

# MICROCHIP-BASED POLYMERIC MULTIFUNCTIONAL MICROBOTS

Gu-Han Kwon<sup>1</sup>, Joong-Yull Park<sup>1</sup>, Eun-Joong Lee<sup>1</sup>, Megan L. Frisk<sup>2</sup>,  
David J. Beebe<sup>2</sup> and Sang-Hoon Lee<sup>1</sup>

<sup>1</sup>College of Health Science, Korea University, Republic of Korea and

<sup>2</sup>Department of Biomedical Engineering, University of Wisconsin – Madison,  
Madison, WI 53706, USA

## ABSTRACT

Recently, electromechanical robots that simulate the locomotion of human walking, snake slithering, and worm crawling have been developed[1-2]. We mimic both the structure and function of natural movement by creating soft, polymeric aquabots that are capable of complex functions in aqueous environments.

**KEYWORDS:** Biomimetic, photopolymerization, Electroactive hydrogel

## INTRODUCTION

Here we present small (micro- to millimeter), soft aquabots that combine multiple functionalities to perform multifunctional operations in aqueous environments, effectively simulating their natural counterparts.

## EXPERIMENTAL

Four parameters to control electroactive hydrogel actuators are (1) magnitude of the applied potential, (2) angle of the applied potential, and both (3) width and (4) length of the actuator. Fig. 1a illustrates the behaviour of a rectangular gel actuator under changing parameters.

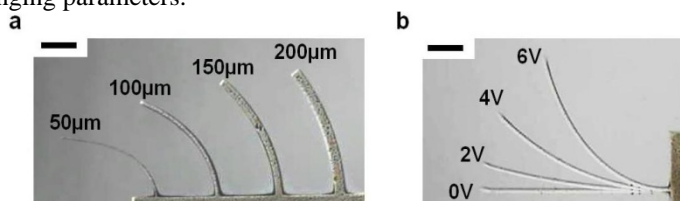
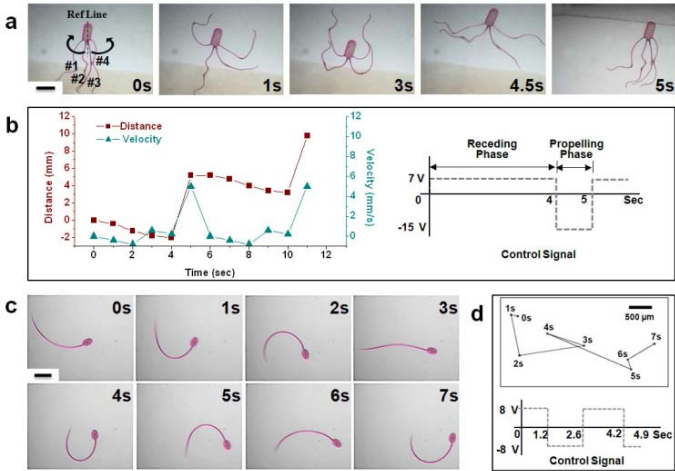


Figure 1. Actuation performance of hydrogel structure

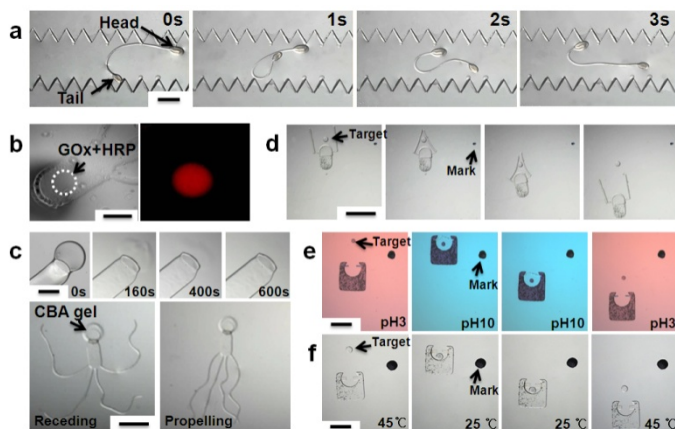
In aqueous solutions, the aquabot flagellum oscillates in response to spatially alternating electrical control signals (Fig. 2c). Continuous application of the control signals results in a mean translational movement. The measured locomotion path of the sperm aquabot corresponded to maximum and mean speeds of 1.35 mm/s and 0.32 mm/s, respectively (Fig. 2d). In very low Reynolds number ( $Re \ll 1$ ), the reciprocal motion of an object does not create any net movement. Therefore, at such small scales where the viscous force dominates, more effective propulsive mechanisms are utilized, such as the “flexible oar”, “cork screw”, and “rotating flagellum”. However, the scale of the sperm aquabot is on the order of a few millimetres and the typical  $Re$  is 1-10. This implies that the inertial forces should be considered and that temporal control will influence net motion; thus, the control of

velocity is an integral factor in determining the resulting motion of the aquabot. Accordingly, when the control signal is symmetric, the bots do not produce net motion; when asymmetric control signals were applied (both amplitude and duration) net motion was observed for the sperm aquabot. The looper aquabot could therefore adapt, or respond, to a rough surface and move along the saw-toothed “leaf” (Fig. 3a), much like the real looper worm. Second, a glucose-sensing aquabot was fabricated (Fig. 3b).

Rather than rely on a fluorescent readout - which can be complicated by expensive instrumentation - a sensor based on gel degradation was incorporated using either a disulfide-crosslinked polymer or a trypsin-sensitive peptide crosslinker as the aquabot “head” (Fig. 3c). Fig. 3d shows the aquabot grabbing the circular target upon application of an electric field and then moving to a specific position via magnetic control. A pH-responsive delivery aquabot was then fabricated with hydroxyethyl methacrylate (HEMA) arms and a magnetic body; its behaviour in different pH solutions as a function of time is illustrated in Fig. 3e. Finally, a temperature-responsive delivery aquabot was developed with (NIPAAm) arms that could expand at lower temperatures and contract at higher temperatures (Fig. 3f).



*Figure 2. Movement analysis of aquabots. a, Locomotion of octopus aquabot under an electric field., scale bar: 1 mm. b, Velocity and distance profile for two periods with corresponding control signal. c, Behavior of sperm aquabot with changing voltage, scale bar: 1 mm. d, Trajectory of sperm aquabot and corresponding control signal.*



**Figure 3.** Stimuli-responsive microbots. *a*, Structure-responsive looped worm aquabot wanders inside the narrow saw-tooth channel, exhibiting its ability to change direction within a confined space. Depending on the structure, the looped aquabot shows diverse behavior, scale bar: 1 mm. *b*, Glucose-responsive aquabot fabricated with an “eye” containing immobilized HRP and GOx (left) that, scale bar: 500  $\mu$ m. *d*, pH-responsive carrier aquabot possesses HEMA legs that shrink at acidic pH ( $\sim 3$ ) and swell at basic pH ( $\sim 10$ ). Using this expansion/contraction mechanism, the aquabot can catch, drag (using an external magnet), and release a target, scale bar: 1 mm. *e*, Temperature-responsive carrier aquabot performs similarly to pH-responsive microbot, but is fabricated with NIPAAm temperature-sensitive legs, scale bar: 1 mm. *f*, Chemical-responsive drug delivery aquabot with a trypsin-sensitive SNAP gel “head” that completely dissolves when exposed to a trypsin solution for 30 min; phase and fluorescent images were taken, scale bar: 500  $\mu$ m.

## CONCLUSIONS

We have demonstrated a simple fabrication technique that uses a combination of stimuli-responsive and non-responsive polymers for realizing miniature aquabots that exhibit a range of diverse functionalities.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] Collins, S., Ruina, A., Tedrake, R., & Wisse, M. Efficient bipedal robots based on passive-dynamic walkers. *Science* 307 (5712), 1082-1085 (2005).
- [2] Ijspeert, A. J., Crespi, A., Ryczko, D., & Cabelguen, J. M. From swimming to walking with a salamander robot driven by a spinal cord model. *Science* 315 (5817), 1416-1420 (2007).