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Air as a Soft Material: Introducing the Ionized-Wind Actuator (IoWA) as an Emerging Haptic Medium in Human-computer Interaction

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Abstract

Replicating the richness of real-world perception has long been the goal of virtual reality technologies. True immersion requires not only sight and sound, but also the ability to feel—to let the body sense and act as naturally in virtual environments as it does in the physical world. Yet today's VR products remain dominated by vision, while essential, is delivered through devices that are heavy, tethered to external power, expensive, rigid in structure, power-hungry, and limited in application scenarios. Instead of supporting seamless immersion, current solutions often compromise it, constraining freedom rather than enabling it. What is missing is a device technology that is light, quiet, and adaptive enough to vanish from notice—yet powerful enough to deliver rich, programmable tactile feedback. Here, we are introducing ionized-wind actuators (IoWA) as a new class of actuators for VR haptic devices}. These actuators generate controllable airflow without moving parts, are inherently lightweight and quiet, and can be fabricated in scalable, conformable formats—opening the door to dense arrays capable of delivering localized, programmable tactile cues across wearable and large-area interfaces. Crucially, this will be the first effort to translate ionized-wind actuation into a device-level interface for human–computer interaction. By opening this unexplored space, we expand not only the design of VR devices but also the scope of HCI—toward systems that orchestrate sight, sound, and touch as equal partners in immersive experience.

Keywords

Ionized-wind Actuator, Dielectric Barrier Discharge (DBD) Plasma Actuator, Electrohydrodynamic (EHD), Haptic Device

Air as a Soft Material: Introducing the Ionized-Wind Actuator (IoWA) as an Emerging Haptic Medium in Human-computer Interaction

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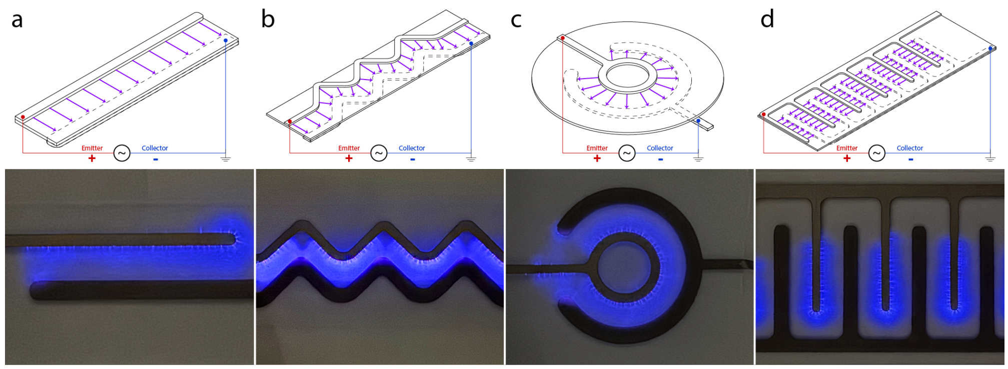

Fig. 1. Prototypes of four IoWA types: (a) Linear IoWA, (b) Angular IoWA, (c) Circular IoWA, and (d) Multi-electrode IoWA. The arrows indicate the direction of the ionized wind.

Replicating the richness of real-world perception has long been the goal of virtual reality technologies [27]. True immersion requires not only sight and sound, **but also the ability to feel**—to let the body sense and act as naturally in virtual environments as it does in the physical world. Yet today's VR products remain dominated by vision, **touch**, while essential, is delivered through devices that are **heavy, tethered to external power, expensive, rigid in structure, power-hungry, and limited in application scenarios** [13, 14, 19, 22, 26]. Instead of supporting seamless immersion, current solutions often compromise it, constraining freedom rather than enabling it. What is missing is a device technology that is **light, quiet, and adaptive enough to vanish from notice—yet powerful enough to deliver rich, programmable tactile feedback**. Here, we are introducing **ionized-wind actuators (IoWA) as a new class of actuators for VR haptic devices**. These actuators generate controllable airflow without moving parts, are inherently lightweight and quiet, and can be fabricated in scalable, conformable formats—opening the door to dense arrays capable of delivering localized, programmable tactile cues across wearable and large-area interfaces. **Crucially, this will be the first effort to translate ionized-wind actuation into a device-level interface for human–computer interaction**. By opening this unexplored space, we expand not only the design of VR devices but also the scope of HCI—toward systems that orchestrate sight, sound, and touch as equal partners in immersive experience.

CCS Concepts: • **Human-centered computing → Haptic devices**.

Additional Key Words and Phrases: **Ionized-wind Actuator, Dielectric Barrier Discharge (DBD) Plasma Actuator, Electrohydrodynamic (EHD), Haptic Device**

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1 Introduction

Virtual reality demands haptic devices that are lightweight, quiet, and capable of rapid, expressive feedback. Actuators—responsible for converting energy into perceivable force—ultimately determine whether haptic feedback can be precise, reliable, and scalable. However, all existing actuator families face fundamental tradeoffs. **Electromagnetic actuators** [8, 29] are fast and inexpensive but generate unwanted heat. **Piezoelectric actuators** [11] offer high precision and frequency response yet require high voltages and exhibit limited displacement. **Dielectric elastomer actuators** [12, 21] and **electrohydraulic actuators** [5, 15] achieve high precision but operate at kilovolt levels and suffer from fragility and durability issues. **Electroadhesive actuators** [6, 28] provide soft, rapid haptic output at low voltage but produce only minimal displacement. **Electroosmotic actuators** [24, 25] offer promising displacement at relatively low voltage, but require liquid containment. **Pressure-driven actuators** such as hydraulics and pneumatics [10, 16] enable large deformation but are bulky, noisy, and inefficient. Finally, **thermal actuators**—including shape-memory alloys [20] and polymers [30]—are lightweight and inexpensive, yet slow and dependent on strict thermal regulation.

In this work, we explore an alternative pathway: **the Ionized-Wind Actuator (IoWA)**, a new haptic medium powered purely by electrical interaction with air. IoWA is built on **Dielectric Barrier Discharge (DBD) plasma actuation** [23]. As shown in Figure 2-b, it comprises three components—an emitter, a collector, and a dielectric layer—through which high-voltage AC fields generate localized micro-discharges that ionize nearby air molecules and produce directed airflow without any moving parts (Figure 2-c). This mechanism yields high power efficiency, minimal mechanical fatigue, and extremely low mass, making IoWA a strong candidate for future wearable VR haptics.

While prior research has characterized DBD actuators in terms of voltage, current, and temperature [9, 17, 18, 23], their **material choices, fabrication processes, and integration with human interaction** remain largely unexplored. As a result, DBD-based ionized-wind devices have remained research prototypes rather than deployable haptic components. **This work represents the first effort to translate IoWA from a laboratory prototype into a device-level actuator for human–computer interaction**, combining the high power efficiency and precise control of electrical actuators with the flexibility and low mechanical fatigue characteristic of gas-based actuation (Figure 2-a). This highlights that the foundation of any such system ultimately hinges on **the actuator design** itself.Our contributions are as follows:

1. **Introducing IoWA as a new pathway toward lightweight, quiet VR haptic devices capable of rapid and expressive feedback** (Sec. 1);
2. **Developing an accessible, rapid, and inexpensive IoWA fabrication method** suitable for entry-level users (Sec. 2);
3. **Demonstrating four IoWA prototypes with distinct geometric configurations** (Sec. 3);
4. **Establishing the design space and potential applications of IoWA** (Sec. 4).

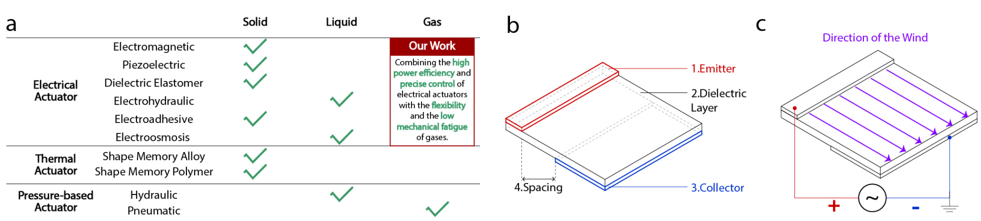

Fig. 2. (a) The contribution of our work lies in a systematic comparison of soft actuators, with green indicators marking the material status of each actuator. (b) Fundamental components of IoWA: emitter, collector, and dielectric layer. A spacing must be maintained between the emitter and collector to prevent electrical breakdown. (c) Working mechanism of IoWA: when the emitter and collector are driven by AC, ionized wind is generated in the direction indicated by the purple arrow.

2 Device Fabrication

2.1 Materials and Fabrication Setup

We propose an accessible, safe, and low-cost rapid fabrication method for IoWAs. In our approach, the emitter and collector electrodes are constructed using conductive fabric tape [7, 31] (although materials like copper tape can also be used, its softness makes it prone to wrinkling, whereas the stiffer fabric tape is much easier to work with), and the dielectric layer is formed using ECOFLEX silicone 00-30 (or 00-50) [1], as softer variants such as 00-10 are prone to tearing during handling. The fabrication tools are equally accessible: rather than relying on a metal blade caster that costs several hundred dollars [2], we use a 3D-printed blade caster fabricated at 80 µm resolution. For driving the prototype, we employ an inexpensive setup consisting of a DC power supply [4] paired with a DC-to-AC converter [3] (output voltage ranges from 15 kV to 20kV with a frequency from 30 to 200 kHz), with a total cost of approximately 50 USD.

2.2 Fabrication Procedure

As shown in Figure 3, the fabrication procedure consists of six straightforward steps:

(1) First, the mixed ECOFLEX silicone is blade-cast into a 1 mm sheet to form the base layer for the collector (Figure 3-a). Although this step is not strictly required, we strongly recommend it. In practice, the thin silicone dielectric layer wrinkles easily, which disrupts the uniformity of the electric field; adding a silicone base helps prevent this issue.
(2) The blade-cast sheet is then cured on a hotplate at 60 °C for 3 minutes (Figure 3-b). Note: avoid overheating, as excess time or temperature can expand trapped air bubbles and cause thickness irregularities, or even melt the material.
(3) Once cured, the collector electrode is placed onto the silicone base (Figure 3-c).
(4) A second silicone layer, approximately 500 µm thick, is subsequently blade-cast over the collector to create the dielectric layer (Figure 3-d).
(5) After this dielectric layer has fully formed, the emitter electrode is positioned on top (Figure 3-d).
(6) Finally, the emitter and collector are connected to the AC power supply, completing the construction of the IoWA device (Figure 3-e).

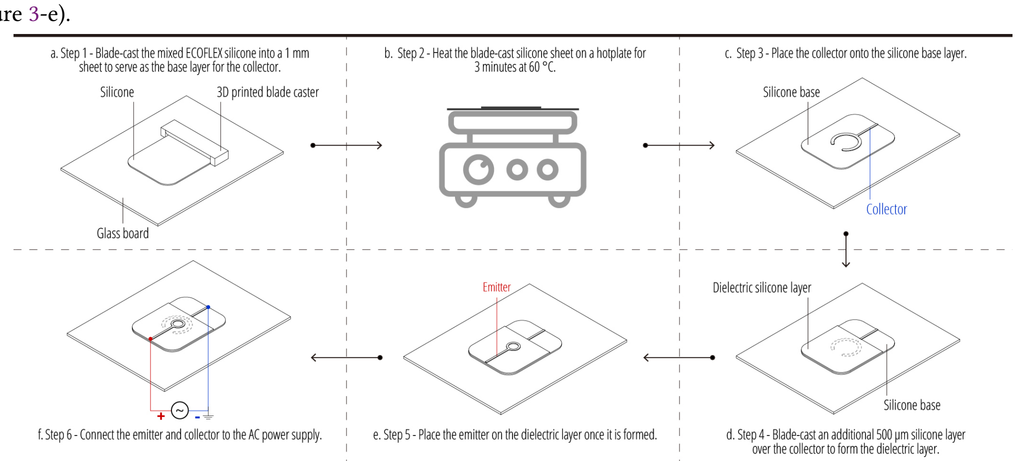

Fig. 3. Fabrication process of IoWA. (1) Blade-cast the mixed ECOFLEX silicone into a 1 mm sheet to form the base layer for the collector. (2) Heat the blade-cast silicone on a hotplate for 3 minutes at 60 °C. (3) Place the collector onto the silicone base layer. (4) Blade-cast an additional 500 µm silicone layer over the collector to form the dielectric layer. (5) Place the emitter on the dielectric layer once it is formed. (6) Connect the emitter and collector to the AC power supply to complete the device.

3 Prototypes

3.1 Linear IoWA

We implemented a **linear IoWA prototype (Figure 4)** to examine ionized-wind generation in its simplest geometry. The device consists of a 3 mm-wide emitter and a 5 mm-wide collector separated by an 8 mm gap and a 500 µm dielectric layer. Under high-voltage AC input, micro-discharges form along the exposed emitter edge, producing a uniform sheet-like airflow toward the collector. At 7 V, plasma is faint with minimal heating, while 10 V yields a brighter and more continuous discharge. This linear configuration establishes baseline actuation behavior and serves as the foundational unit for richer spatial patterns.

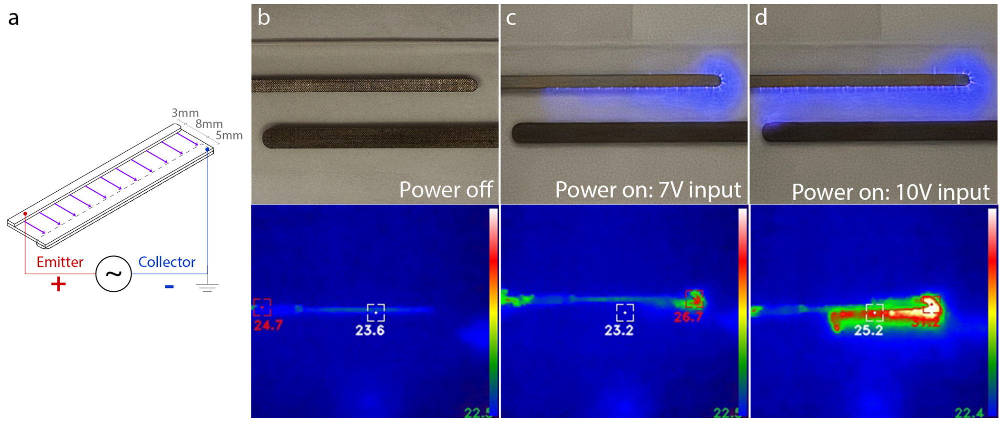

Fig. 4. Linear IoWA prototype. (a) Basic structure with emitter, collector, and spacing; the purple arrow indicates the direction of the ionized wind. (b) Real image and thermal image with the device powered off. (c) Real image and thermal image with the device powered on at a 7 V input. (d) Real image and thermal image with the device powered on at a 10 V input.

3.2 Angular IoWA

To investigate geometric modulation of airflow, we built an **angular IoWA prototype (Figure 5)** using the same 3 mm emitter, 5 mm collector, 8 mm spacing, and 500 µm dielectric thickness arranged in a zig-zag layout. The angled segments redistribute the electric field, causing micro-discharges to concentrate at each corner and creating a sequence of discrete airflow peaks. Compared with the linear version, plasma becomes spatially segmented but remains stable across the structure. Thermal imaging shows localized temperature rise at each bend at 7 V, intensifying at 10 V. This prototype demonstrates how electrode geometry can encode spatial variation in airflow intensity.

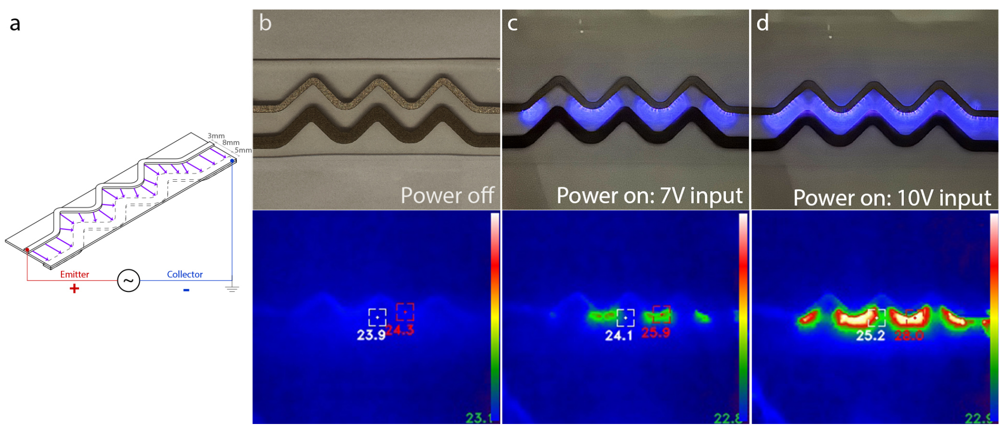

Fig. 5. Angular IoWA prototype. (a) Basic structure with emitter, collector, and spacing; the purple arrow indicates the direction of the ionized wind. (b) Real image and thermal image with the device powered off. (c) Real image and thermal image with the device powered on at a 7 V input. (d) Real image and thermal image with the device powered on at a 10 V input.

3.3 Circular IoWA

We next developed a **circular IoWA prototype (Figure 6)** using the same electrode dimensions—3 mm emitter width, 5 mm collector width, 8 mm spacing, and a 500 µm dielectric layer—arranged concentrically. When driven at 7 V, plasma forms around the inner circumference; at 10 V, the discharge becomes brighter and more continuous, creating a radial airflow that propagates outward. Thermal imaging reveals a ring-shaped temperature distribution consistent with the discharge pattern. This design highlights how non-linear geometry enables haptic effects distinct from linear or angular configurations.

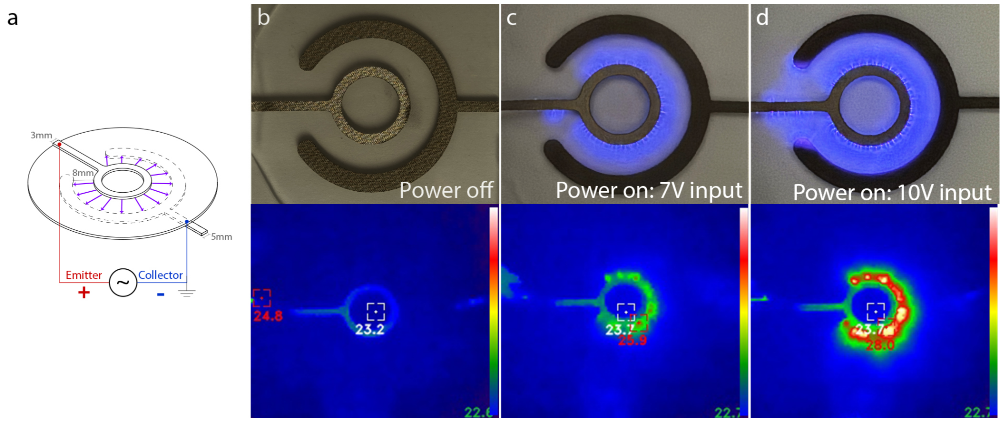

Fig. 6. Circular IoWA prototype. (a) Basic structure with emitter, collector, and spacing; the purple arrow indicates the direction of the ionized wind. (b) Real image and thermal image with the device powered off. (c) Real image and thermal image with the device powered on at a 7 V input. (d) Real image and thermal image with the device powered on at a 10 V input.

We further examined the voltage-dependent behavior of the circular IoWA by gradually increasing the input from 7 V to 10 V (Figure 7). At 7 V, only a partial arc of the emitter edge ignites, producing a faint and discontinuous plasma region. Increasing the voltage to 8 V expands the discharge around the circumference, forming a more uniform glow. At 9 V, the plasma becomes brighter and begins to connect across the full arc. At 10 V, the discharge develops into a continuous, high-intensity ring that closely follows the circular geometry. This progressive transition demonstrates how higher voltage strengthens both the spatial coverage and stability of ionized-wind generation, enabling controllable modulation of airflow intensity in circular configurations.

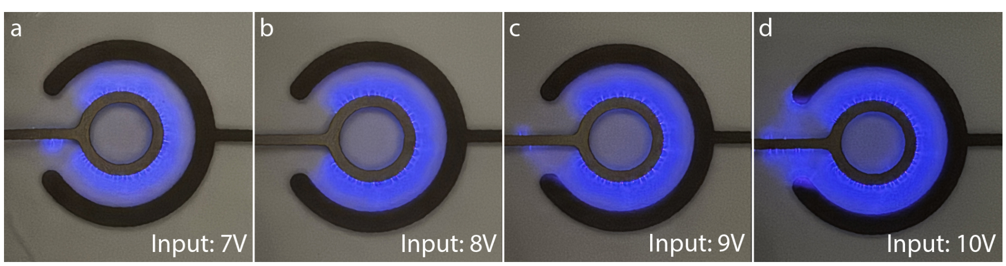

Fig. 7. Circular IoWA under different input voltages. From (a) to (d): 7 V, 8 V, 9 V, and 10 V.

3.4 Multi-electrode IoWA

Finally, we created a **multiple-electrode IoWA prototype (Figure 8)** composed of repeated U-shaped emitter–collector segments, each using the same 3 mm emitter width, 5 mm collector width, 8 mm spacing, and 500 μm dielectric layer. Each U-segment acts as an independent micro-channel, generating a row of discrete plasma sites. At 7 V, several channels activate with weak discharges; at 10 V, all channels ignite, producing synchronized plasma columns and a patterned array of thermal hotspots. This configuration illustrates how IoWA can scale into actuator arrays for multi-point spatial haptic feedback.

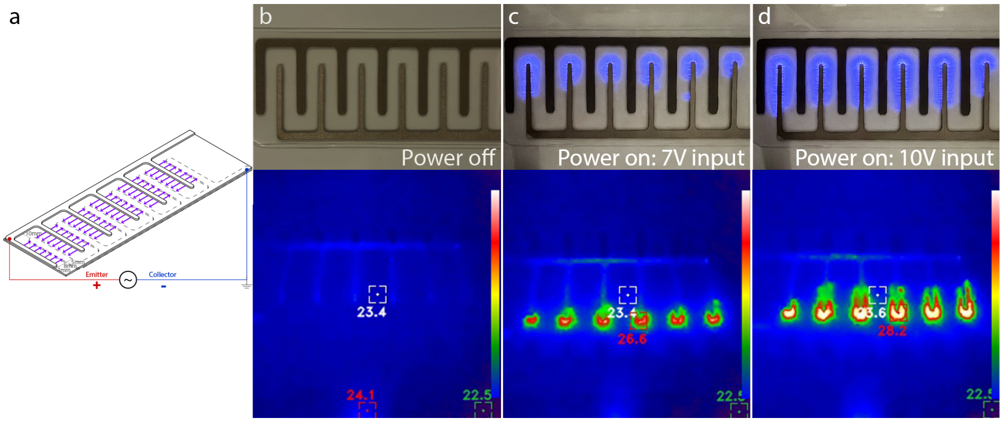

Fig. 8. Multi-electrode IoWA prototype. (a) Basic structure with emitter, collector, and spacing; the purple arrow indicates the direction of the ionized wind. (b) Real image and thermal image with the device powered off. (c) Real image and thermal image with the device powered on at a 7 V input. (d) Real image and thermal image with the device powered on at a 10 V input.

4 Design Space and Potential Applications

The unique properties of IoWA—lightweight construction, quiet operation, directional airflow, and the ability to form dense actuation patterns—open a design space distinct from existing haptic technologies. These characteristics enable interfaces where feedback can be localized, rapid, expressive, and mechanically unobtrusive. Based on these properties, we outline three potential applications:

(1) **Virtual keyboards**, where IoWA's fast and localized airflow feedback can mark each keystroke with a clear tactile cue, supporting confident and eyes-free text entry without mechanical switches;
(2) **Skill-training systems**, such as piano or instrument practice, where IoWA's low-mass, low-fatigue actuation can provide subtle guidance on finger placement or motion patterns without physical resistance;
(3) **Dynamic braille or tactile-information displays**, leveraging IoWA's reconfigurable airflow patterns to create lightweight, low-noise, and customizable haptic arrays for **visually impaired users**.

Together, these scenarios demonstrate how IoWA can extend VR and wearable interfaces beyond audiovisual immersion, enabling practical multimodal interactions grounded in the actuator's unique airflow-based expressiveness.

5 Future Work and Limitations

5.1 Characterization

This work provides an initial demonstration of IoWA's feasibility as a haptic actuator, but a full transition into a reliable HCI device requires rigorous characterization. Future studies should systematically measure voltage–current behavior, wind speed, thermal response, actuation frequency, temporal stability, and long-term durability under repeated cycling.

5.2 High Voltage

IoWA currently operates at kilovolt-level AC inputs. Prior work has explored lowering actuation voltage through electrode rearrangement [23] and by leveraging electromagnetic forces to accelerate ion migration [17, 18]. Extending these strategies to IoWA remains an important direction for improving safety and portability.

5.3 Ozone Generation

High-voltage plasma discharge produces ozone as a byproduct. Although the levels observed in our prototypes are low, prolonged exposure may cause throat irritation, underscoring the need for mitigation strategies such as ventilation, encapsulation, or materials that suppress ozone formation.

5.4 Form Factors

Several form-factor challenges remain before IoWA can be integrated into wearable or handheld haptic devices. Key considerations include heat management, acoustic behavior, the mechanical softness of the dielectric layer, and adapting the actuator to curved or compliant substrates.

6 Conclusion

In this paper, we introduced the IoWA (Ionized-Wind Actuator) as a promising candidate for future VR haptic interfaces, representing the first effort in HCI to advance IoWA from a pure prototype toward a device-level actuator. We presented an accessible and inexpensive rapid-fabrication method, demonstrated four geometric IoWA prototypes—linear, angular, circular, and multi-electrode—and outlined several potential application scenarios. Moving forward, we aim to address key challenges including high-voltage operation, ozone generation, and form-factor constraints, supported by rigorous electrical, thermal, and mechanical characterization.

Acknowledgments

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