Exploring aquatic locomotion using an active soft robotic fish-like model

I. Background

Fish swim using a combination of active and passive movement [1, 2]. Muscles drive the movement in active swimming while passive motion is a result of fluidic forces on the body. An established model for researching fish locomotion uses a plastic passive foil (driven at the leading edge by a motor) to mimic undulatory motion. This simple model has had tremendous impact in the ability to investigate the effects of key variables on swimming (e.g. [3–5]). However, the results apply solely to passive motion. The passive flapper is sometimes too simple and the results do not always agree with live fish swimming data [5]. An active model is needed to fill the gaps in previous research and to advance the field.

Fish-like 'hard' robotic systems with gears and motors are active but complicated, and can be difficult to maintain or alter [6]. This hinders exploring fundamental questions. Soft robotic pneumatic actuators ("pneunets") are simple silicone rubber constructs that are inflated to produce motion [7]. The Lauder Lab at Harvard University developed a novel, active platform using pneunets. This apparatus is capable of producing positive thrust and undulatory motion [8]. (The complete apparatus is hereafter referred to as the 'pneufish'.)

As a PhD student in Dr. George Lauder's Lab at Harvard University, I will use and modify this novel pneufish platform to investigate important aspects of the hydrodynamics and control of fish locomotion.

II. Project Design

Pneufish Design

Pneunets have air channels connecting each individual segment (Fig. 1A). When air is pushed into the channels, the segments inflate and push against each other, causing a unidirectional curvature (Fig. 1B). A pneunet is glued to each side of a flexible backbone foil, which is attached to a rod housing a force sensor and 6-axis ATI torque transducer (Fig. 1C). By alternating which pneunet is inflated in a periodic pattern (controlled by an arduino circuit), the pneufish exhibits undulatory motion. The forces and torques produced by the pneufish are captured by the transducer.

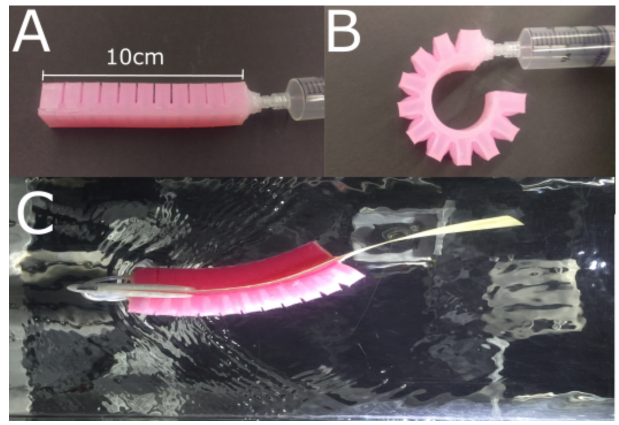

Fig. 1. A) An uninflated pneunet connected to a syringe. B) A fully inflated pneunet. C) As seen from below, a pneufish operating in water. The cuff (left end of the pneufish) connects to a dorsally-located vertical rod housing the force and torque transducer. Image C adapted from [8].

Aim 1: Comparing body stiffnesses

Rationale: Researchers have established that body stiffness affects locomotion by comparing passive foils of varying rigidity [3, 4]. However, passive foils cannot actively modify stiffness during motion. How does actively changing body stiffness influence the hydrodynamics of swimming? I will determine the hydrodynamic effects of modulating stiffness at different points of the undulation cycle. **Significance:** Control of stiffness is an unexplored and critical aspect of aquatic locomotion. **Hypothesis:** By increasing or decreasing the overall body stiffness at critical points in the undulation cycle, the pneufish will swim more or less efficiently than with a constant stiffness. (Fig. 2).

Methods: To establish a relationship between internal pneunet pressure and stiffness, I will directly measure pressure using a digital pressure regulator the resultant curvature of the pneunet on a flat surface. With this pressure-stiffness relationship, I will investigate the

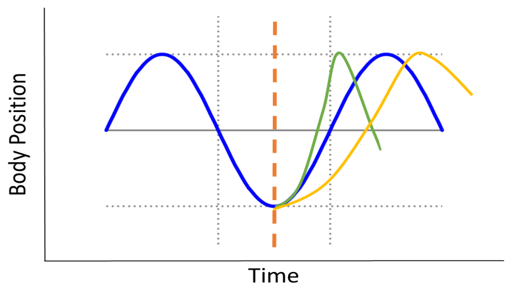

Fig. 2. Predicted results of Aim 1. Body stiffness is modulated at the time corresponding to the orange dotted line. If stiffness is increased (green), the cycle will shorten. If stiffness is decreased (yellow), the cycle will lengthen.

effects of changing the stiffness at different points of the undulation cycle. The force and torque data will be analyzed to determine under what conditions modifying stiffness could increase the swimming efficiency.

Aim 2: Comparing wakes structures

Rationale: When anguilliform fish (e.g. eels) swim, they produce two pairs of vortices per undulation cycle [9]. This is called a 2P wake. In studies comparing the wake structure produced by passive foils and fish, researchers found that the foils produced an unstable 2P wake, whereas fish produce fully stable wakes [5, 9]. Is it possible this loss of stability is due to the foil passivity? I will evaluate the pneufish hydrodynamics under variable conditions to ascertain if the posterior regions of live fish are under active or passive control. **Significance:** Stable wakes indicate fine-tuned musculature control necessary for efficient movement [9]. **Hypothesis:** Comparing pneufish, live fish, and passive foil hydrodynamics will show that active control of the posterior region is critical to achieving a stable 2P wake structure at high flow speeds and high undulation frequencies.

Methods: The current pneufish design poses issues to the experimental hydrodynamics. I will redesign the pneufish such that the pneunets are internalized inside a flexible elongated shell, producing a smooth, fish-like surface with internal activation. Pneufish will be actuated within a large parameter space (e.g. undulation frequency, foil length, and flow speed), modeling swimming anguilliform patterns. The hydrodynamics will be visualized using particle image velocimetry (PIV) and Optoengine solid state lasers. The data will be analyzed using standard PIV processing techniques used for many years in the Lauder Lab [3–5]. I will use ANOVA to compare vortex strength and diameter among treatments.

III. Intellectual Merit

My study will advance the field of aquatic locomotion by solidifying a new physical platform for asking complicated questions about fish and other undulatory organisms, and the results will contribute crucial data to long-standing areas of research within the field. Broadly, the results can be applied to the design of underwater autonomous vehicles (UAVs), as has been done previously. By modifying their design to capitalize upon the integration of active and passive features, UAVs can become significantly more efficient.

IV. Broader Impacts

I will disseminate the results of this project through publications, posters, conference presentations (e.g. SICB, APS Div. of Fluid Dynamics), and a professional website and blog [10]. I will use the Bok Teaching Center at Harvard University to make multi-media presentations to showcase the concepts in this proposal, which will be used in appropriate media, such as the Lauder Lab YouTube page. I will use my research as a means to mentor interdisciplinary undergraduates. Additionally, the pneufish works just as well on dry surfaces as it does in water, making my project fairly mobile. I plan to utilize this unusual feature to give demonstrations at schools, the Harvard Natural History Museum, and the Cambridge Science Festival.

1. Fish, F. et al. *Annu. Rev. of Fluid Mech.* (2006). 2. Lauder, G. *Exp. Fluids* (2011). 3. Feilich, K. et al. *Bioinspir. Biomim.* (2015). 4. Lucas, K. et al. *Bioinspi. Biomim.* (2015). 5. Lim, J. et al. *Bioinspir. Biomim.* (2016). 6. Lauder, G. *Annu. Rev. of Mar. Sci.* (2015). 7. Mosadegh, B. et al. *Adv. Funct. Mater.* (2014). 8. Jusufi, A. et al. *Soft Robotics* (In press). 9. Leftwich, M. et al. *J. of Exp. Biol.* (2012). 10. http://inzaneresearch.wordpress.com.