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Super macroporous hydrogel foams with low voltage and rapid electro-response for soft actuators

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I. INTRODUCTION

Current haptic technologies mostly rely on rigid components that fail to simulate the realistic human sense of touch, particularly force and skin displacement. Soft transducers have emerged as alternatives to conventional rigid metallic electronic components for wearable haptic interfaces. Specifically, hydrogel-based transducers hold significant potential in the development of flexible wearable haptics, as they better mimic biological tissues, owing to their superior properties: viscoelasticity, high-water content, biocompatibility, and ionic- or electrical- conductivity [1]-[3].

Nonetheless, existing hydrogel-based haptics rely on electro- or vibro-tactile feedback only, which is limited to vibrations or sending electrical impulses and does not reflect realistic feedback of skin indentation. Stimuli-responsive hydrogels are promising candidates for actuators due to their biocompatibility, inherent softness, and responsiveness to various external stimuli [1]-[3]. In particular, electro-responsive hydrogels have gained significant interest due to their controllable and remote actuation. However, current hydrogel-based actuators suffer from slow response times (minutes to hours) due to diffusion-limited water transport within the hydrogel matrix [3]. Therefore, the development of a hydrogel-based actuator with rapid response times (~s) is required [2]-[4].

Here, we propose a super macroporous (SMP) polyelectrolyte hydrogel foam actuator driven by electroosmosis, exhibiting significantly enhanced actuation speed under low voltage.

II. MATERIALS AND METHODS

Acrylamide (AAm), 2-Acrylamido-2methylpropanesulfonic acid (AMPS), N,N′-Methylenebis(acrylamide) (MBAA, crosslinker), and the photoinitiator V50 were dissolved in Milli-Q water to prepare the hydrogel precursor solution. Subsequently, a foaming agent, albumin, was added and the mixture was vortexed at 3200 rpm for 120 seconds to generate hydrogel precursor foams with final albumin concentrations of 1, 2, 4, 8, and 16% (w/v) (Fig. 1(a)). To enhance foam visualization, a fluorescent dye (rhodamine B, 1 μg/mL) was added to the hydrogel precursor foam, and the resulting air bubbles were characterized by fluorescence imaging (Revolve) and measured using the image processing software Fiji. Furthermore, the effects of porosity on the hydrogel's actuation response (angular displacement per second, θ/s), swelling behavior, and viscoelastic properties were studied. Lastly, to realize an actuator suitable for mechanical stimulation based on the buckling deformation phenomenon, the porous hydrogel foam was embedded within a less swelling hydrogel. Due to the differential swelling behavior between the two hydrogels, the porous hydrogel underwent buckling deformation, forming a dome-like shape.

III. RESULTS AND DISCUSSION

The hydrogel foam actuator exhibited a highly porous structure, with air bubble sizes ranging from ~100 to 300 μm (Fig. 1(b)), which was hypothesized to enhance actuation response times by increasing the contact area with the surrounding aqueous environment and facilitating ion mobility and diffusion. Albumin concentration significantly influenced foam formation and phase separation. At low concentrations (<2 w/v%), the hydrogel precursor could not fully foam, whereas at higher concentrations (>8 w/v%), poor-quality foams with reduced stability were observed. Therefore, albumin concentrations of 2 and 4 w/v% were selected for further studies.

Under an applied electric field, the porous hydrogel foam actuator exhibited a threefold increase in bending rate ($\theta \cdot s^{-1}$) (Figs. 1(c) and 1(d)), achieving a maximum bending angle of 90°, compared to 65° for the non-porous hydrogel actuator within 60 seconds of stimulation. Additionally, the introduction of macropores led to an approximately 200% increase in swelling capacity (Fig. 1(e)), enabling buckling deformation, and resulted in a lower storage modulus, indicating reduced elastic stiffness and further enhancing the bending deformation response (Fig. 1(f)).

IV. CONCLUSION

The developed SMP hydrogel foam actuator exhibit enhanced rapid response and, therefore, has the potential for use in advanced soft haptics and human-machine interface applications. Future work will focus on developing a compact array of soft actuators with integrated electrodes and insulating encapsulation. Further characterization will assess snapping transition time, response time, and generated force.

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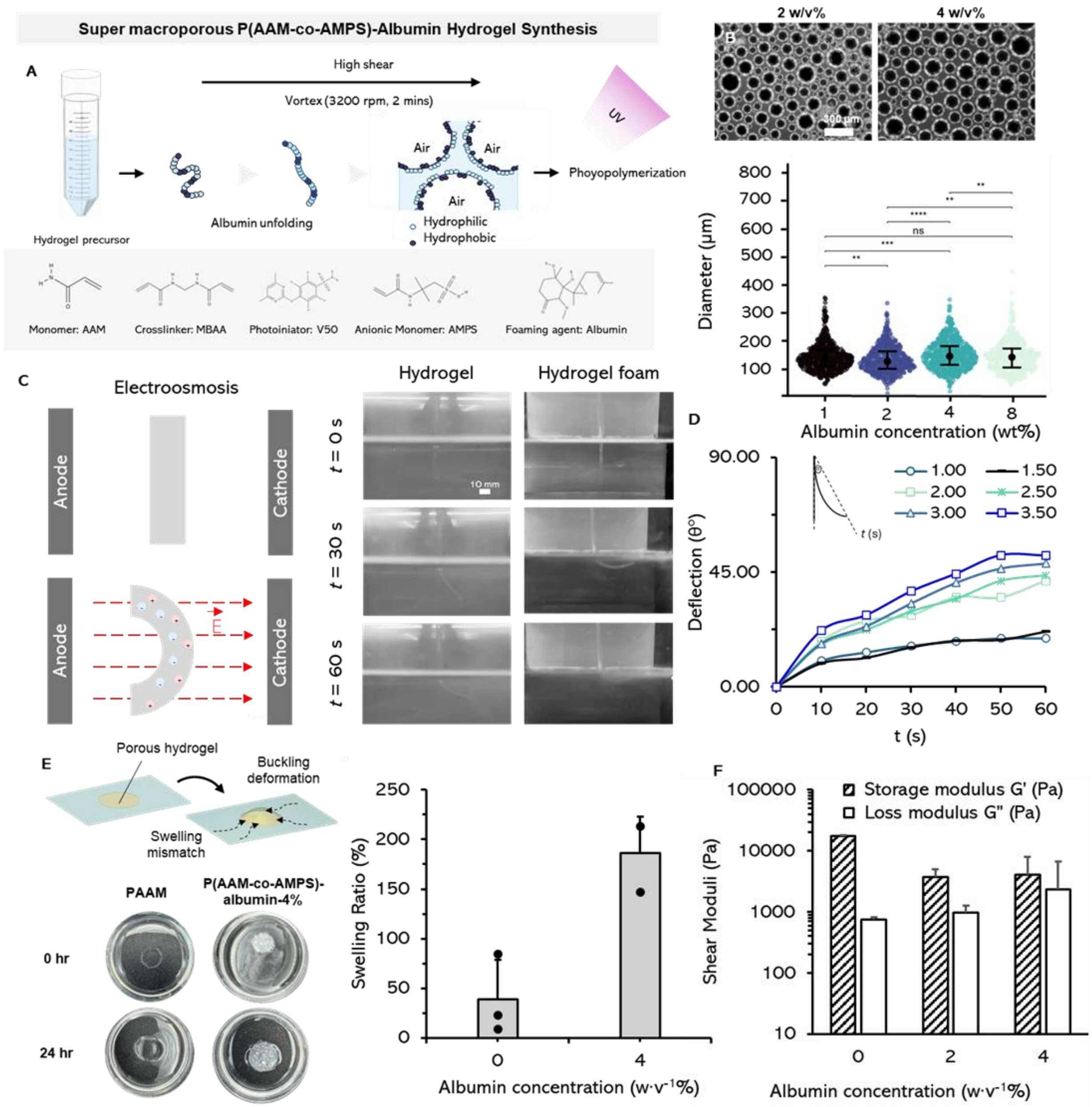

Figure 1: SMP foam hydrogel actuator. a) Hydrogel foam precursor preparation. b) Representative fluorescence images of hydrogel foam precursors with varying albumin concentrations (Scale bar represents 300 μm) and quantification of foam air bubble diameter distribution (ns not significant, $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$). c) Experimental set-up and hydrogel bending behavior experiments at 3.5 V/cm. d) The effects of electric fields on the bending behavior of hydrogel foam 4 w/v%. e) Buckling deformation and swelling properties of hydrogel and hydrogel foam. f) The effect of foaming and various albumin concentrations on the shear moduli the hydrogels.