Bioinspired Hydrogel-Encapsulated Artificial Hair Flow Sensor for Enhanced Fluid Sensing

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Introduction

Scientists and engineers have become interested in studying and mimicking the sensory systems by which biological organisms interact with their surroundings. Hair cells are fundamental to all living organisms, and these simple structures are capable of a wide variety of sensory modes for a broad range of applications – on land, in air, and underwater. Of particular interest are the microscopic hair structures encapsulated within superficial neuromasts located along the head and lateral lines of all fish. The superficial neuromasts are composed of clusters of microscopic hair cells encapsulated in a hydrogel dome called a cupula. These structures are used extensively by fish to enable their superior ability to navigate through complex and diverse hydrodynamic fields in an underwater environment. Although biological hair receptors such as these have been studied by biologists for many years, only recently has microfabrication technology enabled the practical development of artificial sensors to mimic the functions of natural systems.

Using conventional CMOS microfabrication technology, MEMS artificial hair-like microsensors are fabricated to mimic the sensory functions of the neuromasts on fish. The artificial hair sensors exhibit much lower sensitivities than the natural sensors, and the durability of the structures in a harsh, marine environment is a major concern. These issues are alleviated by integrating a hydrogel polymer on the hair structures to significantly improve both flow detection ability and waterproofing durability. However, a major challenge is that the structural cohesive properties of the hydrogel material do not allow the large cupula-to-hair aspect ratio seen in the neuromasts of fish.

Observations of fish cupulae reveal long hair-like structures called cilia located throughout the cupula, which support the viscous hydrogel to assume a structure that is several orders of magnitude longer than the hair cells. In an effort to replicate the cilia structures of fish cupulae, electrospinning is used to generate thin polymer nanofibers by ejecting a polymer solution from a capillary tube under a strong electric field. The objective of this research is to examine the feasibility of using electrospinning to build higher aspect-ratio cupula structures and analyze the conditions under which this process is optimized.

Procedure

During cupula and electrospinning experimentation, SU-8 hair structures were grown on Si wafers by photo-lithography to simulate the structures to be fabricated on cantilever MEMS sensors. PEO-TA was dissolved in methanol (20% by wt.), and a photo-initiator was added to the polymer solution. The polymer solution was drop-cast on the hair structure and dried. The specimen was irradiated by UV radiation under a photo-mask such that only the polymer immediately near the hair structure was exposed. Upon swelling in water, only the photo-crosslinked polymer at the hair structure remained as a hydrogel, while the rest of the polymer dissolved in solution. Electrospun nanofibers were created by connecting a electrode to a solution of PCL in acetone (17.5% wt.) held in a capillary tube, and a high voltage source was used to create an electric field that ejected a thin polymer fiber from the capillary to the collection plate. A hair structure was sputtered with Au so that the specimen would be conductive, and the specimen was positioned at the collection plate such that fibers would collect at the hair. Experimental parameters such as the applied voltage, separation distance, polymer viscosity, and electric field were varied to produce the optimal characteristics of electrospun fibers for high-aspect cupula. Polymer was drop-cast on the electrospun fibers and hair structure, UV-exposed, and swelled in water.

Results

Once immersed in water, the crosslinked polymer adjacent to the hair structure swelled to a water content of approximately 90% and assumed a dome-like shape with height approximately the length of the hair. The sensitivity characteristics of hair structures on piezoresistive mechanical sensors were compared with and without hydrogel cupulae by observing signal response in a controlled marine environment. Figure 1 provides the data observed during experiments of steady-flow and oscillating frequencies, and the data reveals that the cupula-hair design demonstrated a four-fold decrease in the lower threshold limit of flow detection, amplification of the signal output by two orders of magnitude, and the broadening of the dynamic range of the sensor by efficient suppression of background noises within the viscously damped cupula.

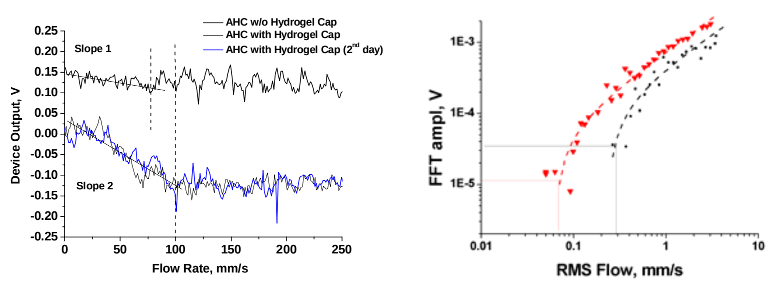

Fig. 1: (a) Steady flow rate experimental data (b) Oscillating frequency flow experimental data

Through fine tuning of the applied voltage, separation distance, electric field geometry, and PCL solution viscosity, electrospinning produced single, non-woven fibers of approximately 1.3 µm in diameter. Concentric copper rings were placed between the capillary and collector to act as electric field lenses to focus the trajectory of the jet upon the hair structure at the collector, and this method produced electrospun fiber structures taller than 30 mm. Structures as tall as 10 mm could successfully support drop-cast polymer, which swelled in water to form a hydrogel cupula of approximately the same height.

Conclusions

Micro fabrication techniques could be used to fabricate artificial hair flow sensors that functioned similarly to the superficial neoromasts of fish. The sensitivity characteristics of the sensors were dramatically improved with the application of a hydrogel cupula on the hair structure. Electrospinning could be used to produce tall PCL fibers to support high aspect-ratio hydrogel cupulae.