Versatile Ultrasoft Electromagnetic Actuators with Integrated Strain-Sensing Cellulose Nanofibril Foams

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As robots more frequently fraternize with humans in everyday life, aspects such as safety, flexibility of tasks, and appearance become increasingly important. Soft robotics is attractive for new human-close applications, but soft actuators constitute a major challenge both in terms of actuation force and speed, and in terms of control and accuracy of the deformable soft actuator body. Herein, several of these challenges are addressed by developing versatile ultrasoft electromagnetic actuators that operate in absence of external magnetic fields, while simultaneously monitoring their states by internal strain sensors. The versatile actuators can compress to less than 50% of their initial length with strain-independent contraction force and operate in both contraction and expansion modes up to 200 Hz frequency while conforming to curved surfaces. The soft multilayer conductive cellulose-based foams are lightweight (3 mg cm$^{-3}$) and provide internal strain-sensing capability and structural support, thereby improving the monitoring and controllability of the actuators while maintaining an axial softness of 0.6 kPa. It is believed that the concept of soft versatile electromagnetic actuators with integrated lightweight strain-sensing foams is promising for a wide range of applications within soft robotics.

1. Introduction

Robots are today an integrated part of society, with a widespread use within the manufacturing industry and rapid growth within several emerging application areas such as health care and home appliances. As robots intermingle with humans in everyday life, aspects such as safety and flexibility of tasks become increasingly important. Conventional rigid robots have limited adaptability to diverse duties, have difficulties to conform to a variety of form factors, and often present safety concerns while interacting with soft living systems. The development of soft robotics has received major attention in recent years due to the promising applications of the technology. Soft robots can be integrated into flexible and deformable systems, thereby enabling the performance of a variety of tasks in a lifelike, adapting, and interacting manner. Actuation is one of the most challenging aspects of soft robotics, and a variety of approaches have been explored, including pressure-driven actuation,[14–16] thermal actuation,[8,9] humidity-driven actuation,[10–12] dielectric elastomeric actuation,[14–16] and electromagnetic actuation.[17–28] Pressure-driven actuators can generate large forces and deformations but have slow response and require relatively high-pressure equipment to function.[6,7] Thermal actuators can generate large deformations and forces, but are hard to control, slow in response time, and require relatively high temperatures.[8,9] Humidity-driven actuators can reach high strains, but are hard to control, have a slow response times, and require special environmental conditions or stimuli to control the water absorption (e.g., electricity, heating, or light) to function.[10–13] In contrast, dielectric elastomer actuators offer fast response, high force, and a large stroke length, but require high voltages in the kV range to operate, which constitute a serious health hazard.[14–16] Electromagnetic actuators are promising for soft robotic applications due to their fast response, low driving voltage, and ease of control. However, most soft electromagnetic actuators require large external magnets[19–23] or strong external magnetic fields[24] to operate. Soft actuators based on intrinsically stretchable conductors are especially dependent on strong external magnetic fields due to their relatively low conductivity, which restricts the number of feasible applications considerably.[17–20,23] While there are some reports on internal magnets for improving the force of soft electromagnetic actuators,[19,25–28] the proposed structures consist of one or two coils, thereby limiting the stroke length. The generated force in such actuators depends both on the actuator deformation and on the excitation current, which makes them difficult to control. Furthermore, most soft electromagnetic actuators are restricted to specific designs, shapes, and deformation modes, for example, bending to a specific form, which limits their usability and versatility. There is thus a lack of versatile soft
conformal electromagnetic actuators that do not rely on external magnetic fields and that can operate over a wide range of deformations.

Self-sensing is another major challenge for soft actuators that needs to be addressed to reach real-world applications. Soft actuator autonomy and interaction with the environment can be improved by the integration of sensing mechanisms. Different sensing approaches come with certain disadvantages, such as an increase in stiffness or weight of the actuator, high-temperature processing, or insensitivity to compressive strain. Conductive foams are interesting in this context due to their potential softness, tunability, and easy processing. Light and soft foams are mostly produced by high-temperature processes, which prevent integration with many other components and materials. However, cellulose nanofibril (CNF)-based foams provide good structural stability in combination with low-temperature processing and tunability of properties, which makes them suitable for system integration. Furthermore, conductive foams must be electrically insulated from the outside environment when integrated into devices, which puts additional requirements on their processability. Until now, it has remained a challenge to meet all the above criteria to enable self-monitoring and enhanced controllability of soft actuators.

Herein, we report on the development of versatile soft electromagnetic actuators capable of contraction, expansion, hopping, and locomotion. The actuators operate in the absence of external magnetic fields and are designed to generate strain-independent contraction forces while internal strain sensors monitor their conformational states. The designs comprise 8- or 12-spaced flexible coils embedded and connected with silicone elastomer structures, a neodymium ring magnet in the center, and an insulated conductive CNF-based foam for strain sensing (Figure 1a). The actuators can compress to less than 50% of their initial length while maintaining a constant contraction force, and they can operate at frequencies of up to 200 Hz. The developed ultralight-weight and ultrasoft (0.6 kPa) core-shell conductive CNF-based foams provide internal strain-sensing capability, thereby improving the monitoring and controllability of the actuators.

Figure 1. Design and simulations of soft electromagnetic actuators. a) Schematic of the actuator design comprising eight discretely spaced flexible coils embedded and connected with soft Ecoflex silicone structures, a neodymium ring magnet, a conductive CNF-based sensing foam core (poly (3,4-ethylenedioxythiophene):polystyrene (PEDOT:PSS), and (3-glycidyloxypropyl)trimethoxysilane (GOPS)), and an insulating outer layer cellulose foam (CNF and GOPS). b) Schematic illustration of the force transmission via the soft interconnects within the electromagnetic actuator during excitation. c) Simulations of the magnetic field intensity and coil rearrangements within the soft electromagnetic actuator before and during actuation. d) Calculated force on a single coil ring at different excitation currents and distances from a ring magnet. e, f) Calculated force at the outer ring in a 12-coil actuator with internal magnet. e) Strain f) versus excitation current.
2. Results and Discussion

2.1. Actuator Design and Operational Principle

The goal was to develop a freestanding soft electromagnetic actuator that could 1) operate without external magnetic fields, 2) conform around objects, 3) generate tunable forces independent of deformations, and 4) incorporate internal strain-sensing capability. A source of inspiration was the classical solenoid actuator, which relies on a fixed coil and a moving plunger. To remake such a rigid actuator into a soft and flexible one, we hypothesized that the translational movement could be transferred from the plunger to the coils, thereby creating an actuator that compresses more evenly as it lacks large rigid parts. Conventional solenoid actuators rely on high-permeability materials for the plunger and casing; however, such high-performance materials are not available in soft formulations. Further, using intrinsically stretchable gallium–indium eutectic (EGaIn) conductors instead of copper wire would increase the resistance by a factor of 17, which would significantly increase driving voltage and power consumption. We therefore decided on an approach where the deformability comes from the internal structure of the device. The developed design comprises copper wire coils and a ring magnet in the center, all interlinked with soft and flexible silicone ribbons holding the structure together (Figure 1a). The core comprises a soft, conducting strain-sensing foam, and the whole device is encapsulated with an outer soft, insulating CNF foam. There are previous reports on single-coil actuators;[17–20,23,25,26,28] however, such designs exhibit a fast decrease in force with increasing coil distance from the magnet, resulting in a short effective stroke length (Figure 1d). We hypothesized that by increasing the number of coils, the effective stroke length could be increased. The proposed operational principle of a multcoil actuator is shown in Figure 1b. The coils are interlinked with springs, which, during actuation, transmit the high forces from the coils close to the magnet to the more distant coils. The magnetic field around the coils and magnet was simulated with a COMSOL multiphysics model, and the forces were calculated based on the Lorentz force law \( F = I / d l \times B \) (Figure 1c). To simulate the rearrangements of the coils, force–strain measurement data (Figure S4, Supporting Information) from the soft interconnect structures was used in a 1D stationary model. The electromagnetic force on each ring coil was in this case assumed to arise from single-ring interaction with the magnet, and the multidimensional problem of finding the ring displacements was solved using the FEA algorithm[43] to satisfy all the governing equations (Figure S5, Supporting Information). Figure 1c illustrates the actuator’s magnetic field intensity in resting and excited states, with the ring displacement visible in the latter case. The ring magnet generates most of the magnetic field in the device, which supports the initial assumptions of the model (see Figure S6, Supporting Information, for more detailed simulations). For a single-coil actuator, the generated force depends strongly on the distance between the magnet and coil, which severely limits the effective stroke length of the actuator (Figure 1d, S3, Supporting Information). In contrast, when simulating the multicoil design, the contraction force remains approximately constant over a wide range of strains (Figure 1e). This greatly enhances the effective stroke length and facilitates good control of the actuator, as the force only depends on the excitation current and not the conformation (Figure 1f). The multiring actuator can also be operated in expansion mode, with a weak force dependency on the strain around the initial conformation but with a nonlinear dependency in the compressed state (Figure 1e). The advantageous force–strain behavior of the multiring actuators can be attributed to the soft interconnect structures, which translate the force within the structure in a favorable manner, thereby generating the strain-independent force profile. Actuators without an internal ring magnet were also evaluated but showed, as expected, much lower generated forces (Figures S1, S2, Supporting Information). We therefore decided to implement and evaluate the multiring actuator design with an internal neodymium ring magnet.

2.2. Soft Actuator Fabrication and Characterization

For optimal resolution and flexibility of the design, a stack of 3D-printed sacrificial poly(vinyl alcohol) (PVA) templates was assembled and fixed together using a bolt and nut (Figure 2a). Flexible 50 μm enameled wire was wound into the grooves of the template to form parallel wire bundles, which were then coated in soft silicone to fixate the coils and to form the soft supporting structures in between the rings. After the curing of the silicone, the PVA template was removed by dissolution in water. Finally, a thin neodymium ring magnet was attached in the middle of the actuator in between the two flexible wire bundles, and two 3D-printed PLA hooks were anchored on the ends of the actuator. A detailed step-by-step illustration of the actuator fabrication process is available in Figures S7 and S8, Supporting Information. The fabricated 12- and 8-rings actuators were soft, compressible, stretchable, and conformal (Figure 2b and 2c). Figure 2d shows the forces related to the compression/stretching of the actuators. The 12-ring design used equally spaced rings that could be compressed to around 60% of their initial length. To improve the compressibility, the 8-ring design had a longer distance between the closest rings and the magnet and fewer coils in total, resulting in a maximum compression of almost 40% of its initial length. The 8-ring design thus showed a wider working strain range than the 12-ring design. Figures 2e and S9a,b, Supporting Information, show generated contraction and expansion forces of the actuators at different currents and strains for the 12- and 8-rings designs, respectively. The contraction force of the soft actuators is independent of the deformation, as predicted by the simulations (Figure 1e,f). Overall, the experimentally measured forces (Figure 2e,f) are in good agreement with the simulated forces (Figure 1e,f), thereby strengthening the operational principle hypothesis. In the contraction mode, the transfer of force to the ends of the actuators relies mostly on the soft interlink structures, as the centrally generated force is mechanically transferred by straining the interlinks within the structure. The axial compression of the centrally located rings is limited by the steep increase in repulsive mechanical force for higher compressions (Figure S4, Supporting Information), which limits the force transmission and generates a more stable force with respect to strain. Under the tested conditions, the actuators generate contraction and expansion forces of up to 50 and 120 mN.
respectively. The discrepancy arises because of differences in force transmission. In the expansion mode of actuation, the interlink structures transmit repulsion forces to the actuator ends through compression, which is more effective than expansion due to the nonlinear stress–strain response of the structure (Figure S4, Supporting Information). Overall, the 8-ring design required lower driving current and power consumption than the 12-ring design for generating similar actuation forces (Figure S9a,b, Supporting Information).

The operational versatility of the soft actuators is demonstrated in Figure 2g–j. The soft actuators can conform around a cylinder while repeatedly lifting a 2 g weight (Figures 2g and S9e, Supporting Information), demonstrating their ability to operate in unconventional geometries. The actuators can also be used as an artificial muscle to move a 3D-printed PLA arm (Figures 2h and S9f, Supporting Information). The expansion mode of the actuators allows them to lift or push objects, as demonstrated in Figure 2i) by the lifting of a 2 g weight. The lightweight and freestanding nature of the soft actuators allows them to operate in locomotion mode as well. By first contracting and then expanding, the actuator can jump several times its own height up into the air (Figure 2j). Finally, the attachment of a leg allows the actuator to crawl along a structured surface (Figure S9g, Supporting Information).

2.3. Sensing Foam Fabrication and Characterization

Soft sensing foams were developed to incorporate structural stability and self-sensing capability into the actuators. CNF-conducting polymer-based foams[39] were chosen for the
development of compressible, pressure-sensitive, and light-weight sensing foams, as they can be processed at low temperatures (<110 °C) and have tunable mechanical and electrical properties. In this approach, CNF provides the mechanical structure and acts as a template for the self-assembly of the conductive polymer poly (3,4-ethylenedioxythiophene): polystyrene (a) (b) (c) (d) (e) (f) (g) (h) Figure 3. Compression sensitive conductive CNF foams. a) Schematic of the fabrication process of the soft CNF-based conducting sensing foam including an insulating outer foam layer. The PEDOT-PSS:CNF-GOPS dispersion is placed in a thick bottom PDMS mold, the mold is immersed in liquid nitrogen to flash freeze the solution, the frozen solution is removed from the mold and placing it in a wider PDMS mold, the insulating foam dispersion is filled around the frozen sample, the mold is again immersed in liquid nitrogen, and the frozen sample is removed and dried in a vacuum freeze dryer. b) Young’s modulus versus solid content for foams at 50% compression. c) Relative resistance changes at 50% compression for different PEDOT-PSS weight ratios in 3 g L⁻¹ density foams. d) Relative sensor resistance for cyclic compression to 50% for two different PEDOT-PSS weight ratio foams. e) Mechanical and electrical performance of the optimized foam (10:3:5 (CNF:PEDOT-PSS:GOPS) weight ratio) for 1000 compression cycles to 50%. f) SEM image of the 12.5 g L⁻¹ solid content foam of 10:10:5 weight ratio. g) SEM image of the 3 g L⁻¹ solid content foam of 10:10:5 weight ratio. h) SEM image of the 3 g L⁻¹ solid content foam of 10:3:5 weight ratio.
(PEDOT:PSS), and (3-glycidyloxypropyl)trimethoxysilane (GOPS) acts as a crosslinking agent for PEDOT:PSS to make the foam stable and elastic. Freeze-dried CNF foams are often anisotropic since the ice crystals growth direction dictates the internal pore structure of the foams. To induce directional-ity in the freezing process, cylindrical PDMS molds with thick thermally insulating bottoms were used to create radial cooling. This resulted in lamellar-structured foams with a lower Young’s modulus along the axial direction, which is desirable for the intended application. A two-step procedure based on multilayer subsequent freezing was developed to make layered foams with a conductive core and an insulating outer shell (Figure 3a). A CNF-PEDOT-PSS:GOPS dispersion in a PDMS mold was frozen in liquid nitrogen and moved to the center of a wider PDMS mold. CNF:GOPS dispersion was quickly dispensed around the frozen core and frozen by immersion in liquid nitrogen, followed by freeze drying in vacuum (Figure S10, Supporting Information). Finally, the foam conductivity was improved by vapor treatment with DMSO. The insulating foam layer plays a crucial role in reducing the risk of electrical shorts and external electrical interference in the sensing signal. The foams produced according to a previous recipe had a Young’s modulus of 20 kPa in the axial direction (averaged over 50% of compression), which is not soft enough for the envisioned application. To further lower the stiffness of the foams, the solid content was decreased from 12.1 to 3 g L\(^{-1}\), which resulted in the Young’s modulus going down from 20 kPa to around 2 kPa (Figure 3b). Further lowering of the solid content

![Figure 4](https://www.advancedsciencenews.com/doi/abs/10.1002/advs.202200449)

**Figure 4.** Soft actuator with integrated sensing foam. a) Schematic of the fabrication process of the soft actuator with self-sensing. Carbon paper was placed in the bottom of the PDMS mold to form a stable electrical connection. The electromagnetic actuator was placed in the mold and the foam solution was filled in, after which it was flash frozen by immersion in liquid nitrogen. The actuator with the frozen core was transferred to a wider mold and insulating foam solution was filled in, flash frozen, and freeze dried. b) Photograph of the fabricated device with internal sensing CNF-based conductive foam surrounded by insulating CNF-based foam. c) Sensor resistance change in response to device excitation by 335 mA current at 10 Hz, with calculated strain level based on the sensor output. d) Resistance change response from the sensor as the device was excited by different excitation currents, together with the corresponding calculated strain based on the sensor signal. e) Relaxed and excited states of the actuator when lifting a weight. f) Relaxed and excited states of the actuator when used as an artificial muscle.
was not possible due to shrinkage of the foams after freeze drying. The electrical sensitivity of the foams to compression was evaluated by a compression test to 50% strain (Figure 3c). Small pieces of carbon paper were incorporated into the contacts of the foams during fabrication to ensure stable electrical contacts. The conducting percolation network was tuned by varying the amount of PEDOT:PSS in the 3 g L\(^{-1}\) foams, which yielded an improvement from 10% to 35% change in the resistance (Figure 3c) while maintaining a low Young’s modulus (Figure S11, Supporting Information). The electrical sensitivity at low strains was also greatly improved by tuning the conductive percolation network within the foams by adjusting the loading of PEDOT:PSS (Figure 3d). The foam stability during compression cycling was evaluated by repeatedly compressing the foams to 50% strain while measuring the resistance and stress (Figure 3e). The foam showed a very consistent change in resistance and stress–strain behavior during 1000 cycles. Cross-section scanning electron microscopy (SEM) images revealed that by lowering the solid content of the foams, the distance between the layers in the foam structure increased (Figure 3f,g), which corresponds to a lowering in stiffness. Reduction of the PEDOT:PSS content also induced a morphological change, as the layers became more fragmented (Figure 3h).

The increase in electrical sensitivity for low PEDOT:PSS loadings can originate from both the macroscopic structure of the foam, as well as the nanoscopic arrangement of conductive domains on the CNF template. The developed sensing foams are exceptionally soft and lightweight in comparison to previously published conductive low-temperature processable (<150 °C) foams (Figure S12, Supporting Information). For efficient integration into actuators, it is essential that the sensing foams are ultralight, low-temperature processable and exhibit a low-temperature modulus dependence (Figure S13, Supporting Information), all aspects which our developed sensing foam material fulfills.

2.4. Soft Actuators with Integrated Self-Sensing

The complete soft actuator with self-sensing was fabricated by combining the processes used for making the soft electromagnetic actuator and the soft insulated sensing foam (Figure 4a). First, the soft electromagnetic actuator was placed inside a smaller diameter PDMS mold, which was then filled with conductive foam solution. The mold was immersed in liquid nitrogen, and the frozen actuator was placed in a wider PDMS mold, after which an insulating foam solution was poured over and around the device. A fast freezing step with liquid nitrogen avoided issues with melting of the conductive core during the process. The full device was finally freeze dried to form the foams, resulting in the device shown in Figure 4b. Figure 4c shows the change in the foam resistance and the corresponding calculated change in the actuator length during pulsed excitation. To further investigate the effect of the current on the actuator contraction, the same procedure was performed for different excitation currents, as shown in Figure 4d, which shows the expected trend. The developed actuators can be used for different tasks, from lifting weights (Figure 4e) to act as an artificial muscle to move a 3D-printed arm (Figure 4f). The sensing foam properties are key for the functionality of the actuator, as the very low Young’s modulus of the foam minimizes the loss of force during compression (0.6 kPa in the axial direction), and its low density makes the actuator lightweight. The novel approach of forming a two-layered foam in one step provides electrical insulation for the sensing foam, which also is of great practical importance.

3. Conclusion

We have developed a new kind of versatile ultrasoft (0.6 kPa) electromagnetic actuator with incorporated self-sensing capability. The softness and compressibility of the actuator were achieved through the structural engineering of the interconnects of the various components, yielding a structure that could easily be bent, compressed, and elongated. The multiring design in combination with the soft interconnects yields an actuator with a long stroke length and strain-independent contraction force characteristics, which constitute a great advantage when controlling the actuator. The actuators show fast response and the ability to lift weights in different geometrical conformation. These features combined allow the actuators to be closely integrated with living systems, as they potentially can flex along bodily motions at proper speeds. To keep track of the conformational state of the actuator, ultrasoft and lightweight (3 mg cm\(^{-3}\)) strain-sensing foams based on CNF and PEDOT:PSS were developed and integrated into the actuators. The conducting foam is soft enough to allow compression without significant loss of force but robust enough to mechanically support the soft actuator without breaking. The sensing foams allow for fast readout of the actuator strain under cyclic operation of the actuators. As soft actuators are especially susceptible to deformations induced by the environment, we believe that the self-sensing concept with integrated strain sensing is attractive for a wide range of emerging soft actuator technologies within soft robotics, especially toward wearable applications.

4. Experimental Section

Simulations: Simulations of actuators were conducted using COMSOL Multiphysics 6.0 software. The axisymmetric geometry consisted of 12 rings (each with a rectangular cross section of 1 × 0.35 mm) with an inner radius of 4.5 mm, distributed equally in the axial direction. The design with an internal magnet had the same configuration, except that there was an additional ring magnet (rectangular cross section of 1 × 1.525 mm) with an inner diameter of 3.175 mm that was added to the center of the actuator at the same distance from the neighboring coils (0.7 mm). The magnetic field and generated force were calculated using the mf module, and ring coils were modeled as 100-turn homogenized multiturn coils. The magnet material was set at N45H (sintered NdFeB), and it was modeled according to Ampere’s law with a remanent flux density magnetization model in the axial direction. The force generation calculations at different strains were performed by changing the distance between the components equally from 0.2 to 1 mm at each excitation current while calculating the sum of the forces generated on the six ring coils on one side of the actuator. To determine the coil ring displacements and simulate the soft structure force transfer mechanism, a 1D stationary model was used (see Figure S5, Supporting Information, for a schematic representation of the model). The rings were modeled as rigid components and the soft structures as springs, for which the force–strain relation was determined by interpolation of force–strain measurement data of the interconnects (Figure S4, Supporting Information). The electromagnetic force on each
single ring coil was assumed to be a function of the ring distance from the magnet at each excitation current (interpolation from simulation data for single-coil ring interaction with a ring magnet [Figure 1d]). The multidimensional problem was solved by using the FFA numerical algorithm[43] to determine the ring displacements while satisfying the governing equations. The total generated electromagnetic force was calculated by comparing the force on the actuator end points in the relaxed and actuated states.

Fabrication and Assembly of Soft Electromagnetic Actuators: Rings of the PVA mold were made using a 3D printer (Ultimaker 2 Extended Plus). The layers were stacked in a specific order and fixed together using a bolt and nut to achieve the actuator PVA mold. For the 12-rings design, the ring neodymium 45H magnet (9.4 mm OD × 6.35 mm ID × 1 mm thick, R1004 N45H, SuperMagnetMan) was included in the middle of PVA mold stack. The PVA mold was used as a template to wind 50 μm enameled copper wire in the ring-shaped grooves, and an extra 50 μm enameled copper wire was passed through structured grooves in between the coils to increase the force transfer capability of the structures. Next, the mold was immersed in a premixed solution of two-component Ecoflex 00-20 (Smooth-On), and the excess solution was removed using swabs. After curing at room temperature for 4 h, the mold was placed in deionized (DI) water at room temperature overnight to dissolve away the PVA template, followed by multiple washes with fresh DI water to remove PVA residues. Excess Ecoflex residues were cleaned off from the actuator, after which it was placed in an oven at 90°C for 2 h to fully cure the Ecoflex. Finally, the middle ring neodymium 45H magnet (9.4 mm OD × 6.35 mm ID × 1 mm thick, R1004 N45H, SuperMagnetMan) and the 3D-printed PLA hooks were connected to the wires using superglue (Gorilla Super Glue Gel).

Fabrication of the Soft Sensing Foams: A dispersion was prepared by first mixing a conductive polymer, poly (3,4-ethylenedioxythiophene): polystyrene (PEDOT:PSS, Heraeus Clevios, PH1000, 1.3 wt% of PEDOT:PSS) dispersion, with CNFs (sulfonated CNFs, 5 pass through microfluidizer, 1% solid content, DS elemental analysis 0.036, Invenntia AB), and DI water using a shear disperser (T 10 basic ULTRA-TURRAX) at speed 5 for 2 min. The crosslinker ((3-glycidyloxypropyl)trimethoxysilane, GOPS, Sigma-Aldrich, 98 wt%) was added to the solution according to the defined weight ratios, and the solution was mixed again using the disperser under the same conditions. The solution was placed in a centrifuge (Eppendorf SB804 R) at 1000 rpm for 1 min to remove the bubbles and was then dispensed into a PDMS mold, in which a piece of carbon paper (Toray Carbon Fiber Paper TGP-H-030) had been placed on the bottom of the mold. Another piece of carbon paper was placed on top of the solution to create robust, low-resistance contact pads for the conductive foams. The mold was immersed in liquid nitrogen, and the frozen solution was removed from the PDMS mold and placed in a freeze dryer (Benchtop Pro, SP Scientific) for 24 h. The resulting foam was baked in an oven at 105 °C for 2 h for crosslinking. To improve the electrical conductivity, the foam was placed in a closed glass crystallization dish with a few droplets of DMSO (dimethyl sulfoxide, Sigma-Aldrich, ReagentPlus, 99.5 wt%) in an oven at 80°C for 1 h, after which DMSO was removed from the foam in an oven at 90°C for 2 h. The carbon paper contacts were connected to 50 μm enameled copper wires for measurements using a conductive silver epoxy glue (MG Chemicals 8330S-21C), which was cured at 65°C for 2 h.

Fabrication and Assembly of the Full Devices: The soft electromagnetic actuator was fabricated according to the procedure above, with the exception that two pieces of carbon paper were glued to the hooks before being attached to the soft electromagnetic actuator ends. Each carbon paper was connected to a 50 μm enameled copper wire using silver epoxy glue (cured at 65 °C for 2 h). The actuator was wrapped in a thin plastic film (taped) and placed in a PDMS mold, after which the conductive foam solution was dispensed inside the actuator. The mold was immersed in liquid nitrogen, and the actuator with the frozen conductive core was removed from the mold (thick bottom, 13.5 mm diameter), and excess frozen solution was removed by peeling off the plastic film. The actuator was then placed in another mold with a thick bottom (13.5 mm diameter), and the insulating foam solution was dispensed on it. The mold was placed in liquid nitrogen to freeze the insulating layer, and the device was removed from the mold and put in the freeze dryer to form the foams. The device was then put in an oven at 105 °C for 2 h to crosslink the foam, after which it was placed in a closed glass crystallization dish with a few droplets of DMSO (Sigma-Aldrich, ReagentPlus, 99.5 wt%) in an oven at 80°C for 1 h. Absorbed DMSO was finally removed in an oven at 90°C for 2 h.

Characterization: Electromechanical characterization was conducted using a custom-made stress–strain–resistance setup consisting of a motorized stage (LSQ300A-E01, Zaber), a force gauge (MS-52 or MS-012, Mark-10), and a multimeter data acquisition system (Keithley 2701 Ethernet). Stress–strain compression and tensile measurements were carried out at a deformation rate of 10% strain s−1. A benchtop DC power supply (2230C-30-6, Keithley) was used for driving of the actuator. SEM images were obtained with a Sigma 500 Gemini (Zeiss). An environmental chamber (ETS 5532 Environmental Chamber, Electro-tech systems) was used as the controlled environment for testing the conductive cellulose-based sensing foams (10.5 mm diameter and 9.2 mm height) at different temperatures ranging from 23 to 45 °C at 30% relative humidity, while the resistance was measured using a multimeter (RS PRO IDM99IV). For testing the device in pulsing excitation mode, a computer-controlled source measurement unit (Keithley 2612B) was used to supply the actuator with the excitation current at 10 Hz while measuring the resistance from the sensing foam at 500 Hz.

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.

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artificial muscles, cellulose nanofibrils, conductive foams, soft electromagnetic actuators, soft robotics

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