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A robotic platform to study the California sea lion foreflipper

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Abstract:	The California sea lion (Zalophus californianus), is an agile and powerful swimmer. Unlike many successful swimmers (dolphins, tuna), they generate most of their thrust with their large foreflippers. This unique form of aquatic propulsion is largely under-explored. This protocol described robotic platform designed to study the hydrodynamic performance of the swimming California sea lion (Zalophus californianus). The robot is a model of the animal's foreflipper that is actuated by motors to replicate the motion of its propulsive stroke (the `clap'). The kinematics of the sea lion's propulsive stroke are extracted from video data of unmarked, non-research sea lions at the Smithsonian Zoological Park (SNZ). Those data form the basis of the actuation motion of the robotic flipper presented here. The geometry of the robotic flipper is based a on high-resolution laser scan of a foreflipper of an adult female sea lion, scaled to about 60% of the full-scale flipper. The articulated model has three joints, mimicking the elbow, write and knuckle joint of the sea lion foreflipper. The robotic platform matches dynamics properties—Reynolds number and tip speed—of the animal when accelerating from rest. The robotic flipper can be used to determine the performance (forces and torques) and resulting flowfields.
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Question	**Response**
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Dear JoVE editors,

We have revised our invited article to the *Journal of Visualized Experiments* based on the peer reviewers' comments.

Please find a revised version of "A robotic platform to study the California sea lion foreflipper," attached. We have addressed the reviewers' comments. Changes to the document have been tracked using Microsoft Word. A detailed account of how each comment was addressed is also attached.

As with the previous version, Dr. Leftwich conceived the study. The flipper was designed and built by Mr. Patel and Mr. Kulkarni. Dr. Friedman obtained the morphological and kinematic data from the California sea lion. The manuscript was written by Dr. Leftwich with significant contributions from Dr. Friedman, Mr. Kulkarni and Mr. Patel.

If you have any questions of need anything else from the authors, please don't hesitate to contact us.

Sincerely,

Megan Leftwich, PhD
Chen Friedman, PhD
Aditya Kulkarni
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TITLE: A robotic platform to study the foreflipper of the California sea lion

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KEYWORDS: Swimming, Sea lion, biorobotics, aquatic propulsion, marine mammals, fluid mechanics

SHORT ABSTRACT:
A robotic platform is described that will be used to study the hydrodynamic performance—forces and flowfields—of the swimming California sea lion. The robot is a model of the animal's foreflipper that is actuated by motors to replicate the motion of its propulsive stroke (the `clap').

LONG ABSTRACT:
The California sea lion (*Zalophus californianus*), is an agile and powerful swimmer. Unlike many successful swimmers (dolphins, tuna), they generate most of their thrust with their large

foreflippers. This protocol describes a robotic platform designed to study the hydrodynamic performance of the swimming California sea lion (*Zalophus californianus*). The robot is a model of the animal's foreflipper that is actuated by motors to replicate the motion of its propulsive stroke (the `clap'). The kinematics of the sea lion's propulsive stroke are extracted from video data of unmarked, non-research sea lions at the Smithsonian Zoological Park (SNZ). Those data form the basis of the actuation motion of the robotic flipper presented here. The geometry of the robotic flipper is based a on high-resolution laser scan of a foreflipper of an adult female sea lion, scaled to about 60% of the full-scale flipper. The articulated model has three joints, mimicking the elbow, wrist and knuckle joint of the sea lion foreflipper. The robotic platform matches dynamics properties—Reynolds number and tip speed—of the animal when accelerating from rest. The robotic flipper can be used to determine the performance (forces and torques) and resulting flowfields.

INTRODUCTION:

While scientists have investigated the *basic* characteristics of sea lion swimming (energetics, cost of transport, drag coefficient, linear speed and acceleration[1-3,] we lack information about the fluid dynamics of the system. Without this knowledge, we limit potential high-speed, high-maneuverability engineering applications to body-caudal fin (BCF) locomotion models[4]. By characterizing a different swimming paradigm, we hope to expand our catalog of design tools, specifically those with the potential to enable quieter, stealthier forms of swimming. Thus, we study the fundamental mechanism of sea lion swimming through direct observation of the California sea lion and laboratory investigations using a robotic sea lion foreflipper[5,6] .

To do this, we will employ a commonly used technique for exploring complex biological systems: a robotic platform[7]. Several locomotion studies—both of walking[8,9] and swimming[10]—have been based on either complex[11] or highly simplified[12] mechanical models of animals. Typically, the robotic platforms retain the essence of the model system, while allowing researchers to explore large parameter spaces[13-15]. While not always characterizing the entire system, much is learned through these platforms that isolate a single component of a locomotive system. For example, the fundamental functioning of unsteady propulsors, like the back-and-forth sweeping of a caudal fin during carangiform swimming, has been intensely explored through experimental investigations of pitching and/or heaving panels[12,16,17,18]. In this case, we can isolate certain modes of this complex motion in ways that animal based studies cannot. Those fundamental aspects of propulsion can then be used in the design of vehicles which do not need the biological complexity evolution provides.

In this paper, we present a novel platform for exploring the 'clap' phase of the sea lion thrust-producing stroke. Only a single foreflipper—the 'roboflipper'—is included in the platform. Its geometry is derived exactly from biological scans of a California sea lion (*Zalophus californianus*) specimen. The roboflipper is actuated to replicate the motion of the animals' derived from previous studies[1]. This robotic flipper will be used to investigate the hydrodynamic performance of the swimming sea lion and to explore a wider parameter space than animal studies, particularly those of large aquatic mammals, can yield.

PROTOCOL:

1. Digitize a specimen of a Sea lion foreflipper

1.1) Scan a specimen of a Sea lion foreflipper.

1.1.1) Obtain a specimen of a sea lion flipper from a deceased individual (**Figure 1(a)**).
NOTE: In our case, they were obtained from the Smithsonian Zoological Park in Washington, D.C.

1.1.2) Hang the foreflipper vertically from its base (where the foreflipper attaches to the animal's body). This both allows the flipper to be straight when scanned, and exposes the entire surface for scanning.

1.1.3) Scan flipper using a high-resolution structured light scanner, with an accuracy of approximately 0.5 mm, and error of approximately 0.1 mm (**Figure 1(b)**).

1.2) Import the point cloud into CAD software and render it as a surface. To do this, click 'Open' and select the desired .obj file. Click on 'Import' to import the file into the CAD software.

1.3) Manipulate the resulting point cloud using a computer-aided design (CAD) software by clicking on 'Extruded cut' and cutting out the flesh part (unwanted part) of the scan. Next, click on 'Scale' to obtain the appropriate scaling for the robotic flipper (68% of the full size). Inspect flipper for sufficient detail capture by comparing to the original specimen (**Figure 2**).

1.4) Create the mold around the flipper.

1.4.1) In a CAD software, use the flipper surfaces to form a mold by creating a surrounding volume around the flipper surface. Do this by extruding a rectangular block by clicking on 'Sketch' to draw a rectangle and then extruding it to more than the height of the flipper to completely encompass it.

1.4.2) Click on 'Assembly' and import both parts (flipper and rectangular block) into the working area. Click on 'Mate' and make the front and top plane of both the flipper and mold as coincident. This automatically places the flipper inside the mold.

1.4.3) Select the mold from the design tree and click 'Edit Part'. Once the part is selected, click on 'Insert>Features>Cavity' to make a cavity of the flipper inside the mold. Sketch a line at the center of the rectangular mold and click on 'Split' to form two parts of the same mold.

1.4.4) Click on 'Cut Part' to separate the surrounding volume into two parts for easy flipper extraction. Insert cavities and pegs on each half of the volume and save it as part one and two of the flipper mold (**Figure 3**).

1.4.5) Convert the '.SLDRPT' files of the mold to '.STL'. Import these files to the proprietary software of the 3D printer and click on 'Print' to generate the 3D printed mold.

2. Design the Bone Structure

2.1) Open the digital foreflipper in a CAD software and obtain an image of the Sea lion foreflipper bone structure for reference (such as Fig. 1 in English, 1977[19]).

2.2) Design three different pieces that mimic the bone structure that will fit inside the digital model of the foreflipper. Throughout this procedure, 'base' refers to the end of a part closer to the base of the foreflipper and 'tip' refers to the end of the part closer to the tip of the foreflipper.

2.2.1) Base Piece

2.2.1.1) Make the length of this piece proportional to the distance between the shoulder joint and the wrist of the Sea lion flipper (measurements are obtained using measuring tape). Do this using a CAD software by clicking on 'Sketch' and designing the shape of the base piece (**Figure 4).**

2.2.1.2) Add knuckles at both ends of the part by clicking on 'Sketch' and drawing two circles. Click on 'Boss Extrude' to extrude the desired length from the plane of the base piece. Click on the sketch of the smaller circle to cut into the extrude by clicking 'Cut Extrude' to make room for the shaft. To strengthen this joint, click on 'Fillet' to smoothen the sharp joints.

NOTE: The dimensions of the circles depend on the size of the shaft to be used during mounting the flipper on top of the water flume. In our case, the diameter of the smaller circle is 0.5 inches and the bigger circle is 1 inches. The base end will be sitting outside the flipper skin geometry, so the size of the knuckles do not fall under the constraints of the skin.

2.2.2) Middle Piece

2.2.2.1) Make the length of this piece proportional to the distance between the wrist joint and the knuckle joint of a Sea lion. Do this by clicking on 'Sketch' and sketching the desired shape (as shown in Figure 4.b) on a plane. Once the geometry is designed, click on 'Extrude' to get the basic three-dimensional shape of the middle piece. Input the extruded length as 0.1650 inches.

NOTE: The desired shape of the middle piece in our experiment is a trapezoid with a height of 2.25 inches and the length of the two bases as 1.625 and 0.850 inches respectively.

2.2.2.2) Add knuckles on both ends. Do this as described in step 2.2.1.2. The diameter of the extruded cut is 0.125 inches. Connect the knuckles on the base end to the tip end of the base piece with an axel to form a hinge representing the wrist joint.
NOTE: The knuckles need to fit inside the volume of the foreflipper, so design accordingly.

2.2.2.3) Add a tower approximately 1 cm in height to the tip end of the piece on both sides.

2.2.2.3.1) To add a tower, click on 'Sketch' and sketch a rectangle on the base of the model. Extrude the sketch by selecting the sketch and clicking on 'Boss Extrude'. The thickness of the tower in this particular case is 0.165 inches.

2.2.2.3.2) Click on 'Fillet' and select the model and one edge of the extruded tower. This strengthens the sharp joint where the tower and the base of the middle piece are connected. It is okay if the tower protrudes from the geometry of the skin. The tower should be thick enough to withstand the forces generated during a flipper clap. See **Figure 4** for reference.

2.2.3) Tip Piece

2.2.3.1) Make the length of this piece proportional to the distance between the knuckle joint and the tip of the longest finger bone of a Sea lion. Do this by clicking on 'Sketch' and sketching a desired shape on a plane. Once the geometry is designed, click on extrude to get the basic three-dimensional shape of the tip piece.

2.2.3.2) Add knuckles on both ends. Do this as described in step 2.2.1.2. The diameter of the extruded cut should be equal to the diameter of the axle, which in this experiment is 0.125 inches. The knuckles on the base end will be connected to the tip end of the middle piece with an axle to form a hinge representing the knuckle joint. The geometry of these knuckles needs to fit inside the geometry of the foreflipper skin, so design accordingly.

2.2.3.3) Add a tower approximately 1 cm in height to the base end of the piece on both sides. Do this described in step 2.2.2.3. The thickness of the tower in this particular case is 0.165 inches. It is okay if the tower protrudes from the geometry of the skin. The tower should be thick enough to withstand the forces generated during a flipper clap. See **Figure 5** for reference.

3. Creating a flipper

3.1) 3D print the skeleton (base, middle and tip pieces) of the flipper. Convert the '.SLDRPT' file from CAD to '.STL' and import it into the printer's proprietary software and click 'Print'. NOTE: The printing instructions are different for each printer.

3.1.1) Reinforce the knuckles of the middle and tip piece with an adhesive (epoxy) and carbon threads. To do this, cut carbon threads of length 0.750 inches. Apply adhesive to the 3D printed bone structures and lay the threads over the knuckles. Stick two layers of carbon threads with the second layer at 45 degrees orientation with respect to the first (high torsional strength). It is not necessary to reinforce the large knuckles on the base piece (**Figure 5(a)**).

3.1.2) Drill holes at the bottom of each tower the diameter of the Kevlar string (strings that will be used to actuate the joints).

3.1.3) Assemble all bone pieces together from base to tip using axles. Do this by placing all the components on a flat table as shown in **Figure 4.** To connect the base and middle piece, align the knuckles of the parts and insert the axle. Use the same technique to connect the middle and the tip piece together. Use an adhesive on each end of each axle to ensure the axle does not move laterally (**Figure 5(b)**.

3.1.4) Cut plastic tubes to the following length. Cut four tubes the length of the base bone piece (L_1 = 8 cm) and two tubes the length of the middle piece (L_2 = 6 cm).

3.1.5) Cut 4 pieces of Kevlar string, each 3 feet in length.

3.1.6) Slide one string through an L_1 tube and then an L_2 tube. Slide another string through an L_1 tube. Repeat the process with the remaining tubes and strings.

3.1.7) Place the tubes on top of the bone structures and use a clear tape to hold them in position temporarily. Using an adhesive, stick the tubes onto the bone structure and then remove the tapes.
NOTE:There is no specific position in which the tubes have to be placed, the critical aspect is to just stick them on the surface of the structure. Use **Figure 5(c)** as a guideline.

3.1.8) Thread the Kevlar string from L_1 tube and L_2 tube through the holes drilled onto the tip and middle pieces as described in step 3.1.2. Make a small but secure knot once the string is through the hole (**Figure 5(d)**).

3.2) Adding the skin of the flipper to create a final flipper.

3.2.1) Measure 200 mL of silicon and silicon medium in two different containers.

3.2.2) Pour both these liquids into a steel bowl. Add paint thinner (not to exceed 10% of weight of the total mixture) to the mixture for easy pouring and mixing.

3.2.3) Use a stand mixer to mix the mixture thoroughly for 3-4 minutes. Color can be added at this step to achieve the desired visual effects. If a stand mixer is not available, use a whisk to mix it, taking care to scrape the sides and bottom of the container.

3.2.4) Insert a rod into the knuckles of the base part and align it with the knuckles of the flipper mold. When the pegs fit into the cavities of the mold, the bone structure is aligned perfectly in the flipper mold. While holding down on the two parts of mold, secure the parts by using a clamp for added compression (this step is critical so that the silicon mixture does not leak from the gap between the two parts).

3.2.5) Once the mixture is mixed, carefully pour it in the mold till the topmost knuckles of the bone structure. Oozing of liquid from the bottom hole in the mold is a sign of the mixture getting uniformly distributed. At the onset of this, plug the hole to avoid further flow of the liquid. Leave the liquid to cure for four hours before removing the flipper robot from the mold (see **Figure 6**).

4. Mounting

4.1) To mount the silicon foreflipper on the water flume (**Figure 7**), create a mounting structure. A CAD representation of the finished assembly is shown.(**Figure 8**).

4.1.1) Design a plate with a carefully extruded cut using CAD software. Click on 'Sketch' and draw a rectangle of dimensions 14 x 19 inches (the height does not matter as the laser cutter uses a .dwg file). Use a rectangular sheet of steel as the base to manufacture this plate. Upload a two-dimensional drawing from the CAD software on a computer attached to a steel laser cutter to attain the desired cuts.

Note: This plate houses the motor and the cut in it allows for the pulley system to work. The width of the plate is equal to the width of the water flume, thus making it easier to slide the plate over the flume. This type of placement helps in easy removal of the mounting assembly to replace parts or the foreflipper model.

4.1.2) Fix the foreflipper and the pulley onto a shaft, which slides into a triangular truss.

NOTE: A three-pulley system is implemented to transfer the torque/power from the motor to the rod.

4.1.3) Use bearings on either side to help the rod to rotate smoothly. To restrict the movement of rod in the lateral direction, place shaft collars on each end of the shaft.

4.2) Set the motion of the flipper by selecting the jogging function on the driver. Pressing the 'Up' button rotates the flipper clockwise and the 'Down' button rotates the flipper anticlockwise. The driver allows for change the revolutions per minute of the motor shaft according to the instructions in the manual[20].

4.3) Insert the right-angled dye port in the water and increase the pressure on the dye system. Adjust the speed of the dye to the freestream velocity of the water so the dye appears as a single smooth filament. Rotate the flipper so that the dye interacts and gets trapped with the resulting vortices generated.

REPRESENTATIVE RESULTS:

The process described above yields a robotic model of a California sea lion foreflipper. The model can be used in two different ways. One is by actuating the flipper only at the root (**Figure 6(a)**). In this case, the driving motor sets the rotational rate of the first joint, but the resulting motion of the flipper is determined by the fluid-structure interaction between the flexible flipper and the surrounding water. Additionally, we can create robotic flippers that are actuated at the two lower joints in addition to the root (**Figure 6(b)**). This is done through the tower structures printed onto the skeleton pieces. Wires connected to the towers are connected to separate motors and can actively control the camber of the flipper during the clapping motion.

The purpose of the robotic flipper is to explore the hydrodynamics of the propulsive stroke of the California sea lion as described in Friedman, 2014[1]. One way to do this, qualitatively, is through dye-based flow visualization. The robotic flipper is mounted to a recirculating water flume (**Figure 7**), using the assembly described above. The motor and flow speed, U, are set to explore a given parameter space—such as the Reynolds number based on the flipper chord ($Re = cU/\nu$ where ν is the dynamic viscosity of water) or angular velocity, ω, or acceleration, α.

The dye visualization shown in **Figure 9** uses fluorescent dye injected just upstream of the leading edge of the flipper. The dye is entrained into the shear layer at the surface of the flipper and allows us to visualize the vortex structure of the wake. **Figure 9(a)** shows the stream of dye being injected upstream (to the right), of the flipper. The disturbances seen on the left side of the image are the result of the previous cycle. As the flipper moved through the injection location (**Figure 9(b)**), low pressure on the upper surface of the flipper causes the dye to be pulled around the flipper. Finally, (**Figure 9(c)**), a vortex forms as the flipper moves fully out of the plane. This structure convects downstream with the mean flow. These results demonstrate how this technique can be used to qualitatively determine the flowfield surrounding a sea lion during the propulsive stroke.

In addition to the qualitative measurements of the flipper wake, we can use particle image velocimetry (PIV) to measure the velocity field surrounding the flipper. Thus, we can obtain qualitative data about the hydrodynamics of sea lion swimming for a variety of reproducible situations.

FIGURE LEGENDS:

Figure 1: Flipper Bottom Comparison. A left foreflipper from a specimen of a female California sea lion is used to determine the robotic flipper's geometric parameters. The top panel (a) is a high resolution, two-dimensional image of the flipper. The lower panel (b) is a three-dimensional, computer-aided design rendering of the flipper from the laser scan.

Figure 2: Wire. The digital image of the scanned flipper retains the geometric features of the animal's foreflipper. This image shows a wire-frame view of the digital flipper. Nine evenly spaced cross sections are shown in grey (every centimeter from the base to the tip of the foreflipper). The two isometric views (cross section 1 and 7) show that the flipper has an airfoil-like shape, with a thicker, rounded leading edge. The flipper is cambered, with its upper surface more convex and its inner surface concave.

Figure 3: Mold. The mold used to create the flexible portion of the robotic flipper is created from the scanned flipper specimen. The mold has two parts: an upper (purple) and a lower section (green) that are aligned with male and female posts, respectively. The robot skeleton (**Figure 4**) is aligned inside the mold before the silicon mixture is poured into the mold.

Figure 4: Skeleton. The flexible robotic flipper is supported by a skeleton printed in three pieces: the base (a), the middle (b) and the tip (c). The base and middle, and the middle and tip, are connected by dowels through knuckles at their joints. This allows for flexibility about those locations of the completed flipper.

Figure 5: Skeleton assembly. After printing, the skeleton parts, the knuckles are reinforces with carbon threads (a), they are connected at the knuckles with axels (b), guide-tubes are affixed to the base and middle pieces (c) and Kevlar threads are connected to the towers (d).

Figure 6: Robotic flipper. The robotic flipper is made of flexible silicone (white) with an imbedded plastic supporting structure (blue). The shaft at the base rotates, emulating the rotation at the elbow and shoulder of the animal. The robotic flipper can be passive (a), where it is only actuated at the root and the resulting motion is based of fluid-structure interactions, or active (b) where Kevlar wires connect to the knuckles provide the necessary changes in camber.

Figure 7: Flume. Flow experiments are conducted in the recirculating water flume at the George Washington University. The flume has a working section of 0.60 (width) by 0.40 (depth) meters, is 10 meters long, and can run at flow velocities of up to 1 m/s. Flow is from right to left, in the figure. The robotic flipper is mounted using the assembly shown in **Figure 8** to the rails at the top of the test section.

Figure 8: Assembly: The robotic flipper is mounted to a recirculating flume with a custom mounting. The mounting holds a servomotor that is connected to the main axis of the robotic flipper (located at the root of the robotic flipper) through a belt and three pulleys.

Figure 9: Dye visualization. Fluorescent dye is injected through a tube upstream of the flapping flipper. Three instances of time are shown: (a) the beginning of the cycle t=0, (b) 40% of the way through the cycle t=0.4, and (c) after 80% of the cycle t=0.8. In the right panel (c), we can see a vortex that has formed around the tip of the flapping robotic flipper.

DISCUSSION:

The robotic flipper apparatus will allow us to understand the hydrodynamics of the swimming California sea lion. This includes the basic thrust producing stroke (the ‘clap’), as well as non-physical variations that animal studies cannot investigate. The robotic flipper has been designed for experimental versatility, thus, step 3—where the flipper itself is made—is critical in obtaining the desired results. While this apparatus is, clearly, just a model of the living system, *in situ* studies of the California sea lion are extremely difficult and the range of possible data is quite limited.

While sometimes possible, velocity field measurements on large aquatic animals are very difficult (e.g. untrained animals, non-research grade viewing glass, no control over the environment), and the errors are higher than laboratory experiments[21]. Furthermore, they require access to the animals that is often impossible to obtain and in such cases robotic platforms like the one we built allow for in depth investigations. In addition to replicating the living system as faithfully as possible, robotic models allow us to modify it in unrealistic ways. For example, the mold can be modified to alter the trailing edge morphology. Or, the texture of the surface can be changed to investigate the role of the microstructure on the swimming performance.

The use of a robotic platform to investigate the performance of a biological system gives only a partial view of that system—this is a limitation of this approach. Furthermore, this particular protocol isolates the foreflipper from the rest of the sea lion body. Thus, the results will not offer a complete view of the system and the body-flipper interactions. Further limitations include the homogenous properties of the flipper and point wise actuation (as opposed to the distributed actuation of musculoskelatal systems). Additionally, that material is compliant and can lead to fluid-structure-interactions that are not present in the physical system. This is minimized by using materials that closely replicate the overall biological properties, but can noever be completely controlled for. Despite these limitations, much can be learned by comparing the performance of different activation modes and flow conditions.

The robotic flipper will form the basis of a rich research project that will provide insight into the fundamental physics of a unique paradigm of efficient swimming—the California sea lion. The platform is flexible, and each flipper can be made quickly with minimal cost. Thus, a large parameter space can be tested as new research questions arise.

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DISCLOSURES:
The authors have nothing to disclose.

REFERENCES

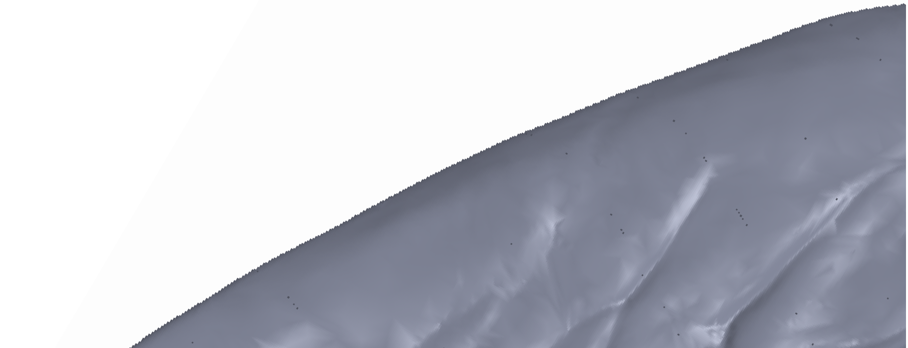
1. Feldkamp, S.D. Swimming in the California sea lion: Morphometrics, drag and energetics. *Journal of Experimental Biology*. **131**, 117–135 (1987).
2. Godfrey, S.J. Additional observations of subaqueous locomotion in the California sea lion (*zalophus californianus*). *Aquatic Mammals*. **11**(2), 53–57, (1985).
3. Stelle, L.L., Blake, R.W., Trites, A.W. Hydrodynamic drag in steller sea lions (*eumetopias jubatus*). *The Journal of Experimental Biology*. **203**(12), 1915–1923, (2000).
4. Yu, J., Wang, L., Tan, M. A framework for biomimetic robot fish's design and its realization. *Proceedings of the American Control Conference.* 1593-1598. (2005).
5. Friedman, C., Leftwich, M.C. The kinematics of the California sea lion foreflipper during

forward swimming. *Bioinspiration and Biomimetics*. **9**(4), 046010, doi: 10.1088/1748-3182/9/4/046010, (2014).

6. Friedman, C., Joel, B.W., Schult, A.R., Leftwich, M.C. Noninvasive 3D geometry extraction of a Sea lion foreflipper. *Journal of Aero Aqua Bio-mechanisms*. **4**(1), 25-31, (2015).
7. Aguilar, J., et al. "A review on locomotion robophysics: the study of movement at the intersection of robotics, soft matter and dynamical systems." *arXiv preprint arXiv:1602.04712* (2016).
8. Holmes, P., Koditschek, D., Guckenheimer, J. The dynamics of legged locomotion: models, analyses, and challenges. *Dynamics*. **48**(2), 207–304, doi: 10.1137/S0036144504445133, (2006).
9. Mazouchova, N., Umbanhowar, P.B., Goldman, D.I. Flipper-driven terrestrial locomotion of a sea turtle-inspired robot. *Bioinspiration & Biomimetics.* **8**(2), 026007, doi:10.1088/1748-3182/8/2/026007, (2013).
10. Hultmark, M., Leftwich, M.C., Smits, A.J. Flowfield measurements in the wake of a robotic lamprey. *Experiments in fluids.* **43**(5), 683-690, doi: 10.1007/s00348-007-0412-1, (2007).
11. 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, doi: 10.1126/science.1138353, (2007).
12. Buchholz, J.H., Smits, A.J. On the evolution of the wake structure produced by a low-aspect-ratio pitching panel. *Journal of fluid mechanics.* **546**, 433-443, doi:10.1017/S0022112005006865, (2006).
13. Lauder, G. V., Anderson, E. J., Tangorra, J., Madden, P. G. Fish biorobotics: kinematics and hydrodynamics of self-propulsion. *Journal of Experimental Biology* **210**(16), 2767-2780, doi: 10.1242/jeb.000265, (2007).
14. Leftwich, M. C., Smits, A.J. Thrust production by a mechanical swimming lamprey. *Experiments in fluids.* **50**(5), 1349-1355, doi: 10.1007/s00348-010-0994, (2011).
15. Leftwich, M. C., Tytell, E. D., Cohen, A. H., Smits, A. J. Wake structures behind a swimming robotic lamprey with a passively flexible tail. *Journal of Experimental Biology.* **215**(3), 416-25, doi: 10.1242/jeb.061440 (2012).
16. Buchholz, J.H., Smits, A.J. The wake structure and thrust performance of a rigid low-aspect-ratio pitching panel. *Journal of fluid mechanics.* **603**, 331-365, doi: 10.1017/S0022112008000906, (2008).
17. Quinn, D. B., Lauder, G. V., Smits, A. J. Scaling the propulsive performance of heaving flexible panels. *Journal of fluid mechanics.* **738**, 250-267, doi: 10.1017/jfm.2013.597, (2014).
18. Quinn, D. B., Lauder, G. V., Smits, A. J. Flexible propulsors in ground effect. *Bioinspiration & biomimetics.* **9**(3), 036008, doi: 10.1088/1748-3182/9/3/036008, (2014).
19. English, A.W. Functional anatomy of the hands of fur seals and sea lions. *American Journal of Anatomy*. **147**(1), 1-17, (1976).
20. "Quick Start Guide." (n.d.): n. pag. Anaheim Automation. Web.

21. Fish, F. E., Legac, P., Williams, T. M., & Wei, T. Measurement of hydrodynamic force generation by swimming dolphins using bubble DPIV. *Journal of Experimental Biology*, **217**(2), 252-260, doi: 10.1242/jeb.087924 (2014).

(a)



(b)

Figure 2

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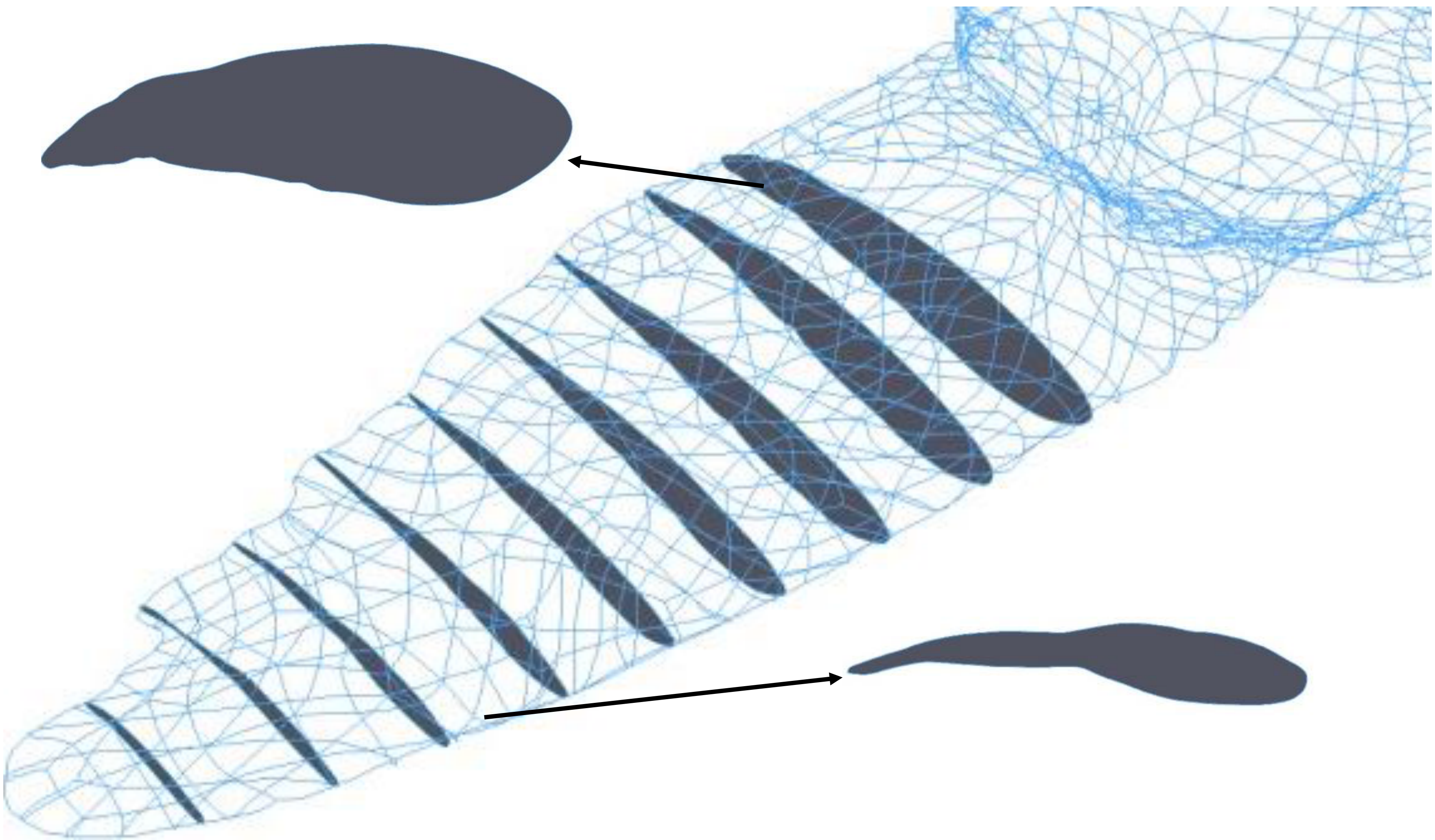

Figure 3

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Figure 4

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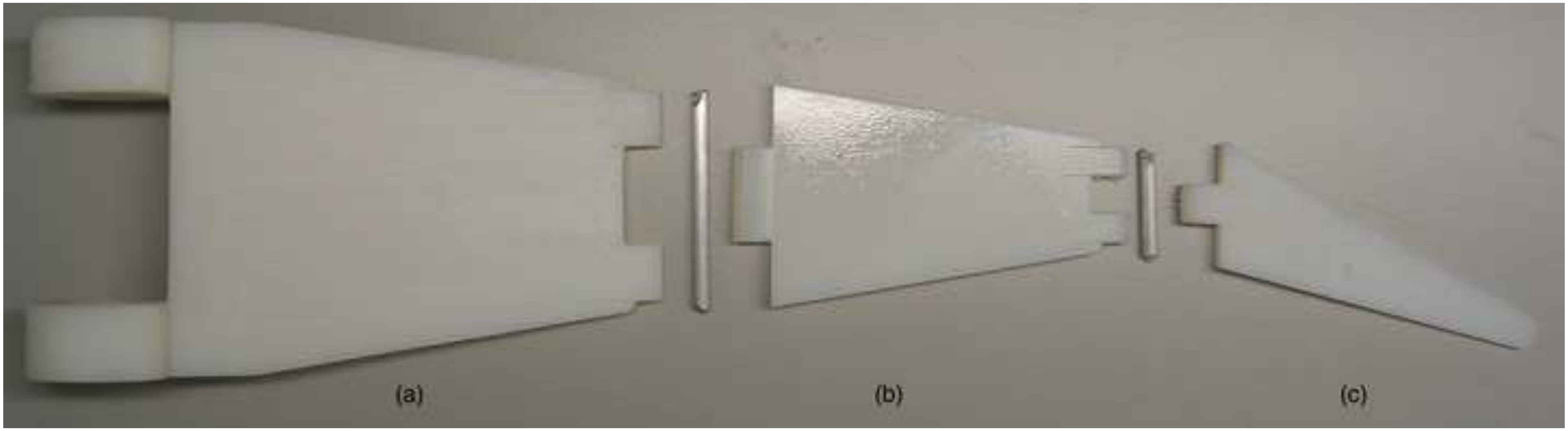

Figure 6

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(a)

(b)

Figure 7

Figure 8

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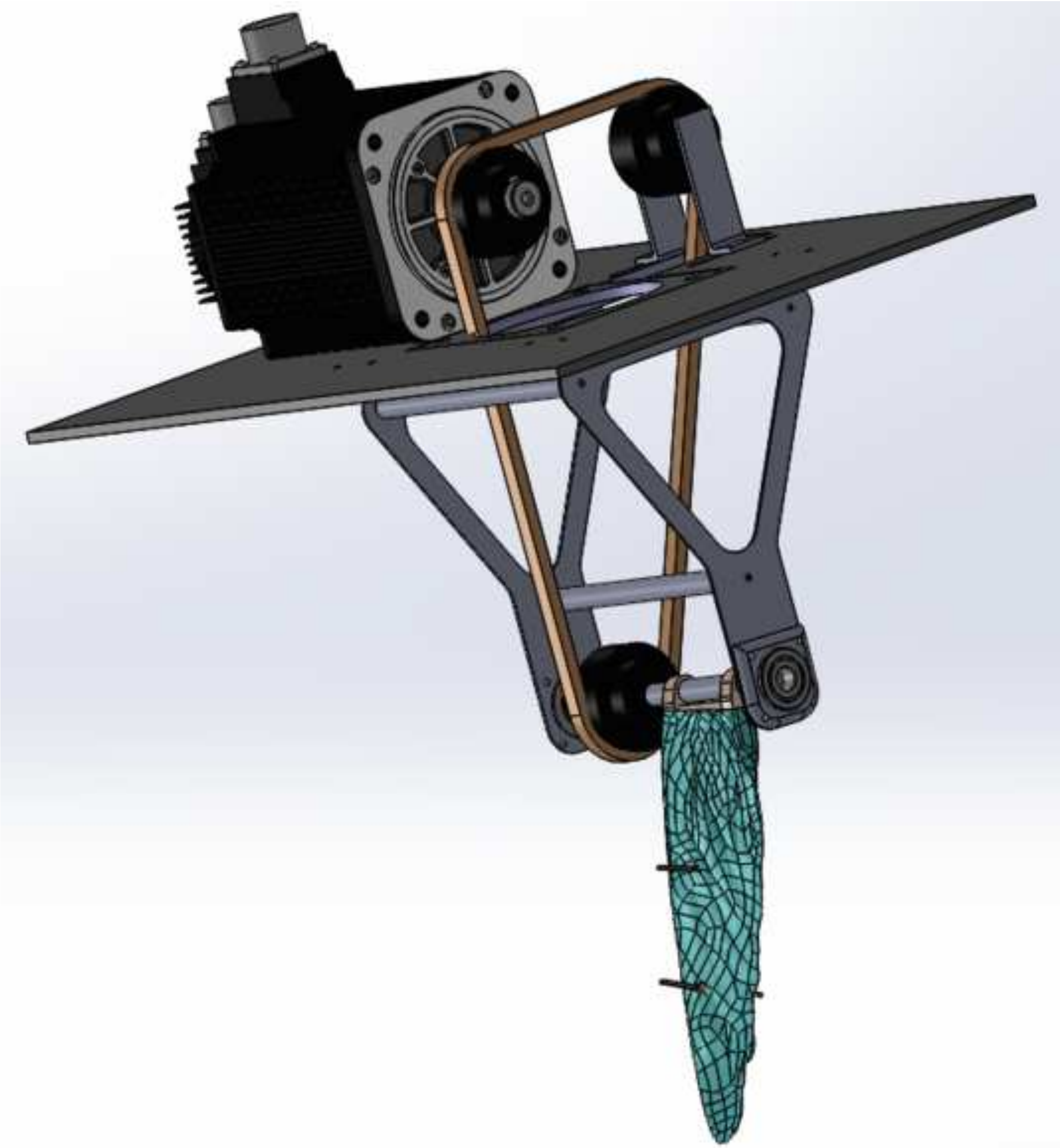

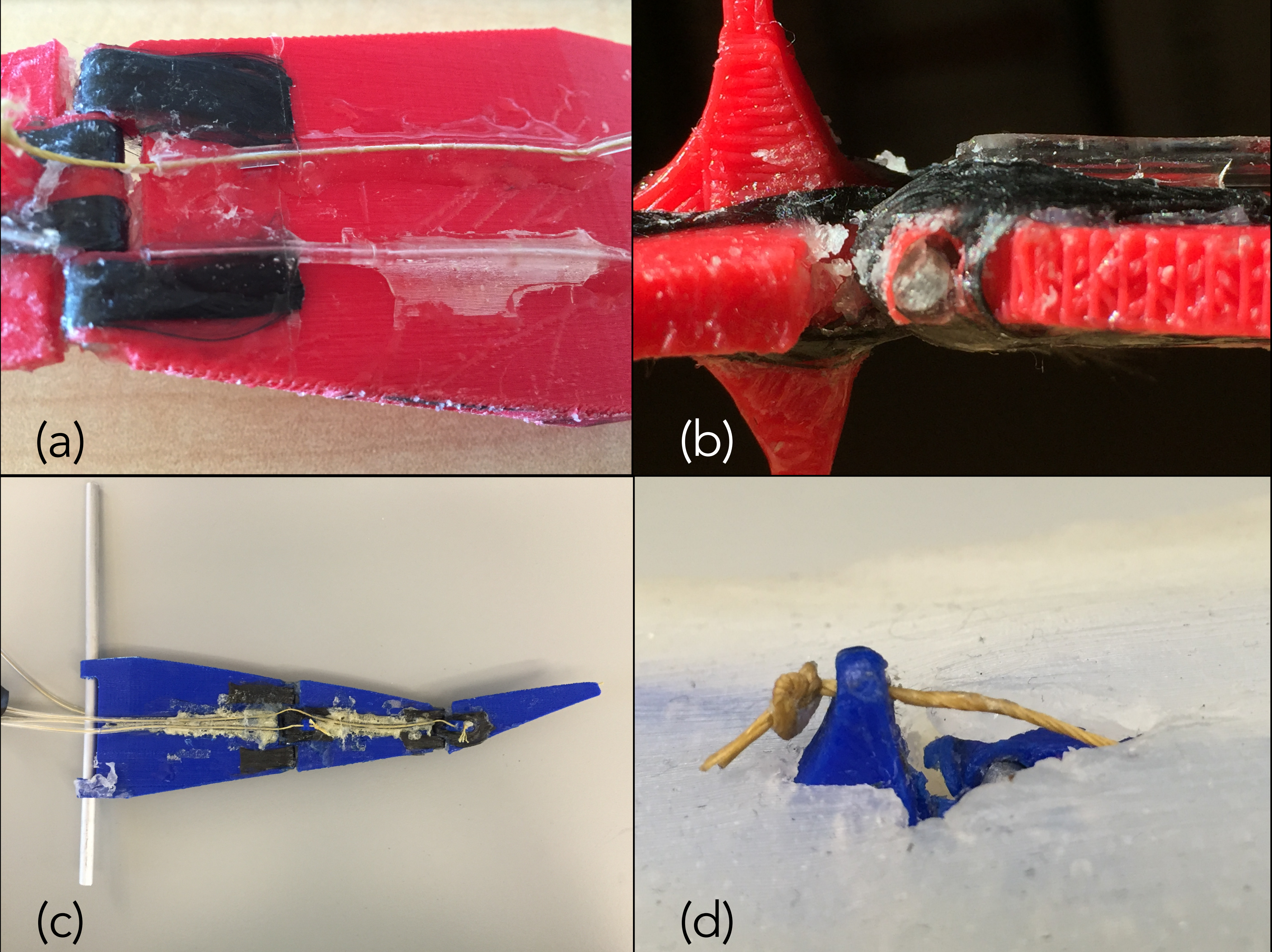
(a)
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(d)

Figure 9

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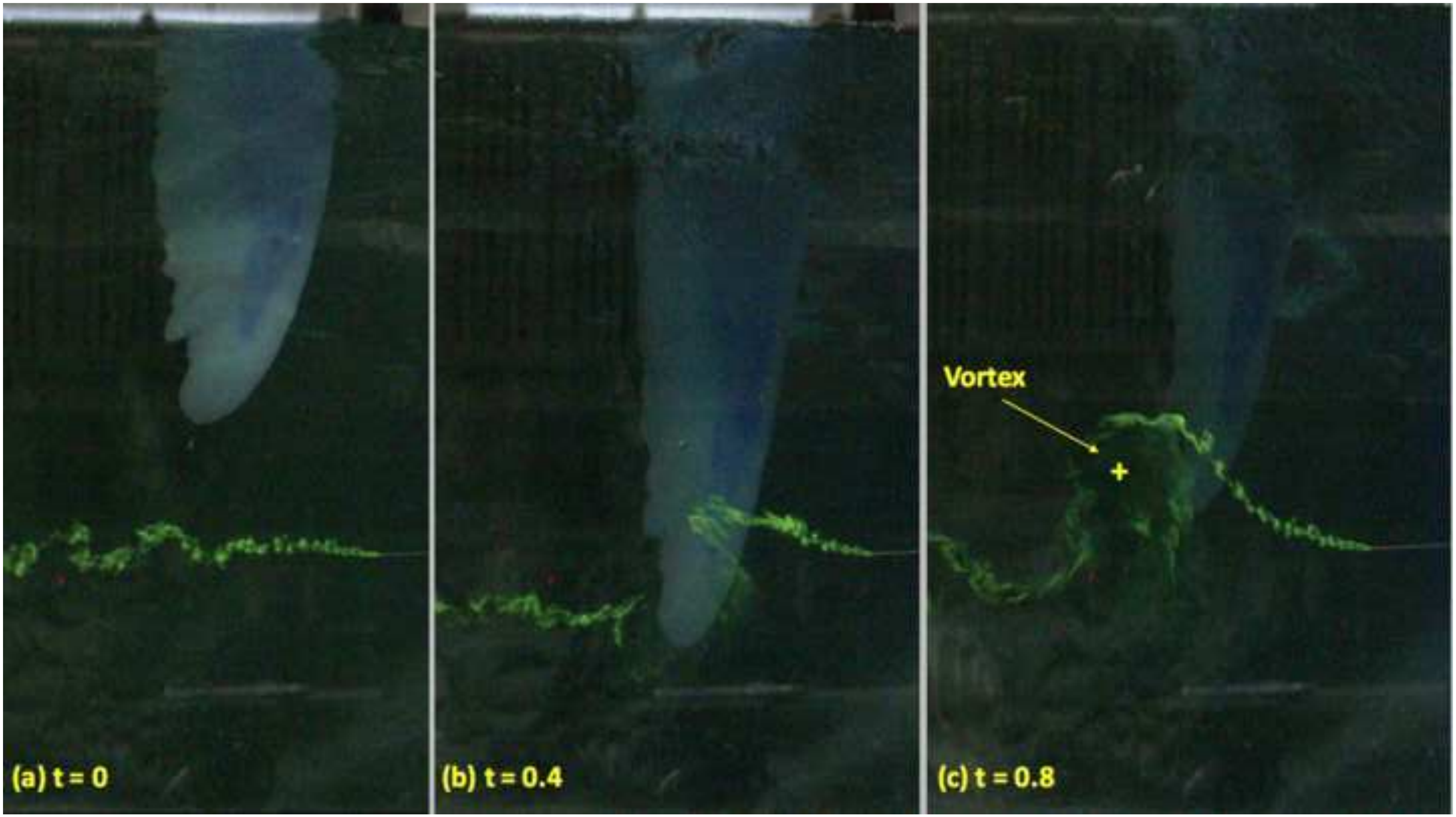

Name of Reagent/ Equipment	Company	Catalog Number	Comments/Description
Dragon Skin 20	Smooth-on		
Dragon Skin 20 medium	Smooth-on		
Object24	Stratasys		3D printer
Stand Mixer	Hamilton		
PKS-PRO-E-10 System	Anaheim Automation	PKS-PRO-E-10-A-LP	Controller and Servo Motor
Artec Eva	Artec 3D		3D light scanner with resolution of 0.1mm
Artec Spider	Artec 3D		3D light scanner with resolution of 0.5mm
Steel plate	Mcmaster		
Carbon Tow	Fibreglast	2393-A	
Hardened Precision 440C Stainless	Mcmaster	6253K49	
Tygon PVC Clear Tubing	Mcmaster	6546T23	
Kevlar Thread	Mcmaster		

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Author(s): Rahi K. Patel, Aditya A. Kulkarni, Chen Friedman and Megan C. Leftwich

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CORRESPONDING AUTHOR:

Name: Megan C. Leftwich

Department: Mechanical and Aerospace Engineering

Institution: George Washington University

Article Title: A robotic platform to study the foreflipper of the California sea lion

Signature: Megan Leftwich Date: 4/26/16

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•NOTE: Please download this version of the Microsoft word document (File name: 54909_R2_072616) for any subsequent changes. Please keep in mind that some editorial changes have been made prior to peer review.

•Please keep the editorial comments from your previous revisions in mind as you revise your manuscript to address peer review comments. For instance, if formatting or other changes were made, commercial language was removed, etc., please maintain these overall manuscript changes.

•Please adjust the highlighted length of the Protocol to no more than 2.75 pages.

•Formatting: Please use italics for Latin phrases, like in situ.

•Length is at the maximum limit of highlighted protocol.

•Grammar:
-Please use American English. For example, “centre” should be “center.”
-Line 45 – “describes robotic platform”
-2.2.2.2 – “The geometry of these knuckles need”
-3.2.5 – “it in the mold making up till the topmost knuckles”
Above comments have been addressed.

•Additional detail is required:
-1.1.1 – How/where are flippers obtained?
From Smithsonian Zoo. Comment addressed

-3.1.1 – Please clarify the layers referred to when the threads are attached. Do you mean second layer when you refer to “last layer?” Are the threads applied after printing the pieces?
The ambiguity in the sentence is clarified. Yes, the last layer was referring to the second layer. The threads are applied after 3D printing the structure.

-3.1.2 – What Kevlar string is referred to?
The strings that will be used to actuate the joints. Given in material table.

-3.1.7 – Please describe in words where all of the tubes are placed. The figure reference is insufficient.
The tubes can be placed anywhere on the structure. There is no specific constraint as to where they can be glued onto.

-3.1.8 – Which strings attached to which tubes?
Thread the Kevlar string from L_1 tube and L_2 tube through the holes drilled onto the tip and middle pieces as described in step 3.1.2.

-3.2.4 – Are the bone structures placed in the mold? What pegs are referred to here? Then are the bone structures placed in the mold before it is clamped down? How or to what is it clamped?
Yes, the bone structures are placed in the mold before clamping it down. The two parts of the mold are compressed using a clamp tool (to avoid a gap between them).

-Please include a step at the end of the protocol to describe the dye-based flow visualization. A citation can be included in lieu of detail, and this step does not need to be highlighted for filming.
Step included for dye visualization.

•Discussion: Please discuss the critical steps of the protocol.

•If your figures and tables are original and not published previously, please ignore this comment. For figures and tables that have been published before, please include phrases such as “Re-print with permission from (reference#)” or “Modified from..” etc. And please send a copy of the re-print permission for JoVE’s record keeping purposes.

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•NOTE: Please include a line-by-line response letter to the editorial and reviewer comments along with the resubmission.

Reviewers' comments:

Reviewer #1:

Manuscript Summary:

This paper investigates the propulsion of the California sea lion from video images in free swimming. The graphics and illustrations are both clear and illuminating, providing an excellent visual description of the research. Moreover, the authors present a compelling approach based on a novel analysis of video data, making this methodology of broad interest to the biomechanics and biolocomotion communities. This combination of data from an animal in a non-research setting with a matched robotic experiment marks a very challenging and creative approach to understand the California sea lion's remarkable and unique locomotion. Finally, the detailed description of their robotic design is a valuable contribution, promoting reproducible research.

I strongly recommend this paper for publication, as the results are important, interesting, and the research presented is both novel and will be directly used by many researchers in related fields.

We would like to thank this reviewer for their time and the consideration of our manuscript.

Major Concerns:

None.

Minor Concerns:

In Steps 1.1-1.2 of the protocol, a Sea lion foreflipper specimen is required. Is there any chance that the authors would be willing to publicly host their scan data, and CAD representation of the point cloud? This would greatly improve the ability for other groups to reproduce this setup even if they don't have access to a foreflipper.

I understand that there may be good reasons not to host the data, but in the interest of reproducible research, I thought I would suggest it.

We agree that making the scan available to other groups is beneficial to the wider science community. At present, we are providing the data to other researchers upon request, but hope to develop a system where the public can easily download the data. It will likely take a few more months for us to get the infrastructure in place, as well as the permission from all parties involved. However, we fully agree that this is important and are working to make this a reality.

Additional Comments to Authors:

N/A

Reviewer #2:

Manuscript Summary:

The authors report a method for making a (slightly) scaled model of the sea lion flipper as an experimental platform for testing fluid dynamics of this unusual form of locomotion. The context is interesting and the need for such a model is well-justified. The methodology is mostly thorough (although the mounting and motor need further specification) and there is definitely a need for more

methods like these to be shared, especially as labs outside the traditional auspices of engineering department take up robotic design and fabrication. I have several comments that should not be too difficult to address and resulting video will make an excellent contribution to JoVE.
Thank you to review #2 for your detailed comments on the paper. We believe that the suggested changes have improved the paper.

Comments:
-How does the model compare in size, Re and other parameters to the animal? Specifically: On L. 298 Report the actual Re achievable and the value for a typical animal. Also in the introduction you suggest you can match the Re, please indicate how much you have to scale U to do so or if you do this in some other way. Overall a table with the model and animal values for the quantities in these sentences would be a nice indication of the success of the final product. It would also give a better sense of scale.
The silicon flipper model is 68% of the actual size of the sea lion flipper. There are two Reynolds number to play with in this scenario – the tip speed Reynolds number (Re_t=750,000) of the flipper and the Reynolds number of the flipper based on the forward velocity and the chord of the flipper (Re_c=200,000).

-Is the deformation of the flipper important during swimming? If so, how elastically similar is the model flipper to the actual flipper (this is a big challenge in the dynamic scaling of insect wings)?
The deformation is definitely important during swimming – concurrently we are trying to use stereo videography to study the kinematics of sea lion flippers during a 'clap' to calculate the pitch angle. We believe it is around 50-60º which is what our model can achieve when actuated.

-Section 4: The mounting needs some additional details. Most significantly please provide information of the motor requirements - especially type, power and torque/speed demands. What are the minimal system requirements for actuation and how were these determined? What are the basic kinematics of a clap?
The motor specifications have been provided in the materials section in compliance with the journal requirements.

-P. 2 L. 71 Don't robotic platforms also allow for interactions with real environmental conditions as opposed to simulations which could also be used to explore large parameter spaces? This might be a nice point to make otherwise why not just do everything in CFD (there are other reasons too of course)?

-L. 105 Why is it scaled to 68%?
Scaled according to fit inside the water channel without being too close to the walls.

-L. 200 Material properties seem like they would matter here. Do you recommend/require specific materials and hence specific types of printers like ABS plastic or resin?
Material properties of the skeleton definitely matter as resin is brittle and snaps when the flipper model spins on the axle. Thus ABS plastic is used to create the skeleton as its stronger and can handle higher torque.

-L. 204 type of adhesive?
Comment addressed. Epoxy

-L. 285 "passive" is misleading. Just state that it is only actuated at the base.
Comment addressed. The use of the word 'Passive' is avoided.

-L. 289 attrition → addition
Comment addressed

-L. 376-377 This sentence seems incomplete. Difficult in what way?
Comment addressed

-Can the CAD and STL files be made available with final publication or in an online repository?
We agree that making the scan available to other groups is beneficial to the wider science community. At present, we are providing the data to other researchers upon request, but hope to develop a system

where the public can easily download the data. It will likely take a few more months for us to get the infrastructure in place, as well as the permission from all parties involved. However, we fully agree that this is important and are working to make this a reality.

Major Concerns:
N/A

Minor Concerns:
N/A

Additional Comments to Authors:
N/A

Reviewer #3:
Manuscript Summary:
The authors describe a protocol to fabricate a robotic platform that mimics the kinematics of a California sea lion flipper for the study of the resulting fluid dynamics. The platform is the first that has been used to study sea lion hydrodynamics. The protocol assumes prior possession of a sea lion specimen and anatomically relevant knowledge of its skeleton. The protocol then describes how to convert the morphology of the specimen to a 3D model that can be used to make a 3D-printed negative mold of the flipper. A hinged model of the skeletal structure (broken up into 3 main segments) is similarly fabricated with CAD software and 3D printing and manual assembly. The "skeleton" is then positioned within the mold and filled with silicone rubber. After curing, the whole flipper is removed from the mold and mounted to a motorized platform that actuates the flipper. The procedure has been successfully used in previously published papers by the same group.
Overall the manuscript is straightforward and the merits of fabricating a robotic mimic to a biological system are clear. Some aspects need clarifying (as described below) and further specifics.
Thank you, reviewer 3, for the thoughtful and detailed comments. We have incorporated your suggestions, and an account of the associated changes is below.

Major Concerns:
As written, the short abstract indicates the focus of the manuscript is the study of the hydrodynamics of the robot flipper. Similarly, the long form abstract suggests that the methodology for obtaining the kinematics (and replicating their motion for the robotic system) is also described in the manuscript. Please revise the abstracts to reflect the manuscript's objective of describing the fabrication of the robotic platform.
We have clarified that this manuscript described the creation of the robotic platform in the short abstract. However, the long abstract mainly focuses on this already. We removed a sentence about the hydrodynamics to increase the emphasis on the robotics, but clearly state, "This protocol describes a robotic platform designed to study . . ."

The authors refer to the tower protrusion as "okay". In what sense is the protrusion acceptable? Does this mean that they are hydrodynamically insignificant (please provide citation if so)?
The protrusions are hydrodynamically significant. However, during dye visualization the flippers were only actuated at the base (No need to add towers – only help in actuating the wrist and elbow joint). We sand the towers down to completely eliminate them during a passive clap. In future, while actuating all joints, we may need to make the protrusions as small as possible so that it doesn't affect the surrounding flow significantly.

The benefits of using robotic platforms to study animal locomotion are abundant and well-described by the authors. The limitations, however, are also plentiful and can be elaborated on, particularly for the benefit of those who are unfamiliar with the method. Some that come to mind include:
- isotropic homogeneous material properties offered by the silicone rubber and the molding technique;
- whether the 1-3 degree of freedom actuation is sufficient to fully describe the kinematics;

- does the soft material lend itself to fluid-structure interactions, and if these are biologically relevant;
- whether the protruding towers affect the hydrodynamics (e.g., vortex formation)

Thank you, the discussion of limitation in the “Discussion” section has been expanded to include these and other relevant limitations of the robotic system.

Another advantage to robotic platforms, which is alluded to in the introduction but perhaps should be made more explicit, is the ability to isolate kinematic components and thus deduce which contribute most to thrust production. For example, for the flipper, whether the active actuation of the two middle joints provides additional thrust, or is thrust primarily determined by the passive flapping. Kinematic model reduction would be interesting from the locomotion point of view, but also could have ramifications when applied to, say, biologically-inspired vehicles, as minimal degrees of freedom would be easier to implement to minimize power and complexity in control.

We wholely agree with this comment. This is, in fact, one of the most interesting aspects of robotic platforms (to the authors). This has been made more explicit in the introduction.

Minor Concerns:

Though some aspects of the protocol will be clarified with the resulting video, for the benefit of those who will primarily reference the manuscript, it would be helpful to annotate and label features in the figures. For example, the "towers" are not self-explanatory and required several re-readings and cross-referencing the figures to deduce what these were. More obvious features could be labeled for clarity.

I am not sure this is particular to the journal, but some steps in the protocol are incredibly specific. For example, while a generic CAD software is referenced, it is clear that the steps apply solely to Solidworks.

(These steps can be achieved by other software’s like AutoCAD but with some variations. The steps outlined provide a reference in extracting data from the point cloud. This journal does not let us mention specific names – hence the generic CAD software)

The wording is occasionally vague and the correct interpretation is not always obvious to the reader. The confusion stems from not being specific enough in detail or from language ambiguity. For example,

line 371: "maximum experimental versatility" -- what does this mean?

“Maximum” has been removed to be less vague.

line 379: "in these situations" -- what situations?

Situations where access to animals is difficult to obtain. Clarified in the manuscript

line 384-385: what is meant by a "partial view"? The isolation of the flipper from the system is subsequently listed as an additional limitation, so it isn't clear what the limitation of the "partial view" refers to.

The partial view refers to the disadvantage dye visualization provides as the images captured are in 2D. In future, a 3 dimensional view would be preferred (e.g PIV) to see how the vortices propagate in 3D.

some minor notes on grammar and spelling:
line 45: "describes *a* "
line 81: no apostrophe for "animals"
line 83: "wider"
line 84: perhaps "explore" may be a better word than "yield"? ***
line 289: "addition"
line 369: "non-physical" -- do you possibly mean "non-biological"? ***
line 373-374: "the range of data *is* ..."

All minor grammatical comments made by 3rd reviewer have been addressed.

Additional Comments to Authors:

N/A