

Stacked electrohydrodynamic pumps with densely perforated electrodes

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Abstract

While electrohydrodynamic (EHD) pumps are attractive for soft robotics owing to their simple, solid-state architecture, improving their performance remains a significant challenge. This study introduces a stackable pump featuring EHD layers with densely perforated electrodes integrated into a double-sided clad structure. The high hole density and integrated architecture enable enhanced electrohydrodynamic force generation while maintaining a lightweight structure. A systematic investigation of how the number of EHD layers, hole diameter, and porosity influence performance provides clear design guidelines and reveals that stacking increases both flow rate and pressure, with the pressure increasing almost linearly. Among the tested pumps, the maximum flow rate and pressure achieved are 2041.0 mL/min and 9.3 kPa, respectively. A five-layer pump weighing 0.64 g achieves the maximum power density, 55.0 W/kg (125.9 W/kg considering only the EHD layers), which represents a more-than-90-fold improvement over existing EHD pumps of similar type. Furthermore, the proposed pump successfully drives multiple soft actuators and a gripper, demonstrating its versatility and applicability to soft robotic systems.

Introduction

Electrohydrodynamic (EHD) interactions represent a physical phenomenon that involves an electric field, generated by creating a high voltage difference between electrodes submerged in a dielectric fluid, driving charge carriers within the fluid to induce flow.^{1–3} The origin of this driving force is the Coulomb force exerted by the electric field on the net space charge in the fluid, and its behavior has been described using theoretical models that couple governing equations related to fluid dynamics and electromagnetism.^{1,4,5} EHD pumps are electrically driven, structurally simple, size-scalable, and operate silently due to the absence of mechanical moving parts.^{3,5–7} Because of these features, EHD pumps constitute promising power sources for fluid-driven systems and have been extensively researched, particularly in the soft robotics field.^{8–17}

In soft robotics, improving the output performance of EHD pumps, typically measured by flow rate, pressure, power density, and efficiency, remains a significant challenge.^{3,9} Herein, the electrodes, including their geometry and structural configuration, are crucial for device performance. Accordingly, various electrode geometries, including needle, ring, planar, wire, mesh, and disk electrodes, have been investigated for EHD pumps.^{3,6,18–20} They have been arranged in configurations such as interdigitated patterns, needle-to-ring assemblies, triangular prism-to-slit pairs, and helical arrangements.^{3,6,11,21,22} These configurations affect pump performance.^{11,18,21,22}

Among these approaches, Tsukiji et al. introduced multiple through-holes into a pair of oppositely polarized planar electrodes arranged in parallel, with a dielectric layer sandwiched between them.^{23,24} In this configuration, the EHD phenomenon occurs at the edges of the through-holes through which the fluid passes. The configuration features a straightforward structure due to the uniform geometries of the electrodes and dielectric layer, while its planar architecture ensures high scalability in the planar

direction. Moreover, previous studies have indicated that increasing the number of holes enhances both flow rate and pressure by increasing the total edge perimeter, as well as by stacking electrode pairs in series.^{23,24}

However, in these studies focusing on this multi-hole electrode configuration, the electrodes and dielectric layer have been employed as independent components, which complicates their alignment and hinders efficient stacking. Furthermore, the number of holes per unit electrode area has remained limited to 2.9 per mm².²³ Additionally, since key structural parameters, such as hole diameter, number of holes, porosity, and number of stacked layers, are strongly coupled, practical design guidelines for this class of EHD pumps remain insufficient. Consequently, the maximum power density for this type of pump remains only 0.6 W/kg,²³ thereby leaving considerable room for improvement.

Here we present a stackable EHD pump with densely perforated electrodes, featuring an integrated electrode–dielectric architecture that affords a substantially higher hole density and enables reproducible planar stacking. This architecture provides a platform for systematically investigating how hole density, hole diameter, porosity, and stacking influence pump performance, while the lightweight and scalable structure supports high output performance (Fig. 1a,b). Figure 1c,d depict the proposed pump in operation upon voltage application (see also Supplementary Movie 1). Its structure facilitates stacking, as demonstrated in the five-layer configuration (Fig. 1b). This design features a pair of electrodes—which apply the potential difference—formed on both sides of a dielectric layer, enabling fabrication with high reproducibility and easy integration into a functional module with excellent planar scalability (Fig. 1e). Among the tested devices, a maximum power density of 55.0 W/kg was achieved, which corresponds to a more-than-90-fold improvement over previously reported EHD pumps of similar type.

Figure 1a illustrates the operating principle of the proposed pump. When it is filled with a dielectric fluid and a voltage is applied across the electrodes, electrons are stripped from the fluid molecules at the anode, which causes some molecules to acquire a net positive charge. Driven by the electric field, these positively charged molecules migrate toward the cathode, where they accept electrons to return to a neutral state. As this process occurs simultaneously at each electrode hole, the migrating charged molecules drag the surrounding neutral fluid molecules through viscous interactions, thereby generating a unidirectional flow. The flows thus produced in individual holes combine to create a bulk flow in a single direction. Alternatively, depending on the properties of the fluid, molecules may instead acquire electrons at the cathode to form negative ions and subsequently release the electrons at the anode. In this case, the direction of the resulting flow is reversed. Figure 1f–h demonstrate the fluid flow induced by voltage application while the pump is filled with a dielectric fluid (see also Supplementary Movie 1).

The objectives of this study were to experimentally investigate the fundamental performance of the proposed EHD pump, provide clear design guidelines for the developed architecture, and validate its effectiveness through demonstrations using soft robotic devices. Specifically, we systematically examined the influence of the design parameters, including the hole diameter, porosity, and number of

stacked layers, on the primary performance metrics of the pump, namely flow rate, pressure, and power consumption, which quantify its efficiency and power density.

Results

In the pumps fabricated and characterized in this study, the EHD layer consisted of a double-sided clad material composed of copper electrodes and a fiberglass (FR-4) dielectric substrate. Through etching and machining processes, the EHD layer was realized as a printed circuit board. The thickness of the dielectric layer, which defines the electrode gap for inducing the EHD phenomenon (d in Fig. 1a), was set to 0.3 mm. The thickness of each copper electrode was 18 μm . The active domain of the pump comprised a 10-mm-diameter electrode centered on a 12-mm-diameter dielectric layer. Identical electrode patterns were formed on both sides of the dielectric layer. In the stacked configurations, adjacent EHD layers were separated by a 1 mm gap. We prepared eight types of EHD layers for pump characterization, with the designs differing in terms of the hole diameter (0.15–0.6 mm), number of holes (74–1195, corresponding to 0.9–15.2 holes per mm^2), and porosity (3.1–50.0%). Supplementary Table 1 summarizes the design parameters (see also Supplementary Note 1 for the definition and calculation of porosity). The dielectric fluid used in the experiments was dibutyl adipate containing 0.2% polyvinyl chloride, which exhibited a conductivity of $61.0 \times 10^{-9} \text{ S/m}$, a relative permittivity of 5.23, and a viscosity of $5.67 \times 10^{-3} \text{ Pa}\cdot\text{s}$.²⁵ In total, 26 pump design conditions were investigated by combining eight types of EHD layers with varying numbers of stacked layers (Supplementary Table 1). Three independent samples were measured for each condition, resulting in 78 pump samples, and the reported performance values represent the mean and standard deviation of the three samples.

Figure 2a shows a typical response profile for a single-layer pump with 0.6 mm holes and 50.0% porosity at an applied voltage of 4 kV (13.3 kV/mm). Under this condition, the electric current was approximately 50 μA . The flow rate and pressure exhibited transient behavior before reaching a steady-state plateau. The response time for the flow rate, characterized by the time constant (i.e., the time required to reach 63.2% of the steady-state value after voltage application), was approximately 1 s. The output performance, specifically the flow rate and pressure, was evaluated using average values over a 10-s interval during the steady-state period.

The stability of the pump output during continuous operation was evaluated by continuously measuring the flow rate and pressure of three independent samples of the single-layer pump with 0.6 mm holes and 50.0% porosity for 3 h at an applied voltage of 4 kV (13.3 kV/mm). The mean flow rate for the 3-h period was $264.5 \pm 3.7 \text{ mL/min}$, and the mean pressure was $0.137 \pm 0.015 \text{ kPa}$. Within each sample, the standard deviations of the flow rate and pressure over 3 h were $6.3 \pm 1.5 \text{ mL/min}$ (coefficient of variation: $2.4 \pm 0.6\%$) and $0.014 \pm 0.002 \text{ kPa}$ (coefficient of variation: $10.6 \pm 1.5\%$), respectively. Additionally, short-term fluctuations after removing slow variation were $1.1 \pm 0.2 \text{ mL/min}$ and $0.0073 \pm 0.0002 \text{ kPa}$, respectively. All values are presented as the mean $\pm$ standard deviation of the three samples. No abrupt drop or failure was observed in any sample. Supplementary Fig. 1 displays detailed time-series data.

We first investigated the effect of the number of stacked EHD layers on the output performance of pumps with 0.6 mm holes and 50.0% porosity. The applied voltage was systematically varied from 1 to 5 kV in 1-kV increments. With the electrode gap set at 0.3 mm, these voltages corresponded to electric field intensities of 3.3, 6.7, 10.0, 13.3, and 16.7 kV/mm, respectively. The tested pumps exhibited voltage-controllable output, with both the flow rate and pressure increasing with the applied voltage (Fig. 2b,c). Furthermore, at all applied voltages, the pressure increased almost linearly with the number of stacked layers, and the flow rate also rose.

Next, we evaluated the influence of hole diameter and porosity on pump performance. When the number of holes was fixed at 139 in the five-layer pumps, the flow rate increased with the hole diameter (Fig. 3a), whereas the pressure increased as the hole diameter decreased (Fig. 3b). Similarly, when the porosity was fixed at approximately 26% and 36%, the flow rate increased with the hole diameter (Fig. 3c), while the pressure exhibited the opposite trend (Fig. 3d). For single-layer pumps, where the differences were relatively small, the flow rate increased from 181.2 ± 14.4 mL/min for 0.3 mm holes to 213.7 ± 8.6 mL/min for 0.6 mm holes at 26% porosity, and from 237.7 ± 11.6 mL/min to 258.8 ± 12.6 mL/min at 36% porosity. Furthermore, when the number of stacked layers increased to two, the enhancement in the flow rate became more pronounced for larger hole diameters. Regarding porosity, when the hole diameter was fixed at 0.6 mm, 0.3 mm, or 0.15 mm, the flow rate increased with porosity, corresponding to an increase in the number of holes and parallel flow paths (Fig. 3e). In contrast, the pressure was generally less sensitive to porosity-related changes than the flow rate for a given hole diameter and number of layers, primarily determined by the hole diameter (Fig. 3f). Among the tested pumps, the maximum flow rate of 2041.0 ± 72.4 mL/min was achieved by the five-layer pump with 0.6 mm holes and 50.0% porosity at 5 kV (16.7 kV/mm), while the maximum pressure of 9.3 ± 0.1 kPa was attained by the five-layer pump with 0.15 mm holes and 3.1% porosity at the same voltage. The reported uncertainties (e.g., ± 72.4 mL/min and ± 0.1 kPa) represent the standard deviation among the three independent samples.

Subsequently, we evaluated the power consumption and efficiency, which are important metrics for assessing pump performance. Power consumption was calculated from the electric current measured during the experiments (Fig. 2a), with the efficiency being determined based on the calculated hydraulic power and power consumption. Specifically, the hydraulic power is defined as one quarter of the product of flow rate and pressure.⁸

Figure 4 shows the power consumption as a function of the flow rate and pressure. In all the tested pumps, both the output and power consumption increased with the applied voltage. For the pumps with approximately 26% porosity (Fig. 4a,b), the flow rate and pressure generally increased with the number of stacked layers, accompanied by an increase in the power consumption. For the five-layer pump with 0.6 mm holes and 50.0% porosity at 5 kV (16.7 kV/mm), the power consumption was 3.8 ± 0.1 W at the highest recorded flow rate of 2041.0 ± 72.4 mL/min (Fig. 4c). Under similar driving conditions, the maximum power consumption recorded was 4.0 ± 0.1 W, achieved at a pressure of 4.2 ± 0.1 kPa (Fig. 4d). The efficiency was calculated to be 3.6% based on the flow rate, pressure, and average power consumption values. Moreover, for the five-layer pump with 0.15 mm holes and 3.1% porosity, the

highest recorded pressure was 9.3 ± 0.1 kPa. Additionally, the power consumption was 0.7 ± 0.04 W, corresponding to an efficiency of 1.9% (Fig. 4d). The flow rate of this pump at 1 kV (3.3 kV/mm) was below the detection limit of the flow sensor and is therefore not shown in Fig. 4c.

Finally, we assessed the power density of the pumps, defined as the hydraulic power divided by the device mass. The maximum power density was 55.0 W/kg, derived from a flow rate of 2041.0 ± 72.4 mL/min, a pressure of 4.2 ± 0.1 kPa, and a mass of 0.64 g (including the EHD layers and case components) for the five-layer pump with 0.6 mm holes and 50.0% porosity. This maximum power density corresponded to approximately 91.7 times the 0.6 W/kg of a previously reported EHD pump of a similar type using multi-hole electrodes.²³ The power density achieved in this study was also higher than those of most other EHD pumps reported for soft robotics (Supplementary Table 2).

To demonstrate its applicability to soft robotic devices, we integrated the proposed pump, specifically in the five-layer configuration with 0.15 mm holes and 26.6% porosity, into two types of soft actuators—McKibben artificial muscles and fluidic elastomer actuators—and characterized their performance. The pump and actuator were both filled with the dielectric fluid, while one end of the pump was connected to a reservoir. Activation of the pump moved the fluid into the actuator, thereby triggering deformation. As seen in Fig. 5a, 5c, and 5e, the pump could be directly connected to the actuators to enable their operation. The EHD-driven McKibben artificial muscle generated $15.9\% \pm 0.6\%$ of contraction strain and 5.0 ± 0.1 N of force at an applied voltage of 5 kV (16.7 kV/mm) (Fig. 5b, see also Supplementary Movie 2). Under the same driving condition, the EHD-driven fluidic elastomer actuator produced $87.9^\circ \pm 4.2^\circ$ of bending deformation and 1.4 ± 0.7 N of force (Fig. 5d, see also Supplementary Movie 3). When the two actuators were combined, the generated actuation was sufficient for grasping and holding spherical objects (mass 5.0 g) as well as cubic objects (mass 5.6 g), as depicted in Fig. 5e (see also Supplementary Movies 4 and 5).

Discussion

The nearly linear increase in pressure with the number of stacked layers (Fig. 2c) can be attributed to the series connection of the layers, where the pressure from each EHD layer accumulates in the stacking direction.^{3,23} The flow rate also increased with the number of stacked layers (Fig. 2b). In a steady flow, the mean flow velocity is uniform across all layers due to mass conservation. Therefore, each layer increases pressure instead of accelerating the fluid successively. Since the flow rate was measured against the finite flow resistance of the test setup, including the tubing and flow sensor, the higher total pressure of the stacked layers drives a larger flow through this resistance. With more layers, the internal flow resistance of the stacked structure is expected to become dominant, leading to a saturation in flow rate despite rising pressure. Consistent with this interpretation, a multi-hole pump featuring square electrodes (10 mm $\times$ 10 mm) and 0.3 mm holes (porosity 38%) showed nearly identical flow rates for 10, 20, and 30 layers, whereas the pressure increased approximately linearly with the number of layers (Supplementary Fig. 2). Therefore, the flow-rate increase observed in Fig. 2b is attributed to the series addition of pressure acting against the flow resistance of the setup. Practical loads such as soft

actuators and fluidic channels have finite flow resistance, making stacking effective for boosting pressure and flow rate in applications.

The flow rate and pressure of the tested pumps increased with the applied voltage (Figs. 2b,c and 3a,b), which can be attributed to the heightened Coulomb force acting on the charge carriers in the fluid as the electric field intensity increased. The systematic investigation of hole diameter and porosity yielded clear design guidelines for the proposed pump. The increase in pressure with decreasing hole diameter (Fig. 3b,d) can be ascribed to the EHD phenomenon mainly at the hole edges. As the hole diameter decreased, the ratio of edge perimeter to cross-sectional area for fluid flow increased, resulting in a greater Coulomb force per unit flow area. However, a smaller hole diameter also increased the flow resistance, thus reducing the flow rate (Fig. 3a,c). These results indicated a trade-off between pressure and flow rate. An increase in porosity, which corresponds to an increase in the number of holes, is analogous to a parallel connection of pump elements. In such a configuration, increasing the number of parallel flow paths increases the total flow rate, whereas the pressure generated by the individual pump elements does not accumulate as it does in a series connection.³ Therefore, the flow rate increased with porosity, whereas the pressure was generally less sensitive to porosity and was determined mainly by the hole diameter. This is because the ratio of the edge perimeter to the cross-sectional area of each hole does not depend on the number of holes. This interpretation is consistent with the experimental observations (Fig. 3e,f). These findings inform device-specific design strategies: the hole diameter should be reduced for high-pressure applications (e.g., powerful soft actuators with relatively slow motion), while both the hole diameter and porosity should be increased for high-flow-rate applications (e.g., rapid soft actuators requiring modest force).

Furthermore, the pump design parameters affected not only the flow rate and pressure but also the power consumption (Fig. 4). In Fig. 4a,b, which compare pumps with a porosity of approximately 26%, the power consumption required to achieve a given flow rate and pressure varied depending on the hole diameter and number of stacked layers. In Fig. 4c,d, comparing five-layer pumps with 139 holes, the flow rate increased with increasing hole diameter, corresponding to an increase in porosity, while the power consumption also tended to increase. In contrast, smaller hole diameters enabled the generation of higher pressure with relatively lower power consumption. This can be attributed to the larger ratio of the edge perimeter to the cross-sectional area of each hole as the hole diameter decreases, which increases the Coulomb force acting per unit flow area, as described above.

However, the magnitude of power consumption alone is insufficient to evaluate energy efficiency. The ratio of hydraulic power to electrical power consumption must also be considered. For example, the five-layer pump with 0.6 mm holes and 50.0% porosity achieved the maximum flow rate with an efficiency of 3.6%. In contrast, the five-layer pump with 0.15 mm holes and 3.1% porosity, which achieved the maximum pressure, consumed less than one-fifth of the power of the former but exhibited a lower efficiency (1.9%). Thus, a lower power consumption does not necessarily lead to a higher energy efficiency. Rather, the efficiency depends on how much hydraulic power is obtained for a given electrical input. Therefore, in pump design, the hole diameter, porosity, and number of stacked layers should not be

individually minimized or maximized. Rather, they should be selected according to the flow rate and pressure required for the target application while balancing the electrical input with the hydraulic output. Since these parameters vary simultaneously in some of the tested conditions, their individual effects on energy efficiency cannot be completely isolated.

Furthermore, the maximum efficiency (3.6%) of the proposed pump is comparable to or higher than the previously reported values for EHD pumps, which range from 0.6% to 2.3%.^{8,12,18,26,27} Additionally, the power density of 55.0 W/kg achieved by the pump is over 90 times that of a previously reported EHD pump of similar type using multi-hole electrodes (0.6 W/kg).²³ In the broader context of EHD pumps for soft robotics, power density values collected from the literature generally range from 0.4 W/kg to 15.2 W/kg,^{8,9,12–15,28,29} although an exceptionally high value of 347 W/kg has recently been reported²⁶ (see Supplementary Table 2 for details). Within this broader context, the proposed pump lies toward the higher end of the reported power-density range.

The high performance of the proposed pump is attributable to the combination of high hole density, lightweight integrated architecture, and scalable stacking. The high power density results not only from the increased hydraulic output but also from the realization of this output with low device mass. In the present pump, the large number of through-holes increases the total edge perimeter per unit electrode area, allowing the EHD force generated near the electrodes to drive the fluid over a wider area. In this study, a maximum hole density of 15.2 holes/mm² was achieved, which is substantially higher than the 2.9 holes/mm² of previous multi-hole EHD pumps of similar type.²³ This high hole density is considered to contribute to the high hydraulic output. Furthermore, integrating the electrodes and dielectric layer into a double-sided clad structure reduced the structural mass compared to assembling them separately. In addition, stacking increased the hydraulic output, whereas the mass per layer, including the case components, was only 0.13–0.16 g, which limited the stacking-related mass increase. Therefore, the high power density achieved in this study may be due to the combination of enhanced hydraulic output through high hole density, reduced mass through the double-sided clad architecture, and increased output through stacking.

The response time of approximately 1 s, estimated from the flow rate time constant in Fig. 2a, reflects the dynamic characteristics of the present pump with the dielectric fluid used in this study and aligns with the range reported for recent EHD pumps (0.2–1.4 s).¹⁴ Fluid selection could further enhance the response due to the dependence of these characteristics on the fluid. Cacucciolo et al. reported that, when FC-40 was used, the pump response was a major factor limiting the response time of a system combining an EHD pump with a thin McKibben actuator.¹⁷ Shimizu et al. showed that adding 0.2% polyvinyl chloride to dibutyl adipate increased the response speeds of the flow rate and pressure of an EHD pump by 115% and 51%, respectively.²⁵ Zhu et al. compared EHD-driven soft linear actuators with HFE7100, linalyl acetate, and dibutyl sebacate. Additionally, they reported that a fluid with high permittivity and low viscosity generated a stronger flow, with the actuator using HFE7100 responding within approximately 0.6 s.¹⁶ Moreover, Luo et al. demonstrated that the pressure, flow rate, and

hydraulic power of EHD pumps strongly depend on the viscosity and permittivity of the fluid.²⁶ Therefore, selecting a fluid with appropriate permittivity and viscosity is a promising approach for improving the response speed.³ Additionally, optimizing the fluidic structure—such as fluid volume in the flow path and flow resistance—can lead to further improvements.

Finally, the successful implementations of the EHD-driven McKibben artificial muscles and fluidic elastomer actuators, as well as the soft gripper, demonstrate the versatility and practicability of the proposed pump architecture.

Future work will focus on more in-depth characterization of the proposed pump in terms of scalability, particularly in the planar direction, long-term operational stability, and performance under various environmental conditions. Although the 3-h continuous-operation test confirmed stable pump output under the tested conditions, it does not establish the ultimate service lifetime or long-term durability of the pump. Therefore, extended-duration and cyclic lifetime tests will be conducted to assess its durability.^{3,5} In parallel, design optimization will be pursued to improve performance, especially with respect to the dielectric layer thickness and the gap between adjacent EHD layers, which were fixed herein. Analytical and numerical models incorporating these parameters are expected to guide systematic optimization.³ Additionally, given a recent report that propylene carbonate (relative permittivity 64) substantially enhances EHD pump output,²⁶ we will explore the use of high-permittivity dielectric fluids in the present pump architecture, which may afford further improvements in output performance compared with dibutyl adipate containing 0.2% polyvinyl chloride (relative permittivity 5.23)²⁵ used in this study. These efforts will facilitate the development of EHD-driven soft robotic systems across diverse size scales.

Methods

Fabrication of pumps

The case and connectors were designed using CAD software (Fusion 360, Autodesk) and fabricated using a 3D printer (Form 3, Formlabs). The material used was an ultraviolet (UV)-curable resin (High Temp Resin V2, Formlabs). After printing, the mating interfaces between the case components and the slits through which the terminals of the EHD layers pass were coated with the same liquid resin (High Temp Resin V2, Formlabs) used to fabricate the components. Before the applied resin was cured, the EHD layers were inserted into the slits of one case component, and the matching case half was assembled to form a temporary structure. Subsequently, a tin-plated wire with a diameter of 0.32 mm was passed through the through-holes of the exposed EHD layer terminals and soldered to establish the electrical connections. Finally, the liquid resin was applied to the connector interfaces at both ends of the case, and the connectors were attached. With all components assembled, a secondary curing process was performed using a UV curing unit (Form Cure, Formlabs) at 80°C for 15 min. During this

process, the uncured resin used as an adhesive and the printed components were co-cured into a single integrated structure, which yielded a fully sealed and mechanically robust pump.

Experimental setup

The setup for characterizing the pumps was identical to that employed in our previous study.¹⁵ It included a reservoir, a flow sensor (FD-XA1 controller with an FD-XS20 sensor head and an FD-XC20R4 clamp set, Keyence), a pressure sensor (ADP5130, Panasonic), and a clamp. The clamp was fabricated from a UV-curable resin (Clear Resin V4, Formlabs) using a 3D printer (Form 3, Formlabs). It was designed to occlude the flow path by compressing the silicone tube between two flat plates tightened with a screw. Silicone tubing (10 mm inner diameter, 13 mm outer diameter) was used to create the flow path, which was entirely filled with the dielectric fluid, namely dibutyl adipate, containing 0.2% polyvinyl chloride. The pump was driven by an amplifier power module (HOPP-10P(A), Matsusada Precision) and a four-channel power supply (PMX32-2QU, Kikusui Electronics). The flow rate and pressure were recorded using a multimeter (Model 2100, Keithley Instruments). During operation, the applied voltage was measured at the voltage monitor terminal of the four-channel power supply, while the electric current was measured using a non-contact clamp-type weak current sensor (HDCC-3mA-D1, Picsor). This non-contact current sensor was employed to avoid potential damage to the measurement equipment during an electrical discharge. The applied voltage and electric current were recorded using the multimeter. Both the four-channel power supply and the multimeter communicated with a PC using the VISA standard, with a program controlling the power supply and recording the data. The sampling rate was set to 100 Hz for the flow rate and pressure measurements. The sensor specifications were as follows: flow sensor (rated range: 0–20.00 L/min; repeatability: ± 20 mL/min at a response time of 50 ms), pressure sensor (rated pressure: 50 kPa; overall accuracy: $\pm 1.25\%$ F.S.), and current sensor (range: 0–3 mA; accuracy: $\pm 3\%$ F.S.; linearity: $<0.3\%$). Since the specified full-scale accuracies of the pressure and current sensors include their offset voltages, which were removed by the zero-referencing described below, the effective measurement uncertainty was smaller than these values.

Flow rate measurement

First, the reservoir and flow path were filled with the fluid, and as many bubbles as possible were removed. Next, the power supply was connected to the pump, and the program was initiated. Before voltage application, a 5-s offset period was recorded without voltage, and the average values during this period served as the zero references. The zero-referenced flow rate, pressure, applied voltage, and electric current were obtained by subtracting the corresponding offset values from the subsequent measured values. After the offset period, a high voltage was applied for 20 s, and the measurement was terminated 5 s after the end of the voltage application. The tested voltage range was 1–5 kV with 1-kV increments. For each sample and applied voltage, the 20-s voltage application was repeated three times, and the average of the three measurements was taken as the representative value for that sample. The reported value for each pump design condition and applied voltage was then calculated as the mean and

standard deviation of representative values obtained from three independent samples. No feedback control of the flow rate was applied; the pump operated at constant applied voltages.

Pressure measurement

First, the reservoir and flow path were filled with the fluid, and as many bubbles as possible were removed. Next, the clamp was attached, and the flow rate was confirmed to be zero based on the flow sensor display. The power supply was then connected to the pump, and the program was initiated. Before voltage application, a 5-s offset period was recorded without voltage, and the average values during this period were used as the zero references. The zero-referenced flow rate, pressure, applied voltage, and electric current were obtained by subtracting the corresponding offset values from the subsequent measured values. After the offset period, a high voltage was applied for 20 s, and the measurement was terminated 5 s after the end of the voltage application. The tested voltage range was 1–5 kV with 1-kV increments. For each sample and applied voltage, the 20-s voltage application was repeated three times, and the average of the three measurements was taken as the representative value for that sample. The reported value for each pump design condition and applied voltage was calculated as the mean and standard deviation of representative values obtained from three independent samples.

Continuous-operation measurement

To evaluate the stability of the pump output during continuous operation, a single-layer pump with 0.6 mm holes and 50.0% porosity was continuously operated for 10,800 s (3 h) at an applied voltage of 4 kV (13.3 kV/mm). Three independent samples were tested for the flow rate and pressure. Except for the measurement duration, applied voltage, and sampling rate, the measurement procedure was identical to that described for the flow rate and pressure measurements. The flow rate and pressure were recorded at a sampling rate of 1 Hz to minimize processing delays during continuous data saving and prevent data loss. For each sample, the mean and standard deviation were calculated excluding the first 60 s after voltage application. Additionally, the short-term fluctuation was evaluated as the standard deviation of the residuals after subtracting a centered 2-min moving average.

Fabrication of EHD-driven McKibben artificial muscles

The actuator consisted of a silicone tube made from silicone rubber (Ecoflex 00–30, Smooth-On) and a braided nylon sleeve (NFL-19, Denka-Electron). The silicone tube was mold-casted to have an outer diameter of 15 mm, a wall thickness of 1.5 mm, and a length of 50 mm. Before casting, a release agent (000122, ICHINEN CHEMICALS) was applied to the mold. The liquid silicone, prepared by mixing Part A and Part B in a mass ratio of 1:1, was poured into the mold and then cured in an oven at 50°C for 40 min. Subsequently, the mold was separated to obtain the silicone tube. All molds were designed using CAD software (Fusion 360, Autodesk) and fabricated using a 3D printer (A1 mini, Bambu Lab) with polylactic acid (PLA) filament (PLA Basic, Bambu Lab). The EHD pump and the end cap were then inserted into the

two ends of the tube and fixed using silicone adhesive (TSE387-C, Momentive). The end cap was fabricated from a UV-curable resin (Clear Resin V4, Formlabs) using a 3D printer (Form 3, Formlabs). The tube was then covered with the braided nylon sleeve, and both its ends were secured with cable ties (AB100-S-100, HellermannTyton).

Fabrication of EHD-driven fluidic elastomer actuators

The actuator consisted of a chamber part filled with fluid and a bottom part functioning as a strain-limiting layer. The chamber and bottom parts were fabricated separately via mold-casting. The molds were designed using CAD software (Fusion 360, Autodesk) and fabricated using a 3D printer (A1 mini, Bambu Lab) with PLA filament (PLA Basic, Bambu Lab). After fabrication, a release agent (000122, ICHINEN CHEMICALS) was applied to the molds. Thereafter, liquid silicone (Ecoflex 00–30, Smooth-On), prepared by mixing Part A and Part B in a mass ratio of 1:1, was poured into both molds and then cured in an oven at 50°C for 40 min. After curing, a thin layer of the liquid silicone was applied to the upper surface of the bottom part, and the chamber part, removed from its mold, was bonded onto it. A silicone tube (inner diameter 10 mm, outer diameter 13 mm) was attached to the rear of the chamber part, with additional silicone being applied and cured to ensure sealing. Finally, the EHD pump was connected to the silicone tube.

Evaluation of soft actuators

The actuator was connected to a reservoir via silicone tubing. By supplying the dielectric fluid to the reservoir, both the pump and the actuator were filled with the fluid. The same equipment used for the pump characterization was employed to apply voltage to the EHD pump, which ranged from 0 to 5 kV in increments of 0.5 kV. For both the EHD-driven McKibben artificial muscles and fluidic elastomer actuators, the deformation under the applied voltage was recorded using a camera (Z5, Nikon) before being extracted using image analysis software (Photron FASTCAM Viewer 4 and Photron FASTCAM Analysis, Photron). The deformation was quantified as the displacement of the actuator with respect to its initial state (without any applied voltage). The blocked force of the actuators was measured by fixing the probe of a load cell (LSB200, FUTEK) to the actuator tip; it was also recorded as a relative value with respect to the initial state (without any applied voltage). Each measurement was performed for three samples, and the average value was calculated.

Demonstration of object grasping

Two EHD-driven fluidic elastomer actuators were used to construct a gripper, with each actuator being connected to an individual reservoir. The actuators were arranged such that their bottom parts connected to each reservoir faced each other. A voltage of 3 kV (10.0 kV/mm) was applied to both actuators, and the bending motion generated by the actuators was used to grasp spherical and cubic objects, which were fabricated with PLA filament (PLA Basic, Bambu Lab) using a 3D printer (A1 mini, Bambu Lab).

Use of AI tools

ChatGPT (version 5.4, OpenAI) was used solely for language editing support during manuscript preparation. All scientific content preparation, data interpretation, and writing were independently performed by the authors. All AI-assisted outputs were thoroughly reviewed and verified by the authors.

Data availability

All data needed to evaluate the conclusions presented in this paper are included in the article and/or Supplementary Information. The raw data are available from the corresponding author upon reasonable request.

Declarations

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Author Contributions

AF, YS, NO, HA, and JS conceived the main idea. AF and SF designed and fabricated the pumps. AF, SF, YK, and AMRA designed and fabricated the EHD-driven soft actuators. AF, SF, YK, AMRA, YS, NO, HA, and JS designed the experiments. AF, YK, AMRA, and YS conducted the experiments and analyzed the data. AF and JS created and edited the figures and media files. AF wrote the manuscript. YS, NO, HA, and JS supervised the project. JS edited the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no conflict of interest.

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Figures

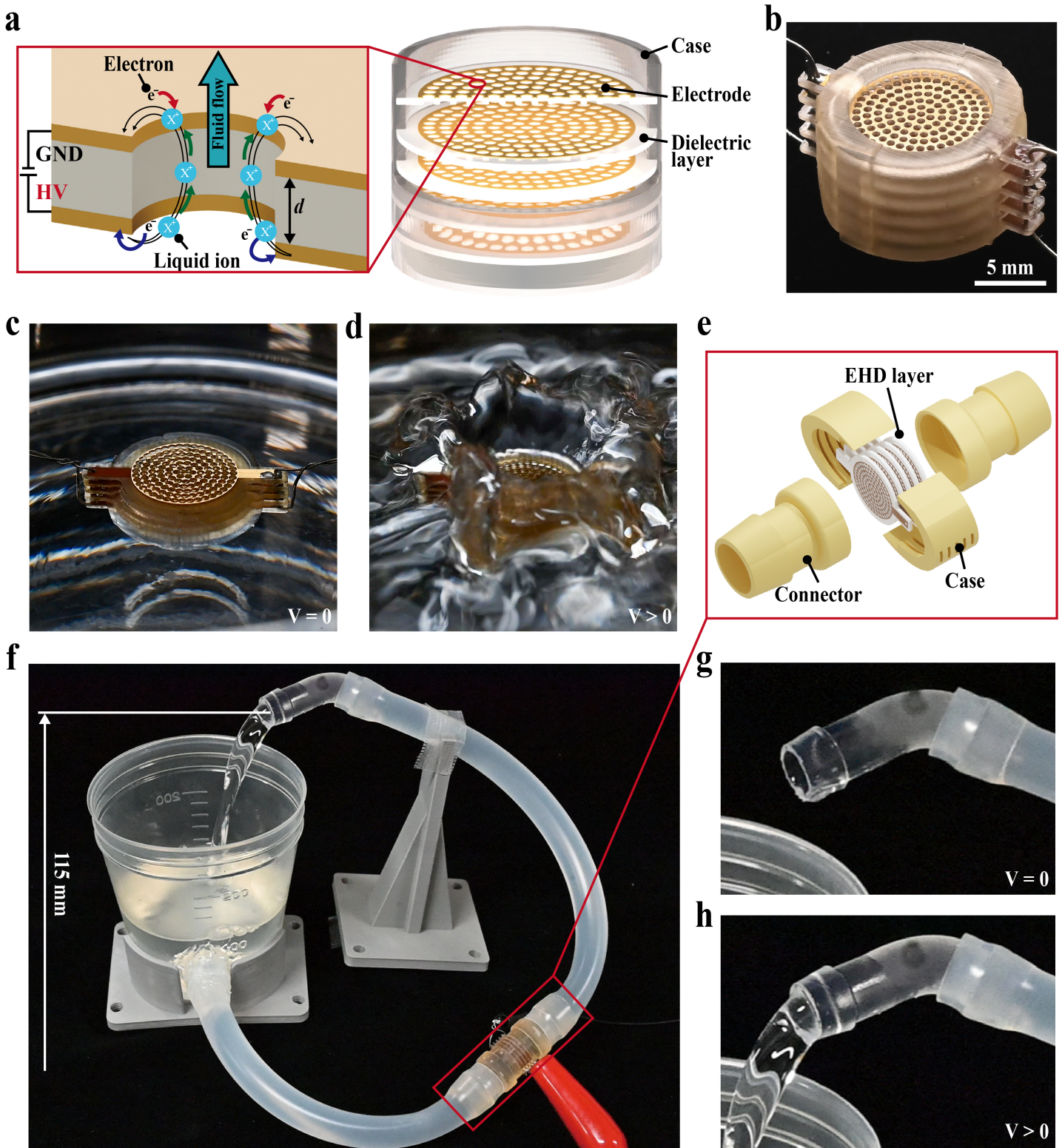


Figure 1

Overview of developed pump. **a** Working principle of the pump, where d denotes the electrode gap, corresponding to the thickness of the dielectric layer. **b** Fabricated pump containing five EHD layers. **c, d** Set of five EHD layers immersed in a dielectric fluid under **c** no voltage and **d** an applied voltage. **e** Structure of pump comprising EHD layers, case components, and connectors. **f** Setup demonstrating fluid circulation driven by developed pump. **g, h** Outlet flow under **g** no voltage and **h** an applied voltage.

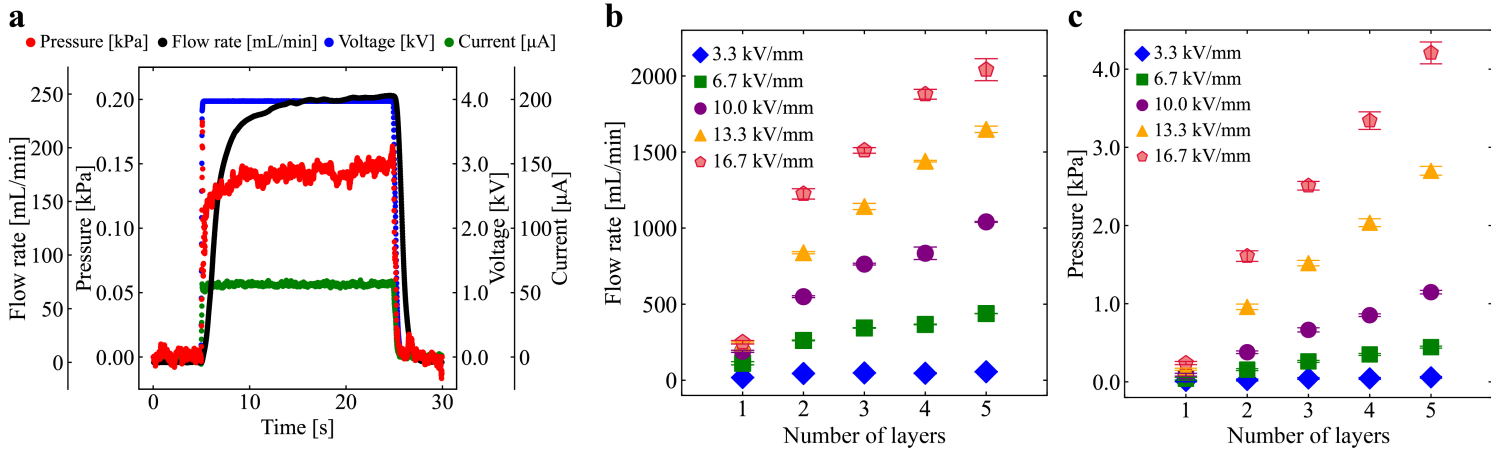


Figure 2

Output performance of proposed pump with 0.6 mm holes and 50.0% porosity. a Typical response profile of single-layer pump, showing flow rate, pressure, applied voltage, and current as a function of time. **b** Measured flow rate as a function of the number of stacked layers under different applied electric fields. **c** Measured pressure as a function of the number of stacked layers under different applied electric fields.

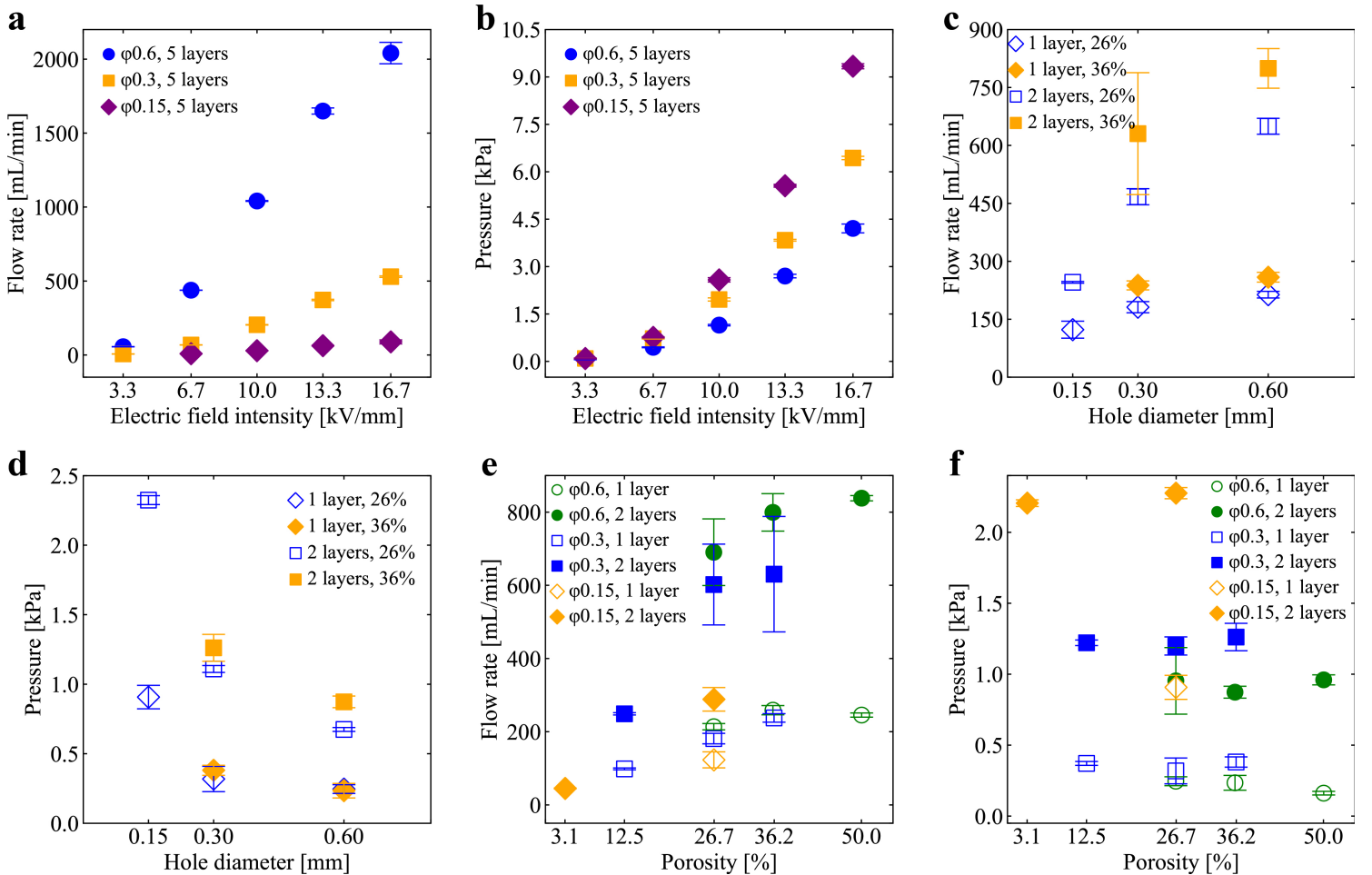


Figure 3

Pump design parameters and measured output performance. **a** Flow rate as a function of electric field intensity for five-layer pumps with 139 holes. **b** Pressure as a function of electric field intensity for five-layer pumps with 139 holes. **c** Flow rate as a function of hole diameter for single- and two-layer pumps with porosities of approximately 26% and 36%. **d** Pressure as a function of hole diameter for single- and two-layer pumps with porosities of approximately 26% and 36%. **e** Flow rate as a function of porosity for single- and two-layer pumps. **f** Pressure as a function of porosity for single- and two-layer pumps.

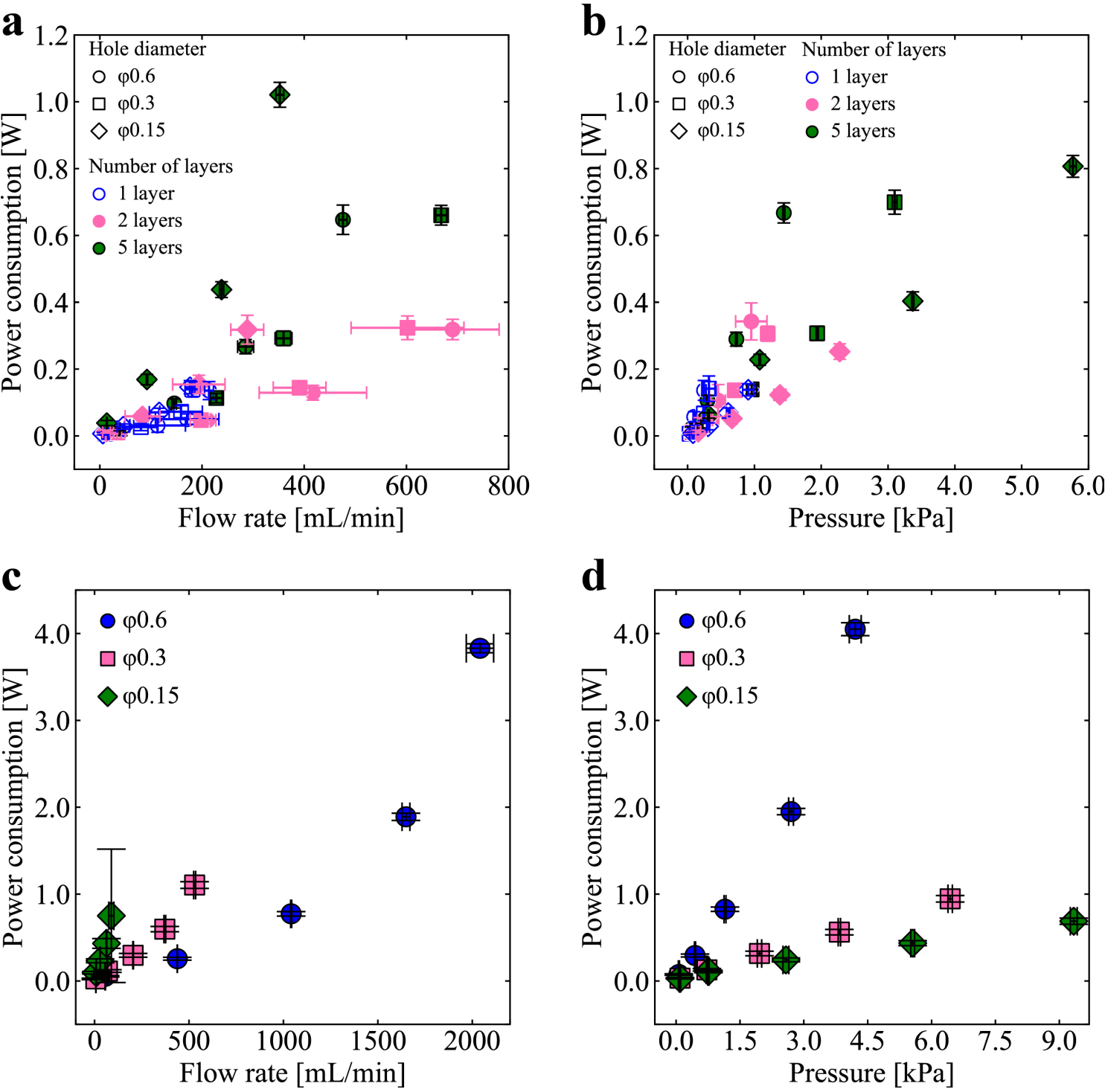


Figure 4

Power consumption of the pumps. **a** Power consumption as a function of flow rate for single-, two-, and five-layer pumps with three hole diameters at approximately 26% porosity. **b** Power consumption as a function of pressure for the same pumps as in **a**. **c** Power consumption as a function of flow rate for five-layer pumps with 139 holes and three hole diameters (0.6, 0.3, and 0.15 mm, corresponding to porosities of 50.0%, 12.5%, and 3.1%, respectively). **d** Power consumption as a function of pressure for the same pumps as in **c**. Each data point corresponds to an applied electric field of 3.3–16.7 kV/mm (1–5 kV), and error bars represent the standard deviations of three samples.

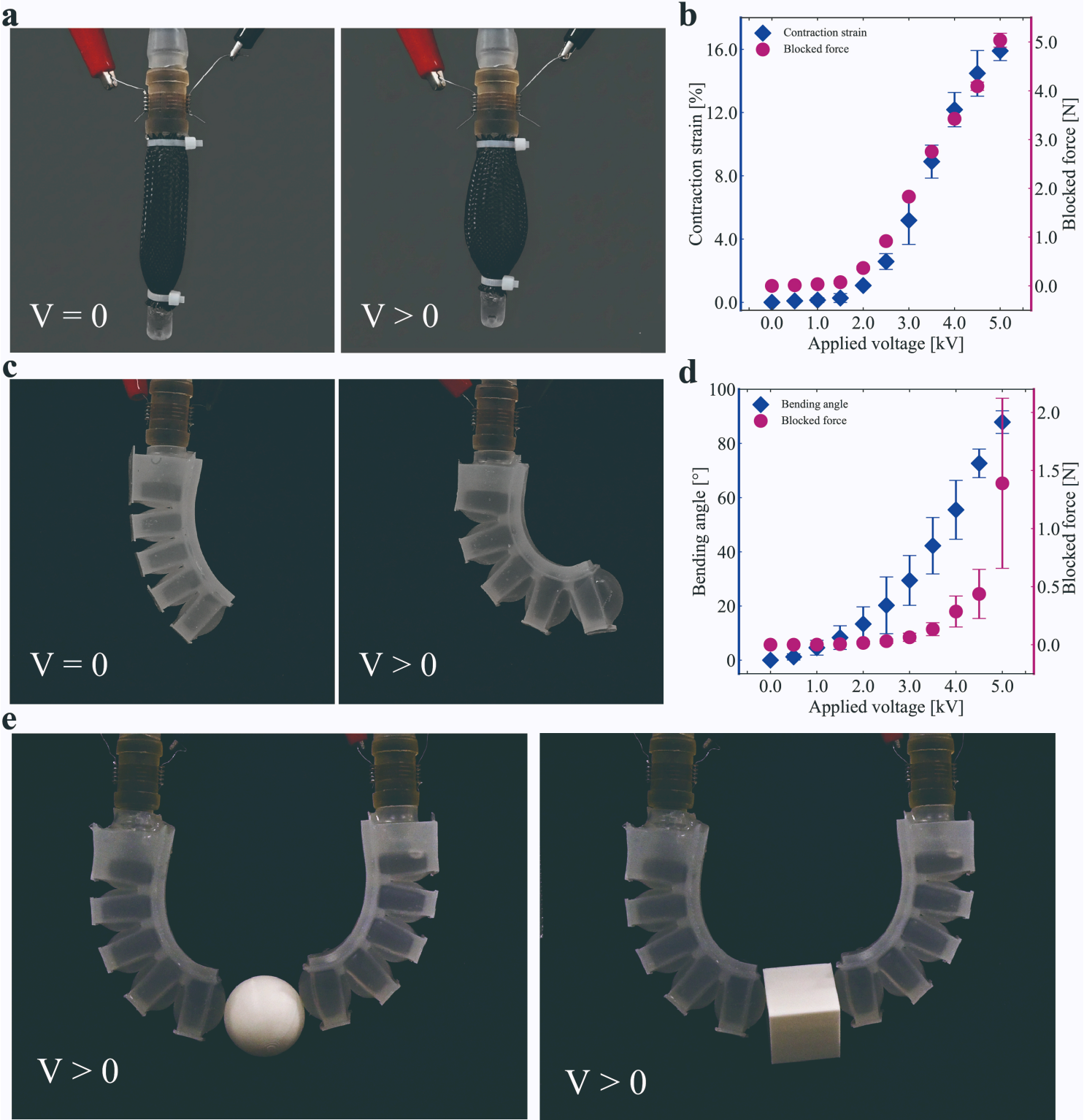


Figure 5

Soft actuators driven by proposed pump. a EHD-driven McKibben artificial muscle in its initial state ($V = 0$) and under an applied voltage of 5 kV. **b** Contraction strain and force of EHD-McKibben artificial muscle as functions of applied voltage. **c** EHD-driven fluidic elastomer actuator in its initial state ($V = 0$) and under an applied voltage of 5 kV. **d** Bending angle and force of EHD-driven fluidic elastomer actuator as functions of applied voltage. **e** Gripping and holding of a spherical object and a cubic object (5 kV).

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