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Prototype of a Fish Inspired Swimming Silk Robot

Cassandra M. Donatelli*1, Sarah A. Bradner*2, Juanita Mathews3, Erin Sanders4, Casey Culligan5, David Kaplan6, Eric D. Tytell7

Abstract—Elongate fishes have evolved hundreds of times throughout the tree of life. They occupy many aquatic environments, from streams and ponds to the deepest parts of the ocean. Due to their long body and numerous vertebrae, they are also highly flexible animals, which makes them useful as bio-inspiration for designs in the field of soft robotics. We present a biodegradable soft robot prototype, inspired by elongate fishes. The robot’s body is primarily composed of a silk hydrogel with embedded fibers to mimic the structure of natural fish skin. When actuated at the front, the flexible gel prototype mimics the undulatory gait of elongate fishes such as eels. Our goal is to use this prototype as a tool to understand the functional consequences of the fibers and other aspects of elongate body morphology in fishes, and to help develop robotic devices for exploring environments previously inaccessible to humans.

I. INTRODUCTION

Fish are the largest and most morphologically diverse group of vertebrates [1], with the ability to maneuver through almost every aquatic habitat on earth, from fast moving mountain streams to complex coral reefs to the deepest ocean trenches. Though fish are vertebrates, and therefore have a spine made from rigid bone, some species are extremely flexible and move like completely soft animals, such as worms and caterpillars [2].

Many elongate fishes, such as eels, gunnels, and oarfish, have evolved to be extremely flexible. They achieve this flexibility because they have eighty or more individual vertebrae in their vertebral columns [3]–[5]. This means that each individual vertebral joint bends relatively little, even when the fish twists and bends at extreme angles to maneuver through crevices and under rocks. The result is a body which behaves more like a continuous flexible elastomer than a stiff jointed animal.

Since the backbone in these fishes is very flexible, they rely on other parts of their anatomy for structural support. One major structure is the skin. Fish skin is a composite material composed of two layers of collagen fibers. The inner layer (called the stratum spongiosum) is composed of an irregular mesh of collagen fibers. The outer layer (the stratum compactum) is composed of highly organized fibers woven into crossing helices around the body, like the fibers in a garden hose, creating an anisotropic material [6] (Fig. 1).

We hypothesize that this organization allows elongate fishes to control their locomotion while remaining flexible. This combination of control and flexibility makes elongate fishes a great source of inspiration for soft swimming robots.

There have been numerous fish-inspired robotic designs [7]–[12]. Though many fish are fairly flexible animals, most of these robots are made from stiff materials which do not mimic the system well. There is a need for robots made from soft, biocompatible materials to explore complex and delicate oceanic habitats [13].

To design soft robots that mimic the flexibility of elongate fishes, we need materials that mimic the material properties of their bodies. Silk is an excellent candidate material. It is a polymer that provides a biocompatible, degradable, and mechanically robust materials system for material design. Silk can be formed into many different formats, including films, gels, sponges, fibers and hard materials. Each of these formats possesses a range of mechanical properties, enabling versatile building blocks for bioinspired hierarchical design. Silk has two other advantages. It can be completely degradable, a desirable quality in soft robotic applications [13]. It is also compatible with other biological systems, and it can be loaded with drugs, which makes it a material with promise for future applications in the biomedical field. These properties make silk desirable for bio-inspired robotics.

This work presents a prototype for an eel-inspired soft robot fabricated from silk fibroin materials. We fabricated
silk hydrogels using an enzymatic-mediated oxidative cross-linking process [14]. We also used silk elastomeric fibers that have 1 MPa to 5 MPa ultimate strength and 100–400 percent ultimate strain [15]. By combining these two materials, we produced a composite anisotropic material, similar to fish skin.

II. RELATED WORK

A. Fish Inspired Robots

Both scientists and engineers have created bioinspired fish robots to navigate real world underwater environments [9], [10], [16], inspire new techniques and capabilities [7], [11], [12], [17], [18], explore the functional consequences of different body shapes [19], [20], and mimic fish behaviors for biological studies [12], [18], [20], [21]. Robots have also been inspired by elongate animals such as eels [16], [17] and snakes [22]–[24]. Most of these robots are not soft, and are even actuated with stiff joints attached to hard components. A few have soft components such as a posterior half of the body or tail [11] and fins [12], but none compare with the flexibility of elongate fishes.

Many autonomous underwater vehicles (AUVs) have been inspired by fish. For example, Pilotfish is a robot that maneuveres extremely rapidly using flexible fins arrayed around a hard hull [10], [25]. Other, more traditional drones, like OceanServer Iver2 (Ocean Server, Fall River MA, USA), REMUS (Woods Hole Oceanographic Institution, Woods Hole, MA, USA), SUBMARAN (Ocean Aero, San Diego, CA, USA), have a standard fusiform body shape that is inspired by fish.

There have also been several recent studies describing relatively soft bodied fish robots. Marchese et al. [11] used hydraulic actuators to flex a soft polymer tail, which propelled a 3D printed head and body through the water. Esposito et al. [12] created a flexible fish robot with soft fins to mimic stiffer fish like bass and bluegill. Ijspeert et al. [17] developed a robot that mimics a salamander by adding several rigid components allowing the system to slither on land and in water.

Though all of these robots have soft components, none of them are completely flexible, and all would be both susceptible to damage when interacting with a tight or unpredictable environment.

B. Biomechanics of the Skin

Many researchers have studied the skin of fishes [6], [26]–[29], quantifying its basic structure in several species, including eels, tuna, trout, hagfish, and sharks. In all fishes, the skin has a cross array of helical fibers that wind around the fish’s body. The angle of the cross-woven collagen fibers play an important role in function [27] and, in some species, may help to transmit muscular forces toward the tail [30].

In particular, elongate fishes could be characterized as fiber-wound tubes. Several studies have discussed these structures, and proposed optimal fiber angles to support different types of movements [31]. For example, to prevent kinking and resist longitudinal expansion of the tube during locomotion, the optimal fiber angle is 55 degrees, but to resist torsion, the optimal angle is 45 degrees [31].

We therefore examined the skin morphology of several species of elongate fishes in order to determine appropriate angles for silk fibers in our mimetic robot design.

III. DESIGN AND DEVELOPMENT

A. Fish Skin Morphology

We collected six species of elongate fishes from the Pacific northwest to gain broader inspiration for prototype structures. To measure the fiber angles, the fish were sacrificed, fixed with formalin, and preserved in 70% ethanol. The skin of several individuals from each species was removed from the body and the pigment was cleared away using standard methods [32].

Once prepared, the skin was observed under polarized light to enhance the visualization of organized collagen fiber layers (Fig. 2). The fiber angle (defined as the angle between the fibers and the long axis of the body) was measured at several points along the length of the body in both the forward and backward direction. Forward was defined as the acute angle made by the fiber and the horizontal axis facing anterior, and backward was the angle facing posterior. In all six species, the fiber angle was between 45° and 55° (Fig. 3). We therefore chose 50° as the fiber angle for our initial prototype, though we hope to test models with fiber angles across the range of those seen in elongate fishes in the future.

B. Preparation of Silk-Peroxidase Precursor Solution

Silk aqueous solutions were prepared using previously established protocols [33]. Briefly, 10 g of Bombyx mori silkworm cocoons were extracted for 30 min in a 0.02 M Na₂CO₃ (Sigma-Aldrich, St. Louis, MO) aqueous solution and rinsed three times for 20 min to remove sericin. The degummed cocoons were dried in a fume hood for more
than 24 hours and then dissolved in a 9.3 M LiBr (Sigma-St. Louis, MO) solution for 3 h to 5 h at 60 °C. The solution was dialyzed for 2 days against distilled water using regenerated cellulose membranes (3500 MWCO, Thermo Scientific, Rockford, IL). The solubilized protein solution was then centrifuged twice (9700 RPM, 20 min, 4 °C) and the concentration was determined by placing a wet volume of solution in a 60 °C oven to measure the final dry weight, where the final solution was between 5-7 w/v%. Silk-horse radish peroxidase (HRP) hydrogels were prepared following our previously established protocols [14], [15], where HRP, type VI (Sigma-Aldrich, St. Louis, MO) lyophilized powder was added to deionized water to prepare a stock solution of 500 Units/mL. The stock HRP solution was added to the silk solution at 50 Units of HRP (20 µL) per 1 mL of 5% silk solution (30 min minute degumming (md)). Enzymatic cross-linking was induced with 10 µL of 330 mM hydrogen peroxide (Sigma-Aldrich, St. Louis, MO) per 1 mL of silk solution and gentle pipetting of all three solutions was performed prior to fiber casting. Fibers were fabricated using previously established methods [15], wherein gel precursor solution was cast into 1 mm inner diameter silicone tubing. Post-casting, tubing was placed in a 60 °C oven for 24 hours. Fibers were ejected and then placed into deionized water to reach swelling equilibrium.

C. Molding

Elastomeric fibers, or dry degummed silk fibers, were wound around two parallel combs at 50° to the long axis

than 24 hours and then dissolved in a 9.3 M LiBr (Sigma-St. Louis, MO) solution for 3 h to 5 h at 60 °C. The solution was dialyzed for 2 days against distilled water using regenerated cellulose membranes (3500 MWCO, Thermo Scientific, Rockford, IL). The solubilized protein solution was then centrifuged twice (9700 RPM, 20 min, 4 °C) and the concentration was determined by placing a wet volume of solution in a 60 °C oven to measure the final dry weight, where the final solution was between 5-7 w/v%. Silk-horse radish peroxidase (HRP) hydrogels were prepared following our previously established protocols [14], [15], where HRP, type VI (Sigma-Aldrich, St. Louis, MO) lyophilized powder was added to deionized water to prepare a stock solution of 500 Units/mL. The stock HRP solution was added to the silk solution at 50 Units of HRP (20 µL) per 1 mL of 5% silk solution (30 min minute degumming (md)). Enzymatic cross-linking was induced with 10 µL of 330 mM hydrogen peroxide (Sigma-Aldrich, St. Louis, MO) per 1 mL of silk solution and gentle pipetting of all three solutions was performed prior to fiber casting. Fibers were fabricated using previously established methods [15], wherein gel precursor solution was cast into 1 mm inner diameter silicone tubing. Post-casting, tubing was placed in a 60 °C oven for 24 hours. Fibers were ejected and then placed into deionized water to reach swelling equilibrium.

D. Assembly

Once cured, the silk gel sheet was modified in three ways for the testing process(Fig. 5): (1) cut into a single layer hydrofoil 2.5 mm thick, (2) cut into two identical foils, sutured together to add thickness (5 mm) to the prototype, (3) assembled into a hollow tube by rolling the gel lengthwise. To secure the seam, silk thread was stitched along the length of the robot and the posterior end of the robot was stitched together to mimic the shape of an elongate fish. This approximates the flat tail of an eel or gunnel, and allows the robot to produce thrust in the forward direction when actuated.

E. Passive Testing

To test the initial prototype, the anterior end was fixed to a 0.25 inch rod by suturing the anterior end using silk thread. The rod was attached to a motor controlled by an Arduino Uno. The robot swam by oscillating at a range of frequencies...
Fig. 5: **Assembled Prototypes and Kinematics.** The three prototypes were actuated over a range of pitching angles and frequencies. Amplitude has been normalized by the body length of the model (BL). The resulting tail beat amplitude depended on both the frequency (lower frequency resulted in lower amplitude) and rotation angle. **A)** A single sheet of silk gel cut to mimic a hydrofoil. **B)** A two silk gels sutured together to add thickness to the foil. **C)** The flat silk film rolled into a tube.

between 0.5 Hz to 2 Hz and with rotation angles from 10° to 45°.

Trials were performed in a flow tank and recorded using a high speed Phantom cameras (Phantom M120, Vision Research, Wayne, NJ, USA). The resulting videos of the silk robot were digitized using the custom Matlab software described [34] as well as ImageJ (imagej.nih.gov). Tail beat amplitude (body lengths (BL)) and tail beat frequency (Hz) were measured for all videos using Matlab R2016A (MathWorks, Natick MA, USA).

**IV. RESULTS: PROTOTYPE COMPARISON TO FISH KINEMATICS**

The results of the video analysis are shown in Figure 5. The tail beat amplitude for the 10° and 15° trials ranged from 0.26 BL to 0.51 BL, where BL is the body length. This range is larger but similar to elongate fish in nature which swim with an amplitude ranging from 0.025 BL to 0.35 BL [35]–[37]. This may be due to the fact that the prototype, though flexible, is slightly stiffer than most elongate fishes.

For the 30° and 45° trials, the amplitudes were much larger, beyond the range of amplitudes typically found for fishes. This difference was due to the fact that fish typically do not move their heads through such large angles during steady swimming [38].

We also compared the midline kinematics of the double foil robot with an elongate fish, the rock prickleback *Xiphister mucosus* (Fig. 6). The traces showed a similar number of waves along the body. The amplitude of these waves, however, was smaller than those of the fish. This difference may be a result of the stiffer silk material, or the fact that we are actuating the device at a single point, where fish have muscle all along their bodies. However, with the tunability of the silk format, multiple parameters can be adjusted to achieve a gel more in line with the flexible of elongate fish in the future. Parameters to change stiffness include the cross-linking variables and fabrication drying time. Parameters such as hydrogen peroxide, silk, and HRP concentrations can be changed to alter overall mechanical properties [39]. Additionally, various fabrication drying times alter crystallinity of the gel and therefore, gel stiffness.

Fig. 6: **Comparison between Fish and Robot.** (Above) Midline traces of the silk robot swimming at a frequency of 0.5 Hz. The black circle represents the rod actuating the prototype. (Below) Midline traces from a video of an elongate fish (*Xiphister Mucosus*) swimming with a tail beat frequency of 1.54 Hz. The prototype is beginning to show multiple waves along the length of the body similar to the fish.
Optimizing these parameters will produce a material with desired flexibility, in line with elongate fish swimming, for soft robots.

V. ACTUATION OF SILK FILM

In future work, we plan to actuate the device with biological actuators. To prepare for this step, mouse myoblast cells (C2C12s) with a stably integrated transgene encoding the optogenetic actuator ChIEF with an IRES dsRED2 driven by a CAG promoter [40] were cultured in Dulbecco’s Modified Eagle Medium (supplemented with 10% fetal bovine serum and 1% antibiotic/antimycotic) (Life Technologies, Grand Island, NY), and were fed every 3 days and then seeded onto elastomeric fibers at cell passage 8-10. Silk-HRP gel formulations used above were adapted for seeding cells onto elastomeric fibers at a density of \(5 \times 10^5\) cells/mL of gel solution. Elastomeric fibers will be preferentially placed at a 50° within the solution to mimic muscle attachment to fish skin. The gel-cell solution will be cast on top of the fiber to attach to composite film and provide a site of actuation. Cell contraction will be initiated with a flexible LED emitting light between the wavelengths of 450 nm to 495 nm [40, [41].

VI. DISCUSSION

We describe a prototype for a fish-inspired soft robot made of silk fibroin. To mimic the flexible skin of elongate fish, we used an elastomeric silk hydrogel. The gel was embedded with anisotropically aligned degummed silk fibers, to approximate the organized collagen fibers of fish skin. Here, we demonstrate silk as a useful material for generating flexible robots inspired by elongate fishes.

In ongoing and future studies, complexity and autonomy will be incorporated into this initial prototype using biological muscle-based actuators placed along the silk composite network, based on measurements of muscle activity in swimming fishes. These actuators will be fabricated from myoblast cells by either applying cell-gel solution on top of elastomeric fibers at designated areas, or by soaking elastomeric fibers in cell solution for adherence onto the silk fibers. The cells used for actuation are mouse muscle myoblasts (C2C12 CAG ChIEF IRES dsRED2) that have been optogenetically modified to contract with a pulse of blue light (450 nm to 495 nm)[40]. The actuator ChIEF was chosen due to its ability to withstand repeated stimulation without loss of function. The cells will be activated using flexible battery-powered LEDs that can be added directly to the fish robot.

The silk robot presented here demonstrates progress toward a robot with superior biocompatibility, biodegradability, and flexibility than previous soft bodied fish robots. Due to greater compatibility with a range of environments, the potential applications are large. The silk robot could impact a range of fields, such as biology, ecology, and anthropology. With the addition of small sensors, such robots would be useful tools for exploring previously unreachable places in the ocean such as reefs, shipwrecks, deep sea habitats, small caves, or collapsed areas in ships and ancient ruins, with little to no impact on the environment.

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