Undulatory Locomotion with a Soft Robotic Fishtail: Steps towards Closing the Loop with Soft Sensors for Body Stiffness Modulation.

Ardian Jusufi[1,*], Daniel Vogt[2], George Lauder[2], and Robert Wood[2].
[1]Max Planck Institute, Germany. [2]Harvard University, Cambridge, USA. [*]Correspondence: ardian@is.mpg.de

Undulatory motion of the body in the lateral plane is the dominant mode of locomotion in fishes, reptiles and many amphibians. While numerous studies of body kinematics and muscle activity patterns have provided insights into the mechanics of swimming (1), it has not been possible to investigate how key parameters such as the extent of bilateral muscle activation affect propulsive performance due to the inability to manipulate muscle activation in live, freely-swimming fishes. Here, we utilize actively-controlled soft bending actuators for shape changes on the body to gain insight into undulatory locomotion and mechanisms for body stiffness control. Two pneumatic actuators were attached on each side of a flexible panel (2, Fig. 1 A-B) with stiffness comparable to that of a fish body. To study how bilateral contraction can be used to modify axial body stiffness during swimming, a parameter sweep of contraction phasing and frequency was performed. Thrust production by soft actuators was measured at cyclic undulation frequencies ranging from 0.3 Hz to 1.2 Hz in a recirculating flow tank at water speeds up to 28 cm/s. Moreover, hyperelastic soft sensors were embedded for curvature estimation of the undulating body (3, Fig. 1 C).

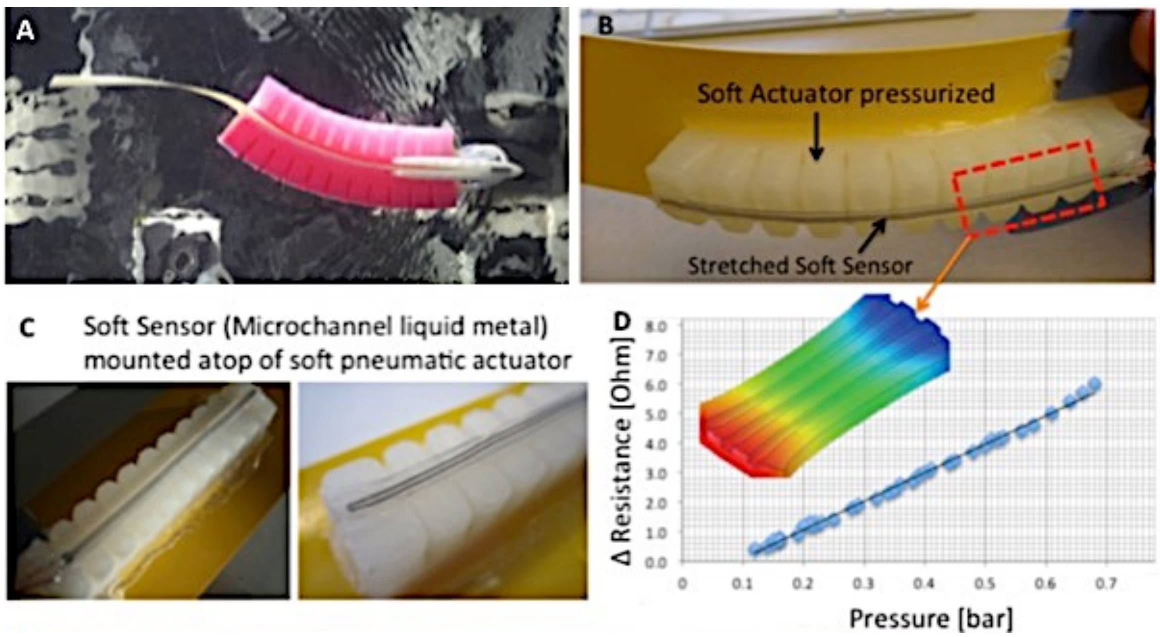

Fig. 1. Soft robotic swimming platform (A) with actuators in a pressurized state (B). Soft sensor integrated with soft actuator (C). Plot shows the measurement of electrical resistance over time (D) with elastomeric material (inset).

To close the loop soft sensors were mounted laterally atop the pneumatic actuator (Fig. 1 B). Soft sensors contained micro-channels filled with liquid metal eGaIn (3). Overall, the robot generated more thrust at higher tail beat frequencies, with a plateau in thrust above 0.8Hz. Self-propelled speed was found to be 0.8 foil lengths per second (~13cm/s). This active pneumatic model is capable of generating considerable thrust, and of producing substantial trailing edge amplitudes with maximum excursion of 1.4 foil lengths. Altering the extent of bilateral co-contraction ranging from 17% to -22% of the cycle period showed that maximum thrust is generated with some amount of simultaneous bilateral contraction of approximately 3% to 5% of the cycle period; thrust was substantially reduced for conditions of greatest antagonistic overlap in left-right actuation, and also for the largest latencies introduced when the system is exposed to water flow. This marks the first time the soft sensor was tested under water, and despite hydrodynamic pressure, it allowed for measurement of strain changes of body curvature. During bending of the soft pneumatic actuator the greater fin curvature and associated length changes correlated with changes in electrical resistance in the liquid metal within microchannels. Resistance increased proportionally with bending, thus enabling control of fin displacement amplitude. Soft sensor information will allow for applying the necessary pressure correction to remain at the desired body-tailfin curvature, at a range of water flow speeds. This platform provides a biorobotic model for exploring body stiffness modulation and swimming performance experimentally.

Refs.:(1) Phys Rev Fluids [2016] 1:073202. (2) Soft Robotics [2017] 4(3):202. (3) IEEE Sensors [2012] 12(8):2711.