**A Soft-Robotic Harbor Porpoise Pectoral Fin Driven by Coiled Polymer Actuators as Artificial Muscles**

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**1. Introduction**

The complex movement of biological organism is caused by the contraction and relaxation of muscles on the skeletal system. The performance of biological muscles is unmatched by man-made actuators; thus, scientists have been striving to construct systems and materials to mimic similar motions for robotics applications. Early achievements are seen through conventional robots where direct current (DC) motors and hydraulics are the driving forces for motion. Hard robotic actuators are typically used for their large actuation strokes, high force output, and linear motions, which simplifies modeling and controlling of the actuators. However, hard robotics often have a large bulk modulus of $10^6$–$10^7$ Pa. Due to their lack of compliance, they are unable to produce smooth touch, have high stress concentrations and contact forces, and cannot manipulate soft material, leaving hard robotics incompatible with human interaction. They have limited adaptability to environments; they are large, heavy, and are costly. Soft robotics, on the other hand, are conveniently scalable, light weight, can produce high actuation strain, have good power–weight ratio, and have a compliance similar to living tissue. They, however, produce an overall low force output and have nonlinear stress–strains relations, which makes modeling and controlling difficult and therefore hard to implement. Soft artificial muscles include ionic polymer metal composites (IPMC) that actuate through the diffusion of an electrolyte; electroactive polymers (EAP), which deform in the presence of an electric field; shape memory polymers (SMP) can change one or more shapes at specified temperature; and now, recently, highly oriented polymer fibers are being used as bending, multidirectional, and torsional actuators. They exhibit anisotropic thermal expansion where fibers, such as nylon 6,6, can axially contract up to 2.5% and radially expand up to 4.5%. Heat can be delivered via convective heating, photothermal excitation, and joule heating. Bending actuators can be fabricated by changing the cross-sectional area of nylon 6,6 filaments from circle to rectangle or square and applying heat to the sides of the body, demonstrating bending in 1D and 2D. Multidirectional and torsional actuators can be fabricated by inducing a twist into the precursor fiber and annealing, and are typically referred to as coiled polymer actuators (CPAs). A one-end-tethered CPA responds to heat by untwisting at the free end; when two ends are tethered and heated, the CPA contracts in the axial direction and, in a particular case, when a two-end-tethered coil is heated in one section, the heated section untwists while the unheated section twists and acts like a torsional spring, overall performing as a torsional actuator. CPAs are often used for being inexpensive, producing up to 49% tensile stroke, power densities over 27.1 kW kg$^{-1}$, and high specific work of 2.48 kJ kg$^{-1}$ with very low to no hysteresis. Previous research has used these multidirectional actuators as artificial muscles in arm and finger prosthetics, wearable wrist orthosis for rehabilitation therapy, and the torsional actuators are used as torsional motors/energy harvesting systems. The limitations for polymer actuators are the heat-transfer rates during actuation and...
Polymers, such as nylon 6,6, are thermal insulators, having a low coefficient of thermal conductivity. Often a coolant, such as water or ethanol, is used to increase the cycling rate.\textsuperscript{[6,8,15]} In addition, there is research in modeling the thermomechanical actuation response, as well as modeling of the temperature-controlled CPA, including the compensation of hysteresis.\textsuperscript{[16–19]} In this study, we combine CPAs and biomimetics. The inspiration for the biomimetic robot is the harbor porpoise whale. They are small-toothed whales, closely related to dolphins and one of the smallest marine mammals, between 1.45–1.6 m and weighing around 50–60 kg.\textsuperscript{[20]} They inhabit the coastal waters of the North Pacific, North Atlantic, and the Black Sea.\textsuperscript{[20]} The harbor porpoise whale displays high locomotion and maneuverability, reaching speeds of 4.3 m s\textsuperscript{−1}.\textsuperscript{[21]} During surfacing, the fin is positioned in a lift-generating position and during swimming they are positioned against the body to reduce drag.\textsuperscript{[22]} The pectoral fin is especially important for generating lift, steering, and braking, essentially behaving as a hydrofoil.\textsuperscript{[23]} The objective of this study is to build a controllable artificial pectoral fin with artificial muscles to obtain a better insight on how to produce more efficient underwater devices, vehicles, and how to manipulate fluid-structure interactions.

2. Results

2.1. Fabricated Pectoral Fin of the Harbor Porpoise Whale

A soft-robotic whale fin is fabricated from CT scans of a harbor porpoise fin using a series of software to obtain 3D printable materials (Figure 1A–D). The fin was scaled down for printability, where the dimensions are shown in Figure 1E. The fin is composed of bone, printed from acrylonitrile butadiene styrene (ABS) plastic for its stiffness, and cartilage, printed from NinjaFlex for its flexibility, encased in an elastomeric body made of EcoFlex. The considerations for the elastomeric body were EcoFlex 00-10, EcoFlex 00-20, and EcoFlex 00-30. The body needed to be stiff enough to attach and hold the actuators in tension without buckling, but flexible enough for deflection. EcoFlex 00-30 was chosen due to its higher stiffness and shore hardness than EcoFlex 00-10 and EcoFlex 00-20. A force-displacement response was performed on the fin for efficient placement of the actuators. The fin was clamped at the base, and a 2 mm pk–pk, 5 Hz, sinusoidal displacement was probed against the fin surface using a TIRA vib, whereas the probing force and tip displacement were simultaneously measured using a load cell and a laser distance sensor. The force and displacement were mapped using a 1 cm x 1 cm grid and the root mean square (RMS) values were displayed as surface plots (Figure 2F,G).

The largest required force to achieve the prescribed displacement is near the base where the fin was clamped and held firmly to the ulna and radius and progressively decreases away from the clamp, approaching nearly zero when in contact with EcoFlex 00-30. The greatest tip displacement results from oscillating the fin at the carpals or center of the fin, where the fin is most flexible, however, produces enough moment to cause deflection at the tip. Therefore, it would be advantageous to attach the actuators at the carpals where it would pull and displace the fin the greatest and at the base where the actuators can be held rigidly.

2.2. Artificial Muscle: the CPA

The artificial muscles are composed of an array of CPA lined along the surface of the pectoral fin. Eight CPAs are fabricated using 0.43 mm diameter nylon (Trilene). The CPAs used on both sides of the fin are of similar lengths: set 1, 18.4 cm; set 2, 14.1 cm; set 3, 9.4 cm; and set 4, 5.3 cm, measured from the base of the fin to the end of the phalanges. A small diameter used is necessary to prevent the fin from buckling under the CPA’s tension. Force and displacement are characterized using a load cell and a magnetic linear encoder. The CPAs are heated from room temperature to $\approx 120^\circ$C (Figure 2). The temperature profiles differ due to the varying Nichrome wire resistance and the power input. The displacements of each set are comparable. The maximum displacement of sides 1 and 2, respectively, for set 1 are 20.7 and 19.3 mm, for side 2 are 14.1 and 19.7 mm, for side 3 are 9.2 and 9.6 mm, and for set 4 are 4.6 and 2.78 mm. Similarly, the forces of side 1 and 2, respectively, for set 1 are 2.6 and 2.8 N, for set 2 are 2.6 and 2.9 N, for set 3 are 2.6 and 2.3 N, and for set 4 are 2.5 and 2.6 N. The displacement and actuation force spikes are caused by the static friction in the testing apparatus that the lower end of the CPAs is attached to.

2.3. Deflection Analysis of the Harbor Porpoise Whale Fin Driven by the CPA Artificial Muscles

The CPAs were attached according to the characterization data of the fin (Figure 3A,B). The displacement of the fin was measured in air at three frequencies, $1/f_1 = 10 \text{ s}$, $1/f_2 = 15 \text{ s}$, and $1/f_3 = 20 \text{ s}$ for four periods; the power was then removed, and the fin was cooled to room temperature. Two displacement tests were conducted, where the fin initially actuated toward side 1 first, and the second where the fin actuated toward side 2 first. The displacement amplitudes differ considering the asymmetric geometry of the fin. Also, in attempt to oscillate the fin around the neutral axis, the power was applied for $(1/f)/4$ on the first side, $(1/f)/2$ on the second side, $(1/f)/4$ on the first side once again, and so on. In displacement test 1 (Figure 3C), $f_1$ exhibited the lowest initial displacement, $f_2$ exhibited the highest initial displacement, and $f_3$ being in the middle. This is the result of the CPA not reaching a significant temperature during $f_1$ causing a low displacement. Lower frequencies allow for longer heating times producing higher temperatures and greater displacements. Furthermore, $f_1$ reaches a larger displacement at the third peak due to the slow cooling rate of the nylon, which when heated again will start above room temperature and thus heating to a greater temperature. $f_1$ does not experience this increasing displacement, because during its initial actuation the temperature is near its plateau temperature, or the highest temperature the Nichrome can achieve with the provided power. In addition, the slow cooling rate of the nylon causes a decrease in the displacement of the fin over time. While heating side 1, side 2 is at room temperature and the fin displaces toward side 1. When heating side 2, side 1 decreases in temperature, however does not reach room temperature, as side 2 increases. In this cycle, side 1’s temperature is still elevated due to its slow cooling rate via low coefficient of thermal conductivity, and a contracting force remains and competes with the contracting force of...
This competing contraction force remains throughout the displacement of the fin. Also, the natural curvature of the fin produces a favorable moment arm on side 1 causing a displacement drift. Moreover, in displacement test 1, side 1 is heated first, whereas there is no competing force on side 2, causing an initial drift. After the power was removed, the fin continued to displace due to side 1 being heated last, therefore, having a higher pulling force than side 2. In displacement test 2 (Figure 3D), similar trends occur; however, at the end of each actuation, the fin displaces toward side 1, even though side 2 was heated last, confirming that the curvature of the fin tends to cause the fin to displace toward side 1.

3. Discussion
This study uses CPAs as an artificial muscle for actuating a lab-fabricated bio-inspired harbor porpoise whale fin.
Figure 2. Characterization of the CPAs where the temperature of the actuator is increased using a Nichrome heating wire, whereas the force and displacement are recorded using a load cell and magnetic linear encoder. A, C, E, G) is sown into side 1, and B, D, F, H) into side 2.
The CPAs were attached on the surface of the fin and heated to cause a deflection in the fin. The tip was measured using a laser displacement sensor. It was found that the tip deflection can be controlled by varying the step input frequency. Lower frequencies cause greater deflection, with the plateau temperature being its limitation. Furthermore, if larger tip deflection is desired, it can be achieved by increasing the number of CPAs lined on the fin. The drawback with this is the power supplied to the CPAs will need to be increased. Sizing motor drivers and Arduino to the power supply will need to be considered. Also, due to the curvature of the fin, the fin tends to drift toward side 1. Increased power to side 2, or a long heating time can remove this drift to an extent. There are some challenges when performing tests in air, most notably, the slow cooling time of the CPA. The CPAs experience a decrease in displacement with prolonged actuation times. A cooling liquid (i.e., water) is recommended to cool the CPA back to room temperature to reduce the decrease in displacement. This, however, will not be an issue for future studies which will be performed in water; water serving as the heat sink for the CPA. The goal of future studies is fluid-structure interactions such as drag, lift, transition phases, and boundary layer control. The plan is to conduct tests in a flow channel by dragging the pectoral fin through still water or by moving water across the fins surface. Measurements of the thrust and drag of the actuating fin at varying frequencies will help understand and in potentially controlling laminar-to-turbulent transitions. Applications are focused on the delaying and controlling of transition periods in underwater and above water vehicles at varying velocities, as seen in harbor porpoise whale locomotion. By controlling transition periods, drag reduction can be achieved, which is important for reducing fuel consumption on marine ships and therefore saving money and reducing pollutants.

4. Conclusion

A harbor porpoise bio-inspired pectoral fin was 3D modeled using CT scans in conjunction with Simpleware ScanIP, Autodesk ReMake, and Fusion 360. The fin was fabricated by casting the 3D printed cartilage and bones in EcoFlex 00-30. A force-tip displacement response was applied to the fin for effective CPA placement. A 2 mm, 5 Hz, sinusoidal input probed multiple points on the fin while the force and tip displacement were measured simultaneously. It was observed that the largest tip displacement occurred when probing the carpals, deeming them an important contact point between the fin and the CPA. Four sets of CPAs were fabricated, tested, and sewn into the sides of the fin with a Nichrome heating wire. Alternating square waves were generated using power supply and controlled with an Arduino.
Nanofabrication and a dual-motor driver to heat the Nichrome. The fin was clamped at its base, and a displacement sensor tracked the location of the fin tip as the CPAs on each side were heated, consecutively. It was found that the tip deflection could be controlled by varying the square wave frequency. Lower frequencies cause greater deflection, with the plateau temperature being its limitation. The greatest tip deflection was about 14 mm pk–pk. The displacement decreases thereafter due to the slow cooling time of the CPA. Greater displacement can be achieved by increasing the number of CPA, though the buckling of fin must be considered. Too many CPA will cause deformations in the fin and possibly collapse the fin. Future work will consist of flow-channel studies, including mounting a force sensor and the fin into a flow channel and observing lift and drag forces as the fin actuates, as well as, the laminar to turbulent transition periods.

5. Experimental Section

Software–Simpleware ScanIP: The digital imaging and communications in medicine (DICOM) images of the whale fin were imported into Simpleware ScanIP (Figure 4A). The threshold feature allowed the user to separate material and create a mask based on the image intensity range. The range could be chosen manually, or a profile line created along the 2D slice or a histogram of the slice could be used to choose the range. In this case, a profile line was stretched across soft tissue and bones (Figure 4B). The grayscale bar was adjusted until a separation between the bone and tissue were made. The threshold for bone ranged between $-687$ to $225$ greyscales, and the threshold of the soft tissue was $-687$ greyscales and below. The threshold also included background objects due to the similar densities. The file was cropped to remove unnecessary objects and empty space; however, not all objects and spaces were removable. A segmentation was applied to the bone and tissue creating two separate masks. Due to the contact between the tissue and the background object, the two were merged (Figure 4C). They were separated using Un-Paint (Figure 4D). Un-Paint removes material, pixel by pixel. Once the objects were separated, a flood-fill was applied to the fin, creating one continuous material, where the undesired background object was deleted. A morphological close and cavity fill was applied to the bone and tissue to fill all holes (Figure 4E). A subtraction was made on the tissue with the bone, completing the two masks (Figure 4F). The cartilage was unable to be extracted from the DICOM images and was created by using a morphological close on the bone. Morphological close merges fine structures and adds connectivity between objects. The morphological close was increased until enough connective tissue was created to resemble a harbor porpoise whale fin cartilage structure. The three masks were converted into surfaces and exported for model manipulation and processing (Figure 4G).

Software–Autodesk: Autodesk, an open-source 3D design software, was used to model the necessary components to build the bio-inspired whale fin from the Simpleware ScanIP standard triangle language (STL) files. Autodesk ReMake was used to repair the inverted meshes and reduced the number of elements for faster computer aided design (CAD) manipulation. A bisecting surface was created from the mid-surface of the fin, which became important for modeling the molds and support structure. Intersecting geometries between the fin and a series of planes were used to obtain 2D sketches of the fins’ surface. At each plane the midlines could be estimated and drawn in with a spline. The series of splines were then lofted to form the bisecting surface. An error can occur when splitting a body with a surface that has similar dimensions; therefore, a copy of the bisecting surface was made and extended on a natural path to split the fin. The fin halves were subtracted from two blocks, slightly larger than the fin halves, for molds 1 and 2. The molds were closed bodies, and to open the molds, a cut was extruded from the original bisecting surface, not the extended copy of the bisecting surface, in the appropriate direction to expose the inner mold surface. Three holes were cut into the molds for inserting EcoFlex 00-30 and allowing passage for air pockets to escape. Excessive material was cut away for faster prints (Figure 5A,B). Support structure 1 was created by extruding the original bisecting surface at an arbitrary distance, and a subtraction was made with the bones and cartilage. This securely fitted into mold 1 and loosely held the bones and cartilage in its natural relaxed state (Figure 5C). Support structure 2 was extruded from one side of the fin, not the bisecting surface, to securely hold the cured fin from mold 1 into mold 2 (Figure 5D). Support structure 3 was extruded from the other side of the fin; the usage of this structure will be discussed later (Figure 5E). The molds, support structures, and bones were 3D printed from ABS plastic and the cartilage was printed from NinjaFlex (Figure 5F–L).

Fabrication Process of the Harbor Porpoise Pectoral Fin: Inner and side surfaces of the molds and support structures were sanded. A silicon-releasing agent was sprayed on the molds and support structures before applying EcoFlex. The ulna, carpals, and surrounding cartilage were fitted, held in place with a clip, and adhered to support structure 1 with EcoFlex 00-30, one-part solution A and one-part solution B (Figure 6A). After curing, the metacarpals were then held in place and adhered. Similarly, the phalanges were adhered, piece by piece. It was important
to adhere in segments to prevent migrations and errors in positioning. The support structure 1 was then placed inside mold 1, clamped together, filled with EcoFlex 00-30, and left to cure. Once cured, the fin half was removed from the mold, and the excessive EcoFlex 00-30 was removed with a razor. The fin surface was placed on the second support structure, fitted into mold 2, clamped together and filled with EcoFlex 00-30, and left to cure. The fin was removed, and the excessive EcoFlex 00-30 was removed once again. Removing EcoFlex 00-30 caused imperfections on the surface of the fin. These imperfections were fixed by applying additional EcoFlex 00-30 to the fin surface and clamping the fin between support structures 2 and 3, completing the artificial fin (Figure 6B). The fabrication process caused the whale fin’s dimensions to deviate from Figure 1E. The fabricated fin increased in the vertical length to 94 mm and shortened in the horizontal length to 157 mm. Also, the thickness decreased to about 23 mm. This is most likely due to the print’s inaccuracy and how the molds fit into one another.

**Characterization of the Pectoral Fin:** The fin was clamped at the radius and ulna, whereas the TIRA vib was used to probe the fin with a 2 mm pk–pk, 5 Hz, sinusoidal input (Figure 7A). The force of the probe and tip displacement are measured using a load cell and a laser distance sensor. A 1 cm × 1 cm grid was drawn on the fin to map out the force and tip displacement measurements (Figure 7B). The data is shown as surface plots of the force and tip-displacement RMS values.

**Fabrication of the CPAs:** One end of the nylon fiber was attached to a DC motor, the other end was attached to a 200 g mass and constrained to prevent rotation. The DC motor coiled the fibers until reaching the predetermined lengths: set 1: 18.4 cm, set 2: 14.1 cm, set 3: 9.4 cm, and set 4: 5.3 cm. The lengths were obtained from measuring from the base of the fin to the end of the carpals and along the phalanges. After coiling, the CPAs were annealed at 120 °C for 30 min, then allowed to cool to room temperature.

**Characterization of the CPAs:** The force and displacement performance for the fabricated CPAs were tested using a load cell and magnetic linear...
encoder. An 80/20 frame held the load cell rigidly in place and a movable linear track ran along the 80/20 frame holding the magnetic linear encoder beneath the load cell. The CPA was attached between these two sensors and heated. The force and displacements were then measured using a NI-DAQ.

Application of the CPAs: The CPAs and Nichrome heating coils were sewn into the sides of the fin, and points of contact were made at the base of the fin, carpals, and at the phalanges. The points of contact at the base were reinforced with EcoFlex 00-30 injected into the holes created by the sewing needle and allowed to cure. The CPAs were then put in tension with 200 g weights and the ends were reinforced with EcoFlex 00-30 while still in tension. After curing, all points of contact were also reinforced with EcoFlex 00-30.

Controls and Tip Displacement: The Nichrome coils were soldered in series to achieve uniform heating, driven by a DC power supply, and the power and frequency were controlled with an Arduino Nano and a dual-motor driver (Figure 8A). The fin was clamped at its base with a laser distance sensor measuring the pectoral fins’ tip location (Figure 8B). A constant input of 30.38 W was supplied to the Nichrome heating wires, on each side, consecutively, such that 1/f_1 = 10 s, 1/f_2 = 15 s, and 1/f_3 = 20 s for four periods. Pins D2, D4, D7, and D8 controlled the direction; however, the direction was not important, rather, the amount of power and the frequency supplied to the Nichrome heating wires was important; therefore, pins D2 and D7 were held high and pins D4 and D8 were held low for an arbitrary clockwise direction. A pulse width modulation (PWM) output with a full-duty cycle was used to achieve the constant power. For example, pin D3 was held high for 1/(4f_1), set to low while simultaneously changing D5 too high for 1/(2f_1), then set to low while D3 was set to high for 1/(4f_1) to complete one cycle.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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artificial muscles, biomimetics, coiled polymer actuators, Simpleware ScanIP, soft robotics

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