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Development of multi-degree-of-freedom tubular IPMC actuators with symmetric electrode architecture via a precision 3D-printed segmentation system

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Abstract

While tubular ionic polymer-metal composite actuators offer advantages for multi-DOF applications, they remain susceptible to technical challenges, including asymmetric metallization and rapid moisture loss in ambient environments. This study presents a fabrication approach designed to address these limitations. By optimizing the electroless plating process, uniform platinum electrode layers ($t \approx 30\text{--}40\text{ }\mu\text{m}$) were formed on both internal and external surfaces, encapsulating the ionomer core to help reduce dehydration rates. To maintain structural precision, a custom 3D-printed segmentation guide and a modular electrical holder were used to facilitate four-quadrant partitioning and stable interfacing. Characterization showed that the tubular geometry—specifically the 0.8 mm diameter model—exhibited improved moisture retention compared to standard strip-shaped counterparts. Electrochemical impedance spectroscopy across 10 pathways indicated that the high-frequency bulk ohmic resistance converged to a consistent baseline ($R_b \approx 35.0\text{ }\Omega$), while low-frequency responses reflected the geometric distinction between radial Core-to-Segment channels and circumferential Segment-to-Segment paths. The fabricated actuators exhibit stable electromechanical performance in both underwater and ambient-air environments, achieving a tip deflection angle of approximately 14° at 5 V. Furthermore, the proposed platform maintains active actuation over a 120 min exposure period under ambient conditions, supporting its potential utility for soft robotic applications operating in variable environments.

1. Introduction

Electroactive polymers (EAPs), often termed ‘artificial muscles,’ have attracted extensive interest due to their unique capacity for electromechanical energy conversion with biomimetic agility. Among various EAPs, ionic polymer-metal composites (IPMCs) stand out for their low operational voltage (typically $<5\text{ V}$), lightweight nature, and remarkable performance in aqueous environments [1–4]. These unique attributes have enabled the development of diverse soft mechatronic systems, ranging from bio-inspired aquatic robots to advanced surgical instruments [5–9]. Currently, the research focus has shifted toward the miniaturization of IPMCs, seeking to optimize their geometry for high-precision tasks such as active catheter steering and microfluidic manipulation [10–12]. In particular, slender and tubular IPMC configurations are emerging as a vital architecture for multi-degree-of-freedom (multi-DOF) actuation in minimally invasive medicine. As clinical procedures move toward ultra-narrow vascular environments, such as the cerebral arteries, the need for sub-millimeter actuators ($<1.0\text{ mm}$) has become a critical necessity [10, 13, 14]. By offering a degree of mechanical compliance that rigid systems cannot match, tubular IPMCs facilitate safer navigation through delicate biological environments, ensuring that both maneuverability and patient safety are maintained during complex procedures [11].

While extrusion remains the standard for fabricating slender IPMC architectures, the resulting tubular actuators continue to grapple with operational hurdles that impede their practical utility. A primary technical bottleneck involves the poor precision of electrode segmentation; traditional techniques, such as manual surface milling, frequently introduce geometric inaccuracies and parasitic electrical coupling, ultimately leading to asymmetric actuation. Beyond fabrication tolerances, conventional tubular designs are prone to rapid dehydration during open-air operation [15, 16]. This accelerated moisture loss stems from a structural deficiency where metallization is confined to the outer surface, leaving the internal core vulnerable. Challenges such as capillary forces and entrapped air bubbles during the plating process often prevent the formation of a necessary internal barrier [11]. Without such a metallic shield to suppress water vapor transmission, achieving stable, long-term 3D maneuvering in open-air environments remains a challenge [1, 17].

While ultra-narrow vascular and endovascular pathways are fundamentally aqueous environments, the capacity to retain internal moisture and sustain electromechanical stability in ambient air holds practical importance for clinical translation. In standard surgical workflows, sub-millimeter catheter systems must undergo pre-operative path calibration and mechanical steering verification by the clinician under ambient operating room conditions prior to insertion. Actuators susceptible to rapid dehydration experience immediate performance drift during these vital setup phases, undermining intravascular steering predictability. Furthermore, within the vascular lumen, the micro-device is intermittently exposed to localized dehydrating stresses, such as the high-osmolality environment induced by continuous contrast agent flushes or transient blood-flow occlusion during balloon angioplasty. Consequently, the internal moisture buffer provided by the dense, symmetric platinum encapsulation serves as a crucial protective barrier. It ensures that the ion mobility required for multi-DOF maneuvering remains stable despite both macro-scale pre-operative handling and micro-scale intravascular fluid fluctuations [14, 18].

To address these limitations, we report an integrated fabrication and design strategy that simultaneously optimizes electrode symmetry, segmentation precision, and environmental resilience in tubular IPMCs. The primary novelty of this work lies in overcoming the longstanding trade-off between multi-DOF maneuverability and open-air operational lifetime through a two-fold engineering approach. First, unlike conventional extruded tubular designs that suffer from outer-surface-confined metallization and subsequent rapid dehydration [11, 15], our plating protocol enforces a highly dense, symmetric platinum barrier on both the inner and outer surfaces. This configuration yields an intrinsic moisture-retaining lumen that extends the open-air operational window without external hydration. Second, we introduce a modular 3D-printed guide system that transitions the electrode partitioning from operator-dependent manual milling [12] to a highly reproducible, standardized protocol. This ensures 90° quadrant symmetry and eliminates parasitic electrical cross-talk. By benchmarking our sub-millimeter platform against these representative single-DOF or larger-scale asymmetric configurations, this study validates a scalable manufacturing framework capable of delivering predictable multi-axial soft actuation in both aquatic and dry environments [14, 19]. The structural configuration of this tubular platform optimizes ion transport and hydration [18]. This double-shielding morphology minimizes rapid localized dehydration, allowing the actuator to retain over 90% of its initial displacement amplitude during consecutive bending cycles, thereby stabilizing the electromechanical performance in non-aqueous environments [20, 21].

In this paper, we systematically evaluate the electromechanical performance and environmental resilience of the proposed actuators. Through electrochemical impedance spectroscopy (EIS) and dynamic current analysis, we quantify the improvements in charge transport efficiency afforded by the symmetric configuration. We specifically focus on the 0.8 mm OD model to demonstrate how the optimized surface-area-to-volume ratio enhances initial moisture capacity and enables sustained bending in ambient air. By comparing these results with conventional strip-type and non-symmetric tubular designs, we validate that our integrated approach not only improves structural precision but also extends the operational lifespan without external hydration. These evaluations underscore the potential of our platform as a reliable solution for high-precision, multi-DOF soft robotic applications in complex environments.

2. Experimental section

2.1. Materials and fabrication of tubular IPMCs

To ensure strong interfacial adhesion between the Nafion membrane and the metal electrodes (Platinum (Pt), Palladium (Pd), and Silver (Ag)), we implemented a multi-stage pre-treatment and fabrication protocol. The process began with the mechanical roughening of the extruded Nafion tubes' outer surfaces using fine-grit sandpaper (#1200 grit, waterproof). This step is essential for increasing the effective

surface area and generating active adhesion sites, both of which are critical for successful subsequent chemical deposition [20]. Following sanding, the tubes were subjected to a cleaning and activation sequence. Samples were ultrasonicated in a deionized (DI) water bath at a frequency of 40 kHz and a power of 120 W for 15 min to eliminate physical debris, followed by boiling in 2% H₂O₂ solution for 30 min and 0.5 M H₂SO₄ solution for another 30 min. This chemical treatment ensures the removal of organic contaminants and achieves full protonation of the membrane's sulfonic acid groups. Finally, a double-cycle electroless plating process was conducted for metallization. The pre-treated tubes were first immersed in a 20 mM platinum precursor solution (e.g. [Pt(NH₃)₄]Cl₂) at room temperature for 12 h to ensure complete ion exchange. After a thorough rinse with DI water, a controlled reduction step was executed by the gradual addition of a 50 mM sodium borohydride (NaBH₄) solution while maintaining the bath temperature at 40 °C over a 4-hour period. This primary plating cycle was repeated to guarantee the formation of a dense, uniform, and highly conductive electrode layer ($t \approx 30\text{--}40\text{ }\mu\text{m}$) on both the internal and external surfaces of the tubular actuator.

2.2. Physical and electromechanical characterization

To evaluate the structural uniformity and comparative characteristics of the IPMCs—fabricated with Pt, Pd, Ag, and Pt–Ag electrodes—samples were first sectioned to expose their internal morphology and then gold-sputtered using a mini sputter coater (SC7620, Emitech). Morphological details were investigated using a TESCAN VEGA scanning electron microscope (SEM) operated at an acceleration voltage of 15 kV. To assess the structural integrity and interfacial bonding of each specific electrode layer, cross-sectional images were captured in both secondary electron (SE) and backscattered electron (BSE) modes. The use of BSE imaging was particularly instrumental in distinguishing the heavy-metal electrode layers from the polymer matrix, providing a clear visualization of the interfacial characteristics.

To evaluate how geometric configurations influence dehydration kinetics, we monitored the time-dependent water uptake (*WU*) and retention capacity of the IPMCs in an open-air environment [12, 21, 22]. Before characterization, all specimens—comprising the flat strip and the tubular models (0.8 mm and 2.8 mm OD)—were immersed in DI water for 24 h to reach maximum swelling equilibrium. After removal, excess surface moisture was carefully blotted with lint-free tissue, and the initial mass of the fully hydrated state was immediately recorded. To track evaporation kinetics under ambient conditions, the wet mass (W_{wet}) was documented at regular intervals (every 5–10 min) over a 120 min period. The gravimetric *WU* was then determined using the following expression:

$$WU(\%) = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100$$

where W_{dry} represents the dry mass of the sample, measured after oven-drying the specimen for 24 h to ensure complete dehydration.

To evaluate the electrical behavior of the tubular and strip-shaped IPMCs, we analyzed their dynamic current responses across a range of stepped DC potentials. A programmable DC power supply (Dr Meter) provided stable input voltages from 1 V to 7 V. To resolve the rapid capacitive charging transients and the subsequent resistive steady-state currents, a high-precision data acquisition system (Keithley DAQ6510) was employed for real-time monitoring. The resulting current-time (*I*–*t*) profiles allowed us to observe the instantaneous peak current—a direct indicator of initial ion migration and interfacial charging—followed by its characteristic decay toward a stable steady-state value. From these curves, the steady-state current (I_{ss}) was extracted to determine the dynamic resistance ($R = V/I_{\text{ss}}$) relative to the applied voltage [23, 24]. This integrated measurement framework enabled the precise quantification of charge transport efficiency and the identification of electrical barriers inherent in each specific geometry.

2.3. Characterization of electromechanical actuation performance

To assess the actuation performance of the fabricated tubular IPMCs, we measured the tip displacement and bending angle under various electrical stimuli in both aqueous and ambient-air environments. Each tubular specimen was vertically cantilevered using a custom-designed modular holder with copper contacts. A DC potential of 5 V was applied to specific segmented electrodes to trigger bending. To ensure accurate data collection, the actuation was recorded with a high-definition digital camera positioned strictly perpendicular to the motion plane, thereby minimizing parallax errors. The lateral tip displacement (δ) was defined as the horizontal shift from the initial neutral state (0 V) to the maximum deflection point. To quantify the deformation, the bending angle (θ) was derived using the Circular Arc Model [25, 26], which assumes a uniform curvature (κ) throughout the actuator's length. The curvature was first determined by the following geometric relationship:

$$\kappa = \frac{2\delta}{L^2 + \delta^2}$$

where L represents the free length of the cantilevered actuator. The resulting bending angle, expressed in degrees, was calculated as:

$$\theta = \kappa \cdot L \cdot \left(\frac{180}{\pi} \right)$$

This modeling approach ensures a consistent comparative analysis of deformation magnitudes across different geometric configurations and operating conditions [11].

2.4. Precision electrode segmentation via 3D-printed guide

To facilitate precise multi-DOF actuation, we developed a customized modular segmentation guide for standardized electrode patterning. The four-quadrant segmentation framework was designed using 3D CAD software (SOLIDWORKS, Dassault Systèmes) and realized through high-resolution 3D printing (Bambu Lab X1 Carbon) [27, 28]. To eliminate mechanical play and ensure a seamless fit, the internal diameter of each modular guide was precisely engineered to accommodate specific tubular IPMC dimensions, including 2.8/2.2 mm, 1.6/1.3 mm, and 0.8/0.6 mm (OD/ID) configurations.

During the patterning process, the platinum-plated tubular IPMC was securely seated within the guide, which featured four longitudinal micro-slits positioned at exact 90° intervals. This structural alignment ensured high quadrant symmetry across the cylindrical surface of the actuator [18]. Segmentation was executed using a precision micro-blade guided along these predefined slits. A key technical requirement was the calibrated control of cutting depth; the blade was adjusted to incise only the external platinum layer and the immediate polymer sub-surface. This localized segmentation effectively established four independent electrical quadrants on the exterior while preserving the integrity of the internal platinum layer, allowing it to remain a continuous common ground.

2.5. Fabrication of segmented electrode and modular holder

To achieve precise multi-DOF actuation, we established a standardized electrode segmentation and packaging protocol utilizing a custom-designed 3D-printed guide system (figure 1). As illustrated in figure 1(a), a modular guide was precisely engineered to facilitate the symmetric partitioning of the external platinum layer. The tubular IPMC is securely seated within this guide, where four longitudinal micro-slits serve as tracks for a precision micro-blade. This setup allows for the physical separation of the outer electrode into four independent quadrants with high geometric accuracy, ensuring uniform force distribution during multi-directional bending.

Figures 1(b) and (c) highlight the customized modular holder developed to provide a stable and reliable electrical interface. This holder features a sophisticated dual-layer contact mechanism: the top-side interface is designed to hold the tubular IPMC as well as electrically contact to the segmented IPMC electrodes via copper tape without damaging the thin platinum layer. Simultaneously, the bottom-side serves as a dedicated terminal for secure lead wire soldering, preventing any mechanical stress from being transferred directly to the actuator.

The cross-sectional schematic in figure 1(d) further elucidates the electrical architecture. The system consists of four independent outer segments (S_1 – S_4) for individual directional control, complemented by a continuous internal core electrode that functions as a common ground. Finally, figure 1(e) shows the fully assembled and wired actuator system. This integrated fabrication and packaging strategy reduces contact resistance and ensures the structural and electrical integrity necessary for consistent 3D movement across diverse operating environments.

2.6. Electrical precision and segmentation validation

To validate the electrical integrity of the multi-DOF architecture, we employed EIS to quantitatively assess the precision of the electrode segmentation. A custom PCB-based interface was developed to provide stable and repeatable electrical coupling between the measurement system and the actuator [29]. The tubular IPMC was seated in a high-precision holder featuring spring-loaded contact pins, which ensured consistent contact pressure across the four external quadrants (S_1 – S_4) and the internal common ground (Core). This standardized interfacing approach was instrumental in eliminating the measurement variability and potential surface damage inherent in manual probing [30]. The electrical characteristics were investigated across two critical configurations: (i) the core-to-segment path, representing the primary charge-transfer mechanism for actuation, and (ii) the segment-to-segment path, which evaluates the degree of electrical isolation between adjacent electrodes. Impedance spectra were collected over a

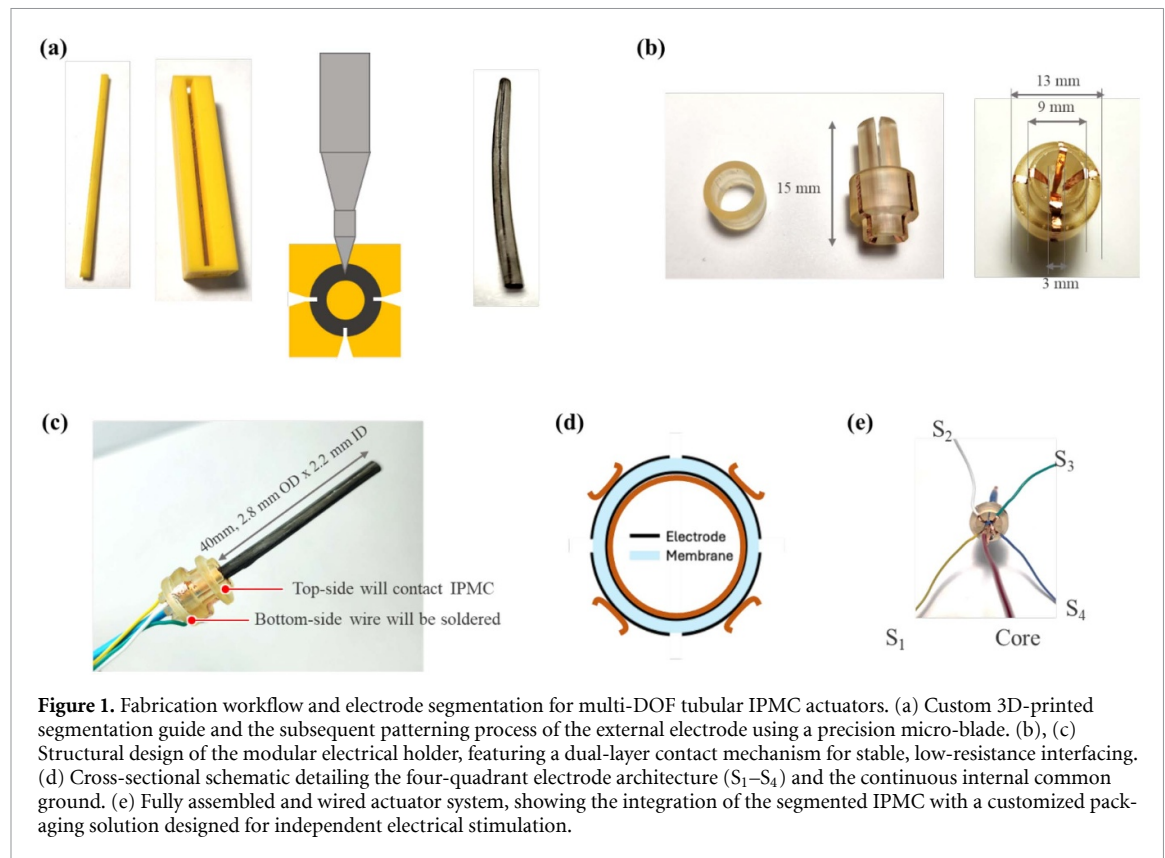


Figure 1. Fabrication workflow and electrode segmentation for multi-DOF tubular IPMC actuators. (a) Custom 3D-printed segmentation guide and the subsequent patterning process of the external electrode using a precision micro-blade. (b), (c) Structural design of the modular electrical holder, featuring a dual-layer contact mechanism for stable, low-resistance interfacing. (d) Cross-sectional schematic detailing the four-quadrant electrode architecture (S₁–S₄) and the continuous internal common ground. (e) Fully assembled and wired actuator system, showing the integration of the segmented IPMC with a customized packaging solution designed for independent electrical stimulation.

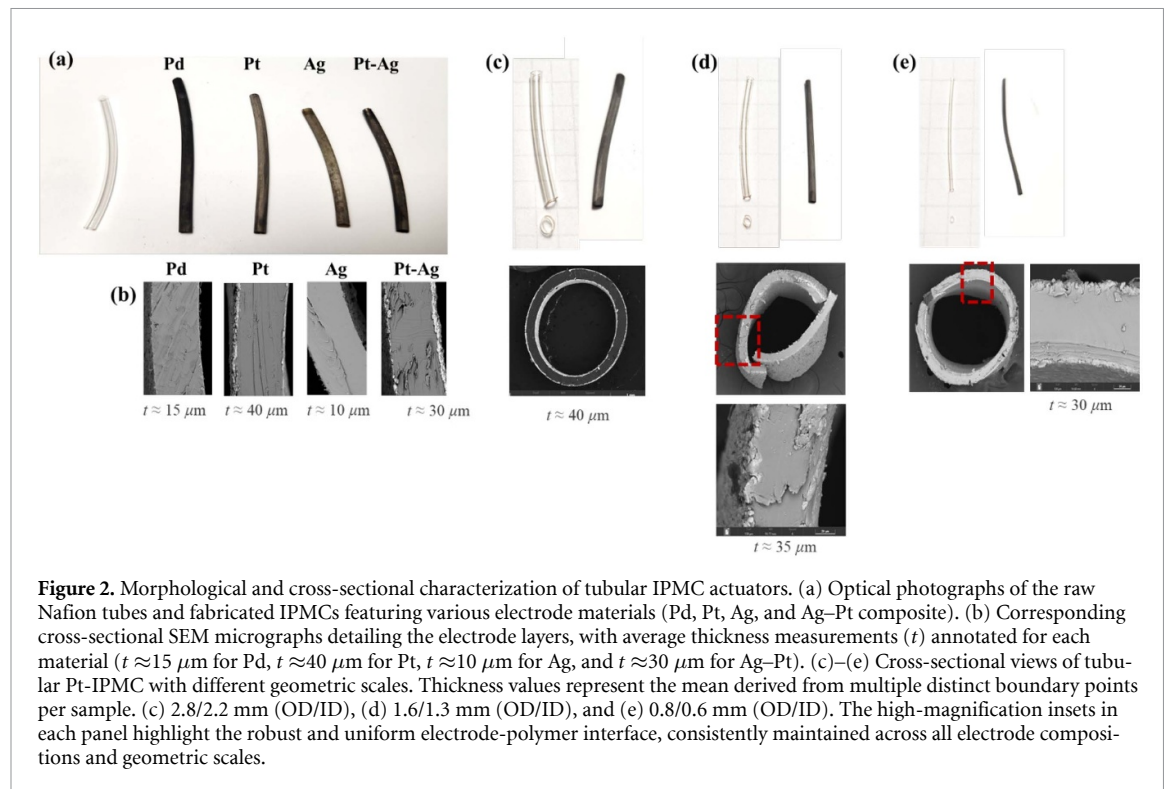
frequency range of 100 Hz to 100 kHz using a LCR meter. This validation protocol confirms that the fabricated tubular IPMCs achieve the electrical precision required for independent quadrant control, effectively suppressing parasitic cross-talk to ensure stable 3D maneuvering [18].

3. Results and discussion

3.1. Morphological analysis and effect of metal plating materials

The surface morphology and cross-sectional microstructure of the fabricated IPMCs were investigated to assess the efficacy of the electroless plating process across various metal precursors and tube dimensions. As illustrated in figures 2(a) and (b), the tubular Nafion membranes were successfully metallized with Palladium (Pd), Platinum (Pt), Silver (Ag), and a Silver–Platinum (Ag–Pt) composite. SEM analysis confirmed the formation of continuous electrode layers securely anchored to the polymer substrate. Notably, the Pt and Ag–Pt coatings yielded relatively thick electrode architectures, with measured thicknesses (t) of approximately 40 μm and 30 μm , respectively. Conversely, the Pd-plated specimens exhibited a thinner layer ($t \approx 15 \mu\text{m}$). These dimensional variations in the electrode layers are primarily driven by the distinct reduction kinetics and catalytic activities inherent to each metal precursor during the electroless deposition [16, 31]. While the greater thickness of Pt-based electrodes lowers surface resistance and enhances power efficiency, a relatively uniform Pd-plated interface may provide improved interfacial cohesion [20]. As detailed in the high-magnification cross-sectional SEM image (figure 2(b)), platinum nanoparticles penetrate several micrometers deep into the ionomer matrix, forming a continuous gradient transition network rather than a discrete surface layer. This mechanical interlocking structure directly suppresses interfacial shear stress, preventing delamination during large compliant deflections [16, 20, 32].

Figure 2(c) through (e) illustrate a comparative overview of the raw Nafion tubes alongside their fabricated IPMC counterparts, supplemented by cross-sectional SEM micrographs for various dimensions (2.8/2.2 mm, 1.6/1.3 mm, and 0.8/0.6 mm). Remarkably, the optimized plating protocol maintained highly uniform and continuous conductive layers on both the internal and external surfaces across all scales, even as the tube dimensions were reduced. Despite the decrease in diameter from 2.8/2.2 mm to the sub-millimeter 0.8/0.6 mm scale, the electrode thickness remained consistently within the 30 and 40 μm range. This dimensional stability underscores the reliability and scalability of our fabrication



methodology. High-magnification SEM analysis further reveals that platinum particles penetrate several micrometers into the polymer matrix, establishing a mechanical interlocking effect. This structural feature is essential for facilitating efficient charge transfer and ensuring long-term durability during complex multi-DOF actuation, particularly under prolonged operational cycles or within aquatic environments.

3.2. Water retention analysis

The influence of geometric configuration on the dehydration kinetics of IPMCs was evaluated by monitoring time-dependent moisture retention under ambient conditions. To ensure reproducibility, all gravimetric measurements were recorded under controlled laboratory conditions at a temperature of $23.5 \text{ }^{\circ}\text{C} \pm 1.0 \text{ }^{\circ}\text{C}$ and a relative humidity of $45\% \pm 5\%$. As shown in figure 3, both tubular architectures (2.8/2.2 mm and 0.8/0.6 mm OD/ID) demonstrated significantly higher initial water retention relative to the conventional strip-shaped counterpart. The tubular architectures exhibited higher initial gravimetric water content and sustained moisture levels than the flat strip configuration. Although all specimens approached dehydration equilibrium after approximately 60 min, the tubular designs sustained higher hydration levels during the transient dehydration period, effectively broadening the operational window for actuation in non-aqueous environments.

The discrepancy in gravimetric water content between the two tubular scales is governed by the scaling laws of the surface-area-to-volume ratio (S/V) [1]. For the sub-millimeter 0.8/0.6 mm tubular IPMC, the reduced diameter yields an elevated S/V ratio compared to the 2.8/2.2 mm variant, thereby shortening the characteristic diffusion path length for water molecules within the hydrophilic Nafion matrix [32]. During the 24 h immersion pre-treatment, this accelerated diffusion kinetics enables the smaller ionomer bulk to achieve a rapid and uniform swelling equilibrium [16]. Consequently, the high density of localized hydration sites within the thin-walled 0.8 mm structure leads to a higher initial mass percentage of entrapped water at $t = 0 \text{ min}$. This elevated initial saturation establishes an internal moisture reservoir that sustains ion mobility and delays performance decay during open-air operation. At the onset of the dehydration ($t = 0 \text{ min}$), the strip specimen exhibited an initial water content of approximately 18%, whereas the 2.8/2.2 mm and 0.8/0.6 mm tubular IPMCs retained approximately 40% and 70%, respectively. While all specimens experienced an expected moisture drop during the first 20–30 min due to evaporation, the tubular designs exhibited a notably more stable moisture profile following this initial transient phase. This enhanced retention is primarily attributed to the optimized surface-area-to-volume ratio and the unique hollow interior of the tubular geometry, which together suppress rapid evaporation and delay the dehydration process. Even as moisture levels approached equilibrium

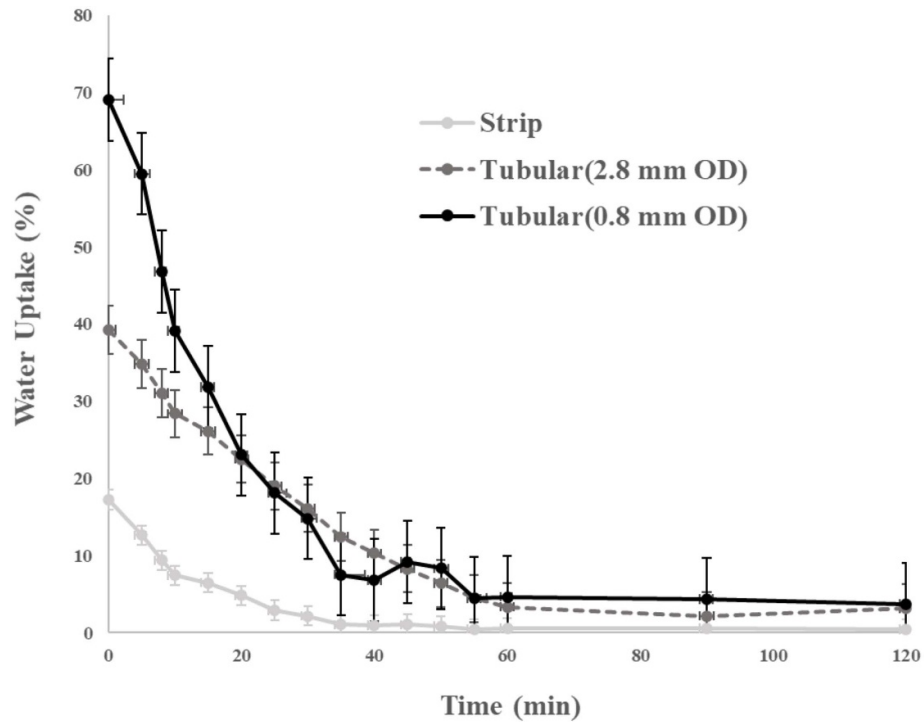


Figure 3. Comparative evaluation of dehydration kinetics and moisture retention. Time-resolved water uptake (%) profiles for conventional strip-shaped and tubular IPMCs (0.8 mm and 2.8 mm OD) under ambient air exposure. Error bars represent the standard deviation ($n = 3$).

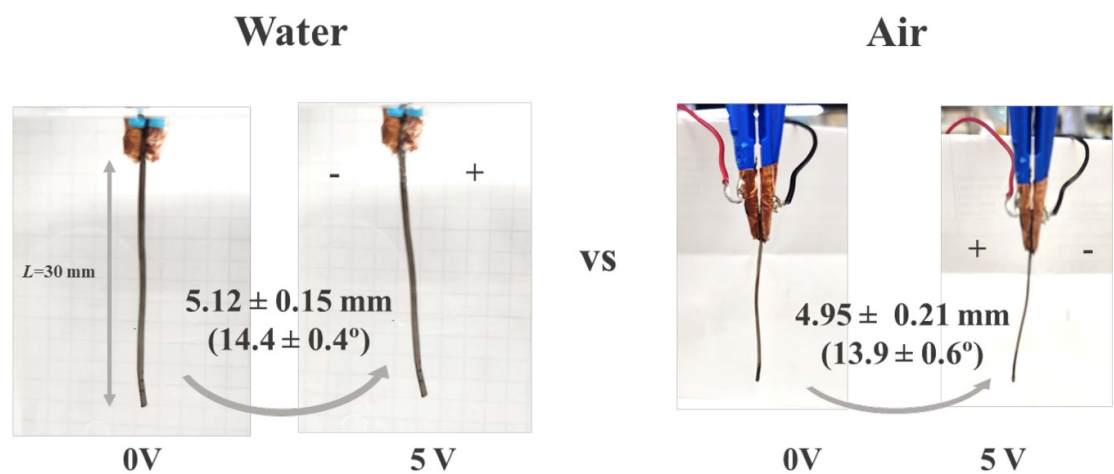


Figure 4. Comparative actuation performance in different conditions. Dynamic actuation profiles under a 5 V DC potential in underwater (left) and ambient-air (right) conditions. The snapshots demonstrate the electromechanical performance of the sub-millimeter tubular IPMC configuration (0.8 mm OD/ 0.6 mm ID) fabricated with symmetric platinum (Pt) electrodes. Data are expressed as mean $\pm$ standard deviation (SD) obtained from triplicate samples ($n = 3$). The annotated vertical arrow indicates the effective cantilevered free length of the actuator ($L = 30$ mm).

after 60 min, the tubular models consistently provided a substantially extended operational window for stable actuation in dry environments [33, 34].

3.3. Actuation performance

To evaluate the electromechanical efficacy of the fabricated tubular platform, active deflections were quantified under a 5 V DC potential across both aqueous and open-air media. As shown in figure 4, the actuator achieved comparable bending magnitudes regardless of the surrounding environment, yielding a maximum underwater tip displacement of 5.12 ± 0.15 mm ($14.4 \pm 0.4^\circ$ bending angle) and a comparable open-air displacement of 4.95 ± 0.21 mm ($13.9 \pm 0.6^\circ$) calculated via the Circular Arc Model. While the bending directions differ due to the reversed electrode polarities between the underwater and

open-air configurations, the actuator exhibited nearly identical displacement magnitudes in both environments. This sustained performance in air validates the efficacy of the tubular architecture in preserving sufficient internal moisture to sustain ion mobility, even without external hydration. For experimental reproducibility, the ambient characterization was conducted under stringently monitored laboratory parameters ($23.5\text{ }^{\circ}\text{C} \pm 1.0\text{ }^{\circ}\text{C}$ and $45\% \pm 5\%$ relative humidity) with a standardized 10 s continuous excitation window [14, 20].

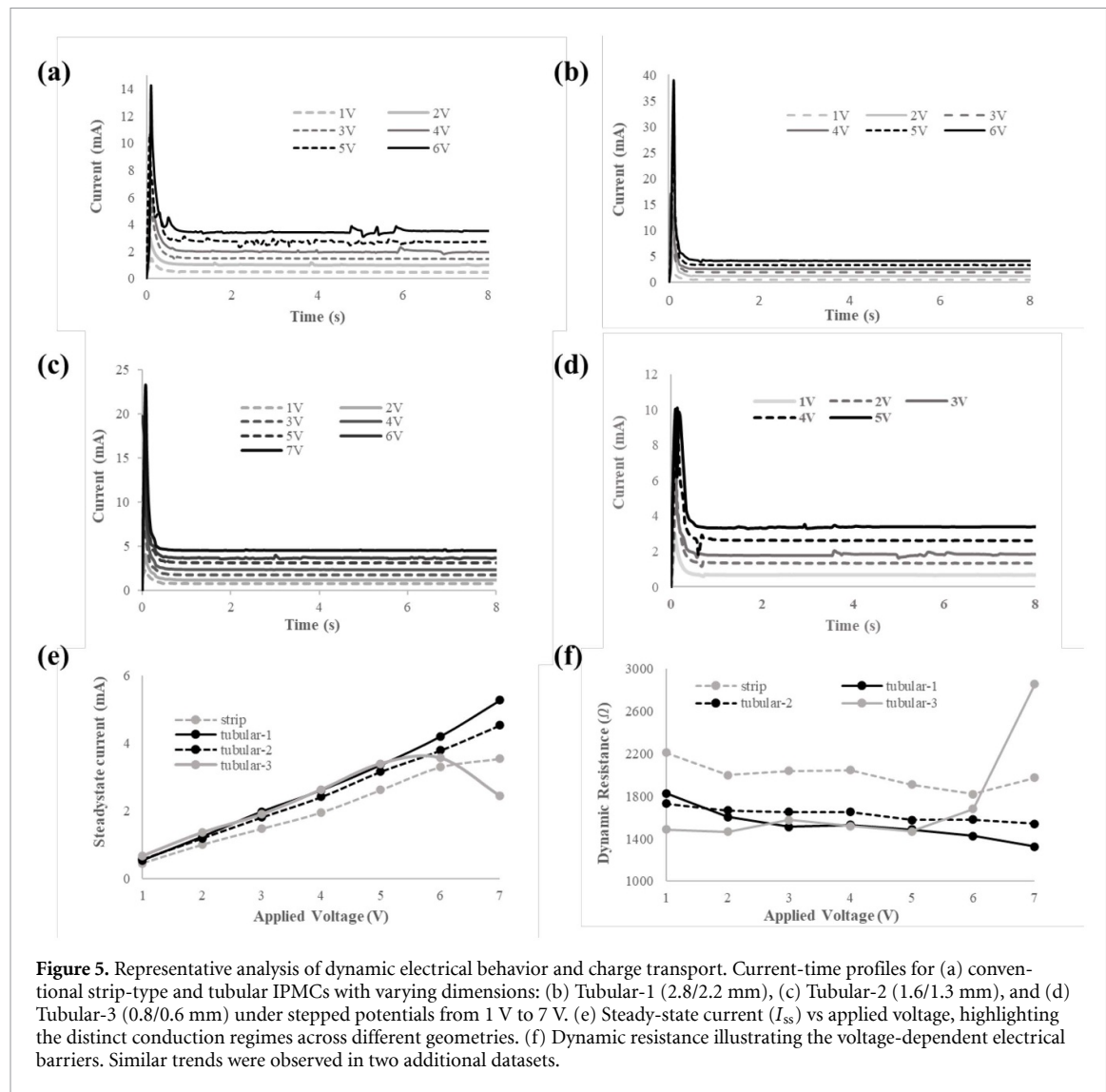
The minimal performance discrepancy—amounting to less than a 4% reduction in peak displacement within the dry environment—quantitatively substantiates the structural advantages of the tubular geometry [18]. By fully encapsulating the core within dense inner and outer platinum boundaries, the unique hollow interior serves as a self-sustaining moisture buffer that preserves the internal ion mobility necessary for electrophoretic migration even under severe dehydrating stress [23, 31]. This double-barrier architecture suppresses the rapid evaporation kinetics and structural desiccation typically observed in conventional strip-shaped or asymmetric designs, where rapid water loss quickly stifles intra-matrix charge carrier transport [19, 35]. Consequently, the tubular architecture provides reliable actuation in both aqueous and non-aqueous environments, supporting its potential for multi-DOF steering applications in soft robotics and precision micromanipulation [14, 31, 33]. During 120 min continuous open-air exposure, the 0.8 mm OD actuator retained over 90% of its initial peak deflection amplitude, providing direct operational proof of durable physical and electrical integration under prolonged actuation.

Although cyclic actuation was not investigated in detail, the symmetric platinum encapsulation and hollow tubular architecture are expected to suppress localized dehydration more effectively than conventional strip-type or asymmetric IPMCs, thereby contributing to stable electromechanical performance under ambient conditions [22, 34]. Compared with previously reported tubular IPMC actuators, which often exhibit limited displacement ($<3\text{ mm}$) or asymmetric bending in non-aqueous environments because of incomplete internal metallization and structural asymmetry [11, 15], the present sub-millimeter (0.8 mm OD) tubular IPMC achieved a stable open-air tip displacement of approximately 5 mm. These results highlight the effectiveness of the proposed fabrication strategy in producing a structurally symmetric tubular actuator with reliable electromechanical performance, demonstrating its potential for compact multi-DOF soft robotic and biomedical manipulation applications [14, 33].

3.4. Dynamic current response analysis and electrodynamic characterization

The electrical response of the IPMC actuators was investigated by analyzing their current-time ($I-t$) profiles across a range of stepped DC potentials (1–7 V). As illustrated in figures 5(a)–(d), all configurations exhibited a characteristic instantaneous peak current upon voltage application, followed by an exponential decay toward a stable steady-state. This transient response is indicative of the rapid capacitive charging and initial ion accumulation at the electrode-polymer interface, which eventually transitions into a steady-state electrophoretic migration of cations through the Nafion matrix. Notably, the Tubular-1 structure (2.8/2.2 mm) yielded a peak current of approximately 40 mA at 6 V, significantly outperforming the conventional strip structure, which remained below 15 mA. This substantial enhancement suggests that the symmetric, large-area metallization of the tubular geometry lowers the interfacial impedance, thereby facilitating more efficient ion transport.

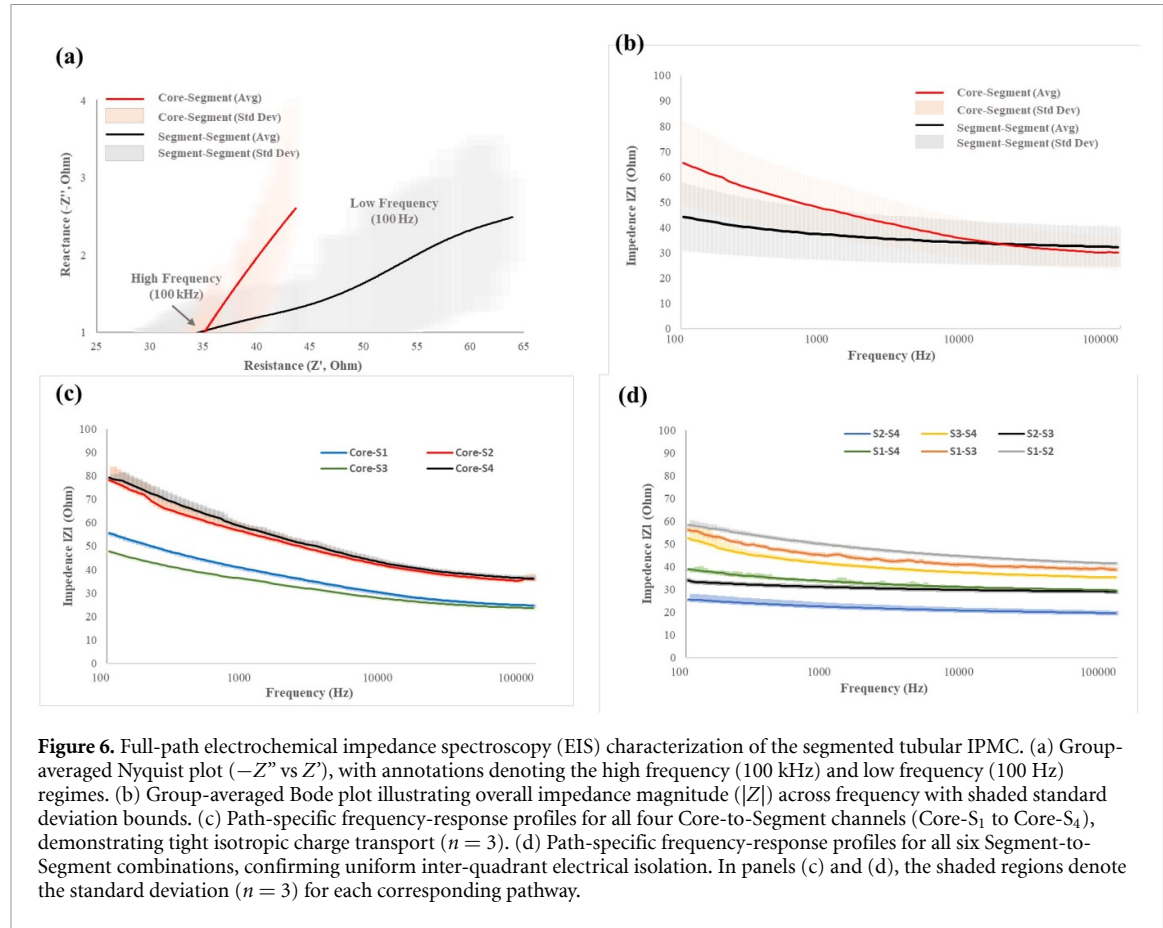
To further characterize the electrical response, we evaluated the steady-state current (I_{ss}) and dynamic resistance (R) as functions of the applied voltage (figures 5(e) and (f)). While most structures showed a near-linear increase in I_{ss} up to 4 V, a clear divergence was observed at higher potentials. Tubular-1 and Tubular-2 (1.6/1.3 mm) maintained a consistent upward progression even at 7 V, whereas the strip and the sub-millimeter Tubular-3 (0.8/0.6 mm) exhibited saturation or erratic current drops beyond 5–6 V. The observed inflection and subsequent decrease in steady-state current for the Tubular-3 sample above an applied potential of 6 V (figure 5) reflects a localized transport limitation rather than a structural failure. At applied potential above 6 V, localized water electrolysis and micro-scale Joule heating induce transient moisture depletion within the thin-walled ($t \approx 100\text{ }\mu\text{m}$) Nafion matrix near the electrode interfaces [16, 23]. This partial dehydration restricts local ion mobility, leading to the recorded increase in electrical resistance [33]. Because the intended operating voltage of the present actuator is 3–5 V, where the maximum bending performance is achieved (section 3.3), this high-voltage resistance increase is unlikely to affect its practical operation. Notably, this resistance surge in Tubular-3 aligns with the dehydration trends observed in figure 3; the smaller volume and higher surface-area-to-volume ratio of the 0.8 mm model make it more susceptible to localized moisture depletion under sustained electrical stress, which in turn restricts ion transport and reduces the steady-state current.



The dynamic resistance profiles (figure 5(f)) further reinforce this observation, showing that the tubular architecture consistently maintained lower electrical resistance than the flat strip configuration. Specifically, Tubular-1 exhibited a continuous decline in resistance with increasing voltage, a trend that suggests a more efficient internal charge transport pathway. Collectively, these results demonstrate that the tubular geometry, particularly the larger-diameter models, effectively balances ion transport and electrical resistance, thereby providing a favorable electrical environment for stable electrochemical actuation [12, 23, 24, 35].

3.5. EIS analysis

EIS spectra were collected across all 10 interconnecting electrical pathways per specimen to evaluate the electrical isolation and quadrant symmetry of the multi-DOF platform. These pathways comprise four Core-to-Segment channels (Core- S_1 to Core- S_4) and six Segment-to-Segment combinations (S_1 - S_2 , S_2 - S_3 , S_3 - S_4 , S_4 - S_1 , S_1 - S_3 , and S_2 - S_4). As shown in the group-averaged Nyquist (figure 6(a)) and Bode (figure 6(b)) profiles, the high frequency bulk ohmic resistance converges toward a relatively uniform baseline $R_b \approx 35.0 \pm 1.5 \Omega$ across both path categories [35, 36]. In the low frequency regime (10^2 Hz), Core-to-Segment channels exhibit a higher impedance magnitude ($|Z| \approx 65 \Omega$) associated with radial double layer capacitance, whereas Segment-to-Segment paths show a flatter response starting near $|Z| \approx 44 \Omega$. While variance bands appear at lower frequencies due to minor contact interface fluctuations, a two-sample t -test indicates that the spectral profiles remain statistically distinguishable between the two groups ($p < 0.001$). To quantitatively examine the electrochemical mechanisms governing charge transport across both configurations, the measured EIS spectra were fitted using an equivalent circuit model based on a modified Randles network. The equivalent impedance is formulated as:



$$Z_{eq} = R_b + \frac{1}{(R_{ct} + Z_w)^{-1} + (j\omega)^n CPE_{dl}}$$

where R_b represents the bulk ohmic resistance of the hydrated Nafion matrix and metallic current collectors, dictating the high frequency response ($>10^4$ Hz). The interfacial processes are modeled by a parallel configuration consisting of a constant phase element (CPE_{dl}), introduced to account for non-ideal double layer capacitive accumulation across the dispersed platinum polymer interface, coupled with the charge transfer resistance (R_{ct}) and a Warburg diffusion element (Z_w). Here, R_{ct} reflects the interfacial resistance to charge transfer, while Z_w captures the low frequency diffusion of hydrated mobile cations through the ionomer channels. Parametric extraction reveals that while the bulk ohmic resistance remains consistent across both pathway groups ($R_b \approx 35.0 \Omega$), the Core-to-Segment channels exhibit a substantially lower charge transfer barrier ($R_{ct} \approx 8.5 \Omega$) and higher interfacial capacitance ($CPE_{dl} \approx 1.2 \text{ mF} \cdot \text{s}^{-n-1}$) compared to the circumferential Segment-to-Segment paths ($R_{ct} \approx 22.4 \Omega$, $CPE_{dl} \approx 0.4 \text{ mF} \cdot \text{s}^{-n-1}$). This distinction confirms that the radial path favors efficient charge accumulation for rapid electromechanical actuation, while the higher inter-segment resistance provides the necessary electrical isolation to suppress cross-talk during multi-channel operation. Figures 6(c) and (d) detail the path-specific frequency responses (10^2 – 10^5 Hz) to observe spatial uniformity across individual combinations. Core-to-Segment channels (figure 6(c)) show a consistent trend toward a lower high frequency impedance limit governed by the radial wall thickness ($t \approx 300 \mu\text{m}$ for the 2.8 mm OD model). In contrast, the Segment-to-Segment paths (figure 6(d)) display higher circumferential levels, which help provide the necessary electrical isolation to reduce potential cross-talk during multi-channel operation [18]. Considering this impedance symmetry alongside directional actuation, active deflections evaluated along two orthogonal core-segment axes yielded symmetric tip deflections (≈ 5 mm displacement, 14.1° bending angle). Coupled with the high-frequency ohmic trend across the 10 pathways, these observations suggest a reasonable level of isotropic electromechanical coupling suitable for multi-DOF trajectory control in micro-vascular applications [10, 14].

4. Conclusion

In this work, we established a fabrication framework and a modular 3D-printed guide system that enables precise electrode segmentation while addressing structural asymmetry. This methodology was evaluated across various tubular dimensions, showing structural consistency across geometric scales.

A challenge in previous tubular IPMC research—particularly studies utilizing extrusion—has been achieving uniform metallization. Conventional electroless plating often results in asymmetrical electrode due to capillary forces and air entrapment within small-diameter lumens, yielding a defined outer layer ($t \approx 25 \mu\text{m}$) alongside a deficient, non-conductive inner surface. This imbalance disrupts electrical symmetry and accelerates moisture loss in ambient conditions. To overcome these limitations, we implemented an optimized plating protocol that forms symmetric electrode layers ($t \approx 30\text{--}40 \mu\text{m}$) on both surfaces, effectively encapsulating the ionomer core. Precision was maintained using a custom 3D-printed segmentation guide, ensuring 90° quadrant alignment and low contact resistance at the wiring interface.

Full path EIS was used to characterize the electrical behavior of this structure. Across all 10 pathways, the high-frequency bulk ohmic resistance converged to a consistent baseline ($R_b \approx 35.0 \Omega$), while low-frequency responses reflected the geometric distinction between radial Core-to-Segment channels and circumferential Segment-to-Segment paths. Water retention analysis further indicated that the hollow interior acts as an intrinsic moisture buffer against rapid evaporation. Consequently, the sub-millimeter actuator maintained stable bending behavior in ambient air, retaining over 90% of its initial tip displacement during a 120 min exposure period without external hydration. While active deflections were characterized along representative orthogonal axes in this study, the combined 10-path impedance profiles and symmetric bending responses suggest that this platform provides a practical foundation for multi-DOF trajectory control. By utilizing commercial Nafion tubes and scalable fabrication tools, this approach offers a viable route for soft robotic applications, extending from biomimetic underwater systems to micro-vascular steering tools operating in dry environments.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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