housing of SEAM-I has eight pillars, each of which has a width of 5 mm, a height of 6 mm, and a tilted angle of 75° from the coil surface. The tilted angle of the pillars facilitated the contraction of the actuator by allowing the magnets to rotate during actuation. The housing of SEAM-II has four straight pillars, each of which has a width of 6 mm and a height of 3 mm. The thickness of the pillars in both cases is 2 mm to prevent tearing during

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![Image](https://onlinelibrary.wiley.com/doi/10.1002/adfm.202302895)
manufacturing. Since there are multiple shape parameters, we found the desired spring force by adjusting the modulus of the elastomer material after determining the shape of the housing (Figure 4G and Figure S3, Supporting Information).

2.3. Experimental Validation of Bistability

2.3.1. SEAM-I

To check whether the designed SEAM-I components satisfied the bistable conditions, the $f_{\text{magnet}}$, $f_{\text{coil}}$, and $f_{\text{spring}}$ for varied distances between the coil surface and the magnet were measured (Figure S3A, Supporting Information). The measured $f_{\text{magnet}}$ and $f_{\text{coil}}$ values showed agreement with the modeling and simulation results (Figure 5A,B), and the measured $f_{\text{spring}}$ also fit well with the simulation result (Figure 5C). Figure 5D shows that the fabricated actuator meets the bistable conditions mentioned above. At the point where the distance becomes zero, $f_{\text{magnet}}$ is higher than $f_{\text{spring}}$ (described in Section 1.1 (i)), and there are two points where $f_{\text{magnet}}$ equals $f_{\text{spring}}$ in the entire travel range (described in Section 1.1 (ii)). The actuator displacement with respect to the input current is shown in Figure 5E. When the electromagnetic force transforms the state of the actuator, the transformed shape is maintained even if the current is not continuously applied due to bistability. Therefore, the bistable mechanism significantly reduces the Joule heating effect by preventing the need for continuous input currents to generate the electromagnetic force to overcome the spring force of the deformed hyperelastic body of the housing.

2.3.2. SEAM-II

To validate the bistability of the proposed SEAM-II, four types of force components in the actuator ($f^{'}_{\text{ferro}}$, $f^{'}_{\text{coil}}$, $f^{'}_{\text{spring}}$, and $f^{'}_{\text{magnet}}$) were measured while varying the distance between the ferromagnetic silicone layer and the magnet and compared with the simulation results (Figure 6A–C, Figure S3B,C, Supporting Information). Even in the presence of the ferromagnetic material, there was no significant change in the electromagnetic force of the coil (compare Figure 6B to Figure 5B). The thin ferromagnetic silicone layers did not act as magnetic cores due to the demagnetization effect that depends on the shape of the cores.[63] Figure 6D shows the bistability of SEAM-II. $f^{'}$ is negative if the magnet is located at the force equilibrium point with a distance of 4 mm (described in Section 1.2 (i)), and $f^{'}$ is positive if the magnet is located on the surface of the ferromagnetic silicone layer where the distance becomes zero (described in Section 1.2 (ii)). With bistability, the electromagnetic force was used as a trigger for the state transition, and the actuator maintained its transformed shape even after the current was cut (Figure 6E).
Figure 6. Validation of the bistability of SEAM-II. Experimental and simulation results of A) the attractive force between the ferromagnetic silicone and the magnet, B) the electromagnetic force of the ferromagnetic coated coil when 6 A current is applied, and C) the spring force of the stretchable housing. The experimental results in (A–C) show the mean values of measurements from five experiments. D) Validation of the bistability through the relationships of the component forces based on the bistable conditions. E) Plots of the input current and displacement of the magnet on the right side of the actuator with time.

2.4. Actuator Characterization

2.4.1. SEAM-I

The contracted and expanded states of the actuator can be detected by measuring the inductance of the coil. The inductance of the coil varies depending on the external magnetic field. A higher inductance value was measured in the contracted state than in the expanded state because the distance between the coil and the magnets was different depending on the actuator state (Figure 7A).

The magnet at each side of SEAM-I enables easy assembly with the same actuators (Figure 7B). In other words, the proposed actuator is modular in design, maintaining bistability. The modularity allows the force and the displacement of a set of actuators to be tunable depending on the configuration or the number of actuator modules. To verify the bistability in the assembly of the modules (Figure S4A,B, Supporting Information), the magnetic force between the combined magnets in series ($f_{\text{M}}$ in Figure S4C, Supporting Information) was evaluated. Although the bistable conditions were still met when multiple actuators were connected, the distance between the two stable positions in each actuator was smaller than that of a single stand-alone actuator due to the increased magnetic force with multiple magnets (Figure S4C, Supporting Information). The operation of the actuator modules is available in Movie S4, Supporting Information.

The force exerted by the actuator is defined as the maximum force that the actuator can withstand while maintaining its contracted state. Since the electromagnetic force induced by the coil generates an additional holding force that increases the maximum force, we measured the forces both with and without the input current. We measured the force for three cases: a single actuator and two actuators connected in series with one of them contracted or expanded state (Figure 7C). The two actuators with one of them expanded (Figure 7C, Case 2) produced a larger force than the single actuator by 0.04 N without an input current and by 0.08 N when an input current of 6 A was applied (Figure 7C, Case 3) due to the additional magnets on the actuator. For the two actuators, the force with one of them in the contracted state (Figure 7C, Case 1) was larger than that in the expanded state by 0.05 N without an input current and by 0.12 N with an input current of 6 A (Figure 7C, Case 2) due to the small distance between the magnets, which eventually generated a larger level of magnetic force. The results show that the magnitudes of the force can be easily tuned by varying the number and the state of the actuator modules.

The contraction and expansion times of the actuator were measured using a motion analysis software package (ProAnalyst, Xcitex) for different input currents. As the input current increased, the response times for both contraction and expansion decreased, while the time difference between contraction and expansion decreased (Figure 7D). The fastest actuation time was 26 ms at a current of 6 A during expansion. The response time for expansion was shorter than that for contraction since a higher electromagnetic force was applied at the beginning of expansion than in contraction, as the distance between the coil and the
Figure 7. Characteristics of SEAM-I. A) Proprioception. B) Modularity of actuator modularization through magnets on both sides of the actuator. C) Actuator forces for three cases. D) Actuation time of each process with varied input. E) Displacement of the magnet on the right side of the actuator for 50 cycles of actuation and F) amplitude change with varied frequencies of the input current.

magnets was smaller. We tested the robustness of the actuator in terms of consistency in the performance of bistability without degradation. By limiting the number of actuation cycles to 50, the actuator was less susceptible to joule heating. The result confirmed the reliability of the actuator during the actuation test (Figure 7E).

The displacement of the magnets on both sides of the actuator was analyzed by applying a current of 6 A with different input frequencies using the same motion analysis software mentioned above. Contraction and expansion of the actuator showed similar responses when the frequency was below 20 Hz, where the actuator was able to fully actuate in either way (Figure 7F, region 1). However, when the input current exceeded 20 Hz, the responses of the actuator for the two modes were different depending on the initial state. When the actuator was initially in the expanded state, the displacement decreased as the frequency increased (Figure 7F, region 2). On the other hand, when the actuator was initially in the contracted state, the actuator gradually reached the expanded state, which lasted until 66 Hz. When the frequency of the input current exceeded 66 Hz, the actuator was not able to fully expand with decreasing displacement (Figure 7F, region 3). Movie S5, Supporting Information shows actuation behaviors at different frequencies.

2.4.2. SEAM-II

The force that held the magnet attached to the coil surface was 0.046 N without an input current (red dotted line in Figure 6D). We define the force exerted by SEAM-II as the repulsive force of the attached magnet when the current is applied. The force varied depending on the amount of current and had a value of 0.182 N when 6 A was applied, which is the sum of the passive holding force and the active electromagnetic force.

Figure 8A shows the measured response times of SEAM-II with respect to the current applied. The overall actuation rate of detachment was faster than that of attachment since a higher repulsive electromagnetic force was applied to the attached magnet due to the shorter distance from the coil. The shortest response time was 12 ms at 6 A during detachment. An actuation test (50 cycles in total) also confirmed the reliability of the actuator’s bistability (Figure 8B).

The actuator fully operated up to 30 Hz with a current of 6 A (Figure 8C, region 1). At frequencies above 30 Hz, the displacement in either way of the actuator decreased differently (Figure 8C, region 2). Overall, SEAM-II showed a higher operating frequency than SEAM-I, indicating that it can be useful in applications that require high-frequency operation.

2.4.3. Demonstration

We demonstrated four robotic applications utilizing the unique features of the proposed soft actuators. First, taking advantage of the modular design, crawling locomotion was achieved by simply connecting multiple actuators in series using the integrated stretchable magnets. Second, a soft gripper was developed using the bistable function, consuming electric energy only for the
motions of gripping and releasing, not for maintaining a static state. Third, given the functionality of extension of the structure by the modular design, a manipulator with multiple degrees of freedom (DOFs) was designed and prototyped. Finally, the vibration mode of actuation of SEAM-II was employed in a swimming robot for underwater locomotion.

2.4.4. Crawling Robot

Crawling locomotion was achieved through repeated motions of contraction and expansion of the actuators. Three prototypes of SEAM-I were connected in series to form a crawling robot, and a tail was attached to the last actuator to make directionality in the friction between the robot and the ground. Figure 9A-a shows the initial state of the robot before locomotion with all three actuators fully contracted. The overall locomotion process consists of three steps. First, the first actuator expands (Figure 9A-b), making a forward motion of \( \approx 3.3 \) mm (Figure 9A-e). In the next step, the last actuator expands while the first actuator contracts (Figure 9A-c). Finally, the middle and the last actuators contract (Figure 9A-d). The middle actuator needs to create an active contraction to minimize the pulling effect by the last actuator even though it is already in the contracted state. In the last two steps, the robot moves slightly backward, but the first step makes a larger forward displacement than the backward displacement, resulting in the robot moving 2 mm per cycle with a speed of 6 mm s\(^{-1}\) (Figure 9A-e and Movie S6, Supporting Information). The speed can be controlled by the amount of the input current applied. The bistability of multiple actuators with this modular configuration was also demonstrated by shutting the power off after the locomotion step for a certain period of time.

2.4.5. Soft Gripper

A soft gripper that consumes energy only during the motion of gripping or releasing was developed using a SEAM-I. The fingers attached to the sides of the actuator were fabricated by mixing polydimethylsiloxane (PDMS, Sylgard-184, Dow Corning) and carbonyl iron powder (BASF) to create an attractive force with the magnets in the actuator, eliminating the need for chemical adhesion or mechanical fasteners (Figure 9B-a). For a pick-and-place demonstration with a robotic arm (UR5e, Universal Robots), the gripper was placed inside a custom-designed holder installed on the end-effector of the arm. As mentioned above, the input current was applied only for a short period of time for gripping or releasing the target object. The gripper was able to hold the object successfully using the gripping force produced by the bistability without consuming electric power. Figure 9B-b shows that two actuators can be paired to pick up a large-size object with a higher gripping force. As shown in the experimental result in Figure 7C, different gripping forces were achieved by changing the number of actuators. The full pick-and-place demonstration in both cases can be seen in Movie S7, Supporting Information.

2.4.6. Multi-DOF Manipulator

A multi-DOF underwater manipulator was demonstrated utilizing the advantage of the modular design of the SEAM-I. The manipulator consists of two rows of three actuators configured at 120° intervals, and thus, a total of six actuators were used. The top and the middle of the manipulator were attached to a ferromagnetic sheet to constrain its motion (Figure 10A-a). An end-effector was attached at the bottom of the manipulator. The demonstration was made underwater to show the advantage of the fully sealed actuators that made the manipulator completely waterproof and to minimize the effect of gravity during actuation. The manipulator was operated by applying the input current selectively to each actuator. To change the overall length of the manipulator, the actuators in the same row were contracted or expanded simultaneously. Meanwhile, to produce bending motions, the actuators in the same column were either contracted or expanded simultaneously (Figure 10A-b–f). The range of motion of the manipulator can be adjusted depending on the number of actuators by taking advantage of the modularity. The manipulator with six actuators was able to contract up to 13.6 mm and to bend up to 38° at the maximum (see Movie S8, Supporting Information).

2.4.7. Swimming Robot

A swimming robot was realized using the functionality of vibration of the SEAM-II. A tail was made by attaching two flexible
Figure 9. Robotic demonstration of the proposed actuators. A) Crawling locomotion of three SEAM-I modules and a tail at the end. Three locomotion states: a) initial state, b) expansion of front module, c) contraction of front module and expansion of rear module, and d) contraction of middle and rear modules. e) Displacement of the actuators with respect to time. B) Soft gripper using a single SEAM-I module with soft ferromagnetic fingers attached to both sides. a) Soft ferromagnetic fingers attached to SEAM-I and bistable state transformation. The actuator shows the gripping of an object with current input, and the object is dropped with the inverted input current. b) Soft gripper with two SEAM-I modules capable of gripping a large object with the same actuation principle used with the single-module actuator.

plastic sheets of transparent film to the two sides of the SEAM-II using custom-built thin stretchable magnets (Figure 10B-a). The other ends of the two sheets of film were glued to each other. The length of the tail was \( \approx 70 \) mm. A buoy was used to submerge the robot to a constant depth and prevent the interference of the electric wires during swimming. As the actuator vibrated by the input current, the tail deflected (Figure 10B-b–d), and the robot moved underwater following the principle of carangiform swimming.[65] The displacement of the robot is shown in Figure 10B-e,f when a current of 3 A at 10 Hz was applied. The robot was able to swim at a velocity of 5.75 mm s\(^{-1}\) (see Movie S9, Supporting Information). The maximum temperature of the coil reached 40°C under water, showing a better temperature response compared to the actuation in the air (Figure S2C, Supporting Information).

3. Discussion and Conclusion

Two fully soft electromagnetic actuators, SEAM-I and SEAM-II, were proposed and fabricated. While existing state-of-the-art fully soft electromagnetic actuators produce only bending motions due to the small electromagnetic forces they can generate,[40–42] the SEAM-I is able to make active linear motions of contraction and expansion. Unlike the vibrational motion realized by a single magnet in the work by Do et al.,[40] the SEAM-II showed the motion of bidirectional vibration with symmetry by the magnets on the sides of the actuator.

Compared to the coil manufactured in the previous study with an overall diameter of 40 mm and five turns,[42] we were able to fabricate a multilayered liquid–metal coil with an overall diameter of 24 mm and 21 turns using a direct printing method, which significantly enhanced the density of the electromagnetic field.

To the best of our knowledge, this is the first effort to integrate bistable mechanisms with fully soft electromagnetic actuators for stable operation and low energy consumption. Although there have been groups that showed the feasibility of integrating bistable mechanisms with actuators, they relied on buckling of rigid materials for bistability, making rigid materials essential in soft actuators. However, we achieved bistability through a combination of the spring force of the hyperelastic housing and the magnetic forces generated by the soft coil and magnets without compromising the physical compliance of the soft actuator. In our design, the electromagnetic force of the coil was used only for making transitions between one equilibrium state and the other. Otherwise, a continuous operation without bistability, which causes massive Joule heating, is required to hold a
current state. Since the bistable characteristic was realized based on the force relationships among multiple actuator components, we conducted parameter studies for the relevant components.

We were able to drive the proposed actuators only with electric power at high speeds without bulky peripherals. During operation, the actuators showed physical robustness against impacts and an innate waterproofing ability. In addition, the stretchable magnets located on both sides enabled the modularity of the actuator. Depending on the number of actuators connected, it is possible to generate different forces and displacements for various applications. Furthermore, objects with different materials can be connected to the ends of the actuators, enabling functionalities in various soft robotics applications, including ground and underwater locomotion, gripping, and manipulation.

Meanwhile, there is room for further improvements to increase the performance of the actuators. Although the soft microfluidic coil has a double-layered structure with a relatively high density, it requires a high current to generate a sufficient electromagnetic force for actuation. The input current can be reduced by increasing the number of turns of the coil to produce the same electromagnetic force, which increases the resistance and expedites Joule heating. Therefore, it is crucial to optimize the design of the coil, as there is a trade-off between the number of turns and the resistance. Moreover, FEA simulations regarding the forces were carried out using a commercial multiphysics simulation tool (COMSOL Multiphysics) (Figures S3 and S4, Supporting Information). Based on the results of the modeling and the simulation, the geometry of the actuator that satisfied bistable conditions was determined.

4. Experimental Section

Modeling and Simulation: To realize bistability using different forces generated by the actuator components, a quantitative analysis of the relationships of the forces was conducted. Based on the Bio-Savart law, an equation describing magnetic fields, the magnetic and electromagnetic forces were modeled with respect to the geometries of the magnets and the coil (Figures S5 and S4, Supporting Information). Moreover, FEA simulations regarding the forces were carried out using a commercial multiphysics simulation tool (COMSOL Multiphysics) (S5, Supporting Information). Based on the results of the modeling and the simulation, the geometry of the actuator that satisfied bistable conditions was determined.
Fabrication of the Soft Microfluidic Coil: A direct printing method was used for patterning a liquid–metal coil. Silicone elastomer (Dragon Skin 10, Smooth-on) and a white pigment (SILC PIC, Smooth-on) were mixed and poured onto a black glass substrate and spin-coated at 300 rpm for 30 s (Figure S6A-a,b, Supporting Information). The white pigment was required for precise measurement of the stand-off distance between the tip of the printing nozzle and the spin-coated elastomer. Circuit layer using a laser distance sensor in the dispensing system (Super ΣΣΜΜΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙΙII V2, Musashi). After curing at 60 °C for 30 min, the silicone layer was placed on the stage of the dispenser system, and the coil pattern of the first layer was printed with eGaln (Gallium 75% and Indium 25% in weight), which is widely used in stretchable electronics (Figure 1b, Figure S6A-c, Supporting Information).[77–80] The inner diameter of the nozzle, the pressure, and the printing speed were 300 μm, 5 kPa, and 3 mm s⁻¹, respectively. The interconnection between the first-layer coil and the second-layer coil was made by printing eGaln vertically (Figure S6A-d, Supporting Information). Once the printing of the first-layer coil was complete, the same silicone was used again to cover the first-layer coil (Figure S6A-e, Supporting Information). During this process, the top of the vertical eGaln interconnect was kept straight and exposed to air for electrical connection to the second-layer coil. The second-floor coil was printed in the same way (Figure S6A-f, Supporting Information) after the silicone that covered the first coil was cured. The second-floor coil was then covered with the same but transparent silicone. Once the top silicone was cured, the complete coil structure was cut by a laser cutter (Speedy 300, Trotec) (Figure S6A-g,h, Supporting Information). Finally, signal wires were connected and were firmly fixed with a silicone adhesive (Sil-oxey, Smooth-on) in their positions (Figure S6A-I, Supporting Information).

Fabrication of the Stretchable Magnet: To fabricate a stretchable magnet, silicone elastomer (EcoFlex 00-30, Smooth-on), NdFeB particles (SP1202-0.6, mesh size: 300 mesh, Sinopro), and silicone oil (Sigma–Aldrich) were mixed using a planetary centrifugal mixer (ARE-310, Thinky). The cylindrical shape of the magnet was created by compressing the mixture with molds on both sides, and it was cured at 80 °C for 30 min between two NS2-grade neodymium permanent magnets (Figure S6B, Supporting Information). While the higher proportion of magnetic particles makes the stretchable magnet stiffer, the addition of silicone oil decreases the stiffness of the magnet with the same proportion of magnetic particles (Figure S7A,B, Supporting Information) without changing the magnetic force generated, as shown in Figure S7C, Supporting Information, compared to Figure 4B.

Fabrication of Ferromagnetic Silicone: To fabricate the soft ferromagnetic silicone layer to be attached to the coil structure for SEAM-II, carboxyl iron powder (BASF) and silicone (EcoFlex 00-30) were mixed using a centrifugal mixer. This mixture was then poured into a cylindrical 3D-printed (Objet 360, Stratasys) mold and cured (Figure S8A, Supporting Information).

Fabrication of the Silicone Housing: The fabrication process consisted of several steps that create fully 3D shapes. First, the stretchable magnet was placed at the center of the bottom mold (Figure S8B-a, Supporting Information), and silicone was poured around the magnet. The arrow-shaped parts were then placed over the magnet to create a lattice structure of the actuator, after which the coil was placed above them (Figure S8B-b,c, Supporting Information). Subsequently, the same silicone was poured around the coil, and the arrow-shaped parts were placed in the opposite direction over the coil (Figure S8B-d, Supporting Information). Finally, the top mold was placed above the other molds, the magnet was placed in the center, and silicone was poured again on top (Figure S8B-e, Supporting Information). The assembled molds were cured at 60 °C for 40 min. For SEAM-I, we mixed two different silicone materials (EcoFlex 00-30 and Dragon Skin 10) with a weight ratio of 8:2 with the addition of a 5% silicone thinner to the overall weight, and for SEAM-II, EcoFlex 00-30 was used only with the addition of a 3% silicone thinner.

Actuator Driving and Sensor Readout Circuit: A circuit that can provide a high current to the coil and detect the state of the actuator at the same time was built. Since the high input current applied to the actuator may damage the inductance-to-digital chip (LDC) (LDC1314, Texas Instruments) if the inductance of the coil is measured while the current is applied, the actuation and sensing circuits were separated using a relay. In the default state, inductance sensing is on. However, if the user applies an actuation signal including the information on the direction, the frequency, and the application time of the current to the main computer connected to the microcontroller, then the sensing part is temporarily paused. The actuation part, composed of an H-bridge motor driver (MDD-10A, Cytron), then starts to operate. A block diagram for the circuit and the printed circuit board (PCB), which was capable of operating up to four actuators simultaneously, can be found in Figure S9A,B, Supporting Information, respectively.

Actuator Component Force Measurement: Experiments to measure the forces from the actuator components with respect to the displacement were conducted using a motorized test stand (ESM303, Mark-10) and a load cell (F/T Sensor Nano 17, ATI Industrial Automation). To measure the magnetic force between two stretchable magnets, the magnets were placed in holders where one was fixed to the bottom platform and the other was mounted on the load cell (Figure S9C, Supporting Information). The holders were designed to provide a sufficient height to ensure that no attractive magnetic force from the test environment was applied to the components. The force data were collected while varying the distance between the magnets. A similar experimental setup was used to measure the magnetic force between the ferromagnetic silicone layer and the stretchable magnet. For measurement of the electromagnetic force of the coil, force data were collected while applying a constant current of 6 A to the coil (Figure S9D, Supporting Information).

Material Stiffness Measurement: To measure the stiffnesses of the actuator components, a dog-bone-shaped specimen was fabricated using the same material for each component. The dimensions of the specimen were 25 mm in length, 10 mm in width, and 2 mm in height. One end of the specimen was fixed at the bottom of the test stand, and the other end was fixed to the load cell (Figure S9E, Supporting Information).

Actuation Time Measurement: A commercial motion analysis software package (Pro-Analyst, Xcite) was used to measure the exact times taken for the actuation of SEAM I and SEAM II. A tracker was attached to one end of the actuator, and the motion of the actuator was recorded at 240 fps. By tracking the displacement and the velocity of the tracker tip, the time required for actuation was found (Figure S9G,H, Supporting Information).

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.

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


