Biological and Robotic Synthesized Cuttlefish Fin Biomechanical Model

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Abstract

Cuttlefish (Sepia Officinalis) use a distinctive form of propulsion driven by the sinusoidal motion of their muscular hydrostat fins, providing a method for underwater locomotion. This study integrates research on cuttlefish fin anatomy, musculature, and energy dynamics to set up a biomechanical benchmark for understanding their motion. By synthesizing biological data with robotic modeling, this benchmark offers a framework for developing advanced biomimetic robots capable of replicating cuttlefish fin propulsion despite lack of experimental research into posterior fin thrust. The results underscore the value of cuttlefish-inspired designs in advancing energy-efficient, adaptive underwater propulsion technologies while finding avenues for future experimental validation to refine the benchmark further.

Introduction

Although biomechanics is fundamentally the study of biological movement it also encapsulates how engineering-based designs can be used to create biomimetic robots. Therefore, it is essential that animal biology is understood, more specifically, animal mechanics. By analyzing and understanding animal mechanics it opens avenues to not only create biomimetic robots but to compare them to their animal counterparts. The goal for biomimetic robots is not to replace animals but to improve upon their designs and beat evolution in a faster period, allowing innovations in propulsion, energy efficiency, and sensors.

Cuttlefish (Sepia Officinalis) are a unique cephalopod that differs from their fellow Decapodiformes in multiple ways. This paper focuses on their distinct sinusoidal fin motion, mechanics, and musculature. A cuttlefish's fin is a muscular hydrostat that surrounds the entirety of their posterior body of the cuttlefish. Its sinusoidal motions use Newton's third law in a unique way to accelerate water across the fin. By studying this unique locomotion, it is possible to unravel a new propulsion system that improves upon modern day designs.

Purpose

Understanding cuttlefish is akin to understanding millions of years of careful evolution and understanding their mechanics can be used to inspire modern day robotic designs. This paper aims to corroborate research papers from multiple sources to create a mechanical cuttlefish "benchmark." This benchmark can then be used to compare cuttlefish to each other and to design biomimetic robots that can use the sinusoidal fin motion as a new way of underwater propulsion.

This benchmark includes overall cuttlefish biology, sinusoidal fin motion, force and velocity equations for fin thrust, and energy efficiency. Although this benchmark focuses on the cuttlefish fin, understanding the entire cuttlefish's biology is essential to understanding how each component works together as a whole (i.e., size, shape, organs, habits, lifecycle, etc.). The next step focuses more on the fin mechanics as understanding the relationship between fin frequency, wavelength, and amplitude will determine how good of a fid a sine curve fits to a cuttlefish fin and how each part of the wave relates to each other. By determining the force, acceleration, and velocity of the cuttlefish fin for a set wave it allows us the most crucial part of our analysis, how fast the fin can propel itself, and therefore its efficiency for movement. Only by solving each of the previous components can we finally solve for the energy efficiency for the cuttlefish fin and how the cuttlefish fin can compare to other underwater propulsion mechanisms by comparing force produced for energy used.

Methodology

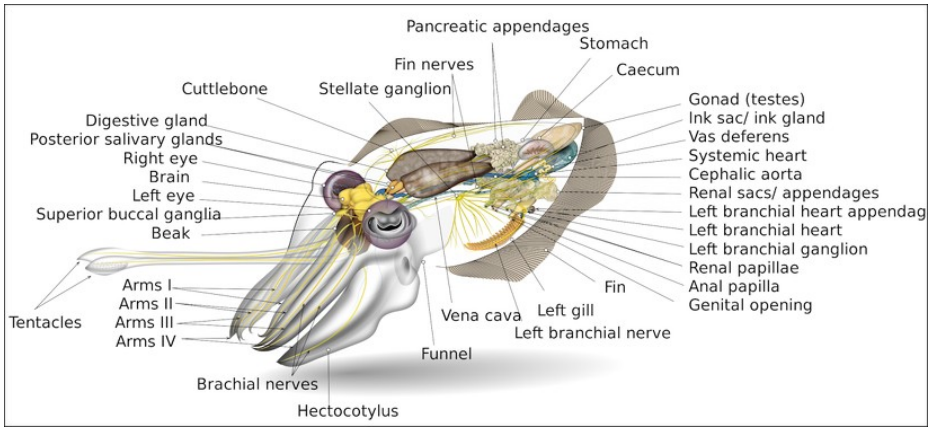


Fig 1: Cuttlefish anatomy diagram [(11)]

The first step in creating the biological benchmark is discovering overall biological information of the cuttlefish. Cuttlefish differentiate themselves from other cephalopods due to their cuttlebone, fins, and habitats. In other cephalopods the gladius is a hard organ that allows it to regulate its buoyancy and therefore its depth. However, in the cuttlefish this takes the form of a soft-bone structure high in calcium and is much thicker than a gladius that acts in a comparable manner despite a different structure. The fin of a cephalopod in squids (Loliginidae) usually only are present in the distal portion of the mantle having the squid primarily focus on jetting as its primary method of propulsion. The cuttlefish however has fins covering its entire mantle and uses them more frequently as a method of slow aerobic movement to sneak up on prey. Living around 100m to up to 600m deep, depth changes during life cycle with shallower and warmer waters are preferred for breeding. They exhibit rapid growth and high food intake, reflecting their carnivorous nature, requiring them to hunt actively for prey. Cuttlefish vary in size, ranging from 1.7 to 20 inches in length. Adaptations among species include the ability to produce ink for defense, as well as poisons and venoms for hunting or protection. One final notable trait of cuttlefish is their dynamic coloration, which is used both for communication and effective camouflage.

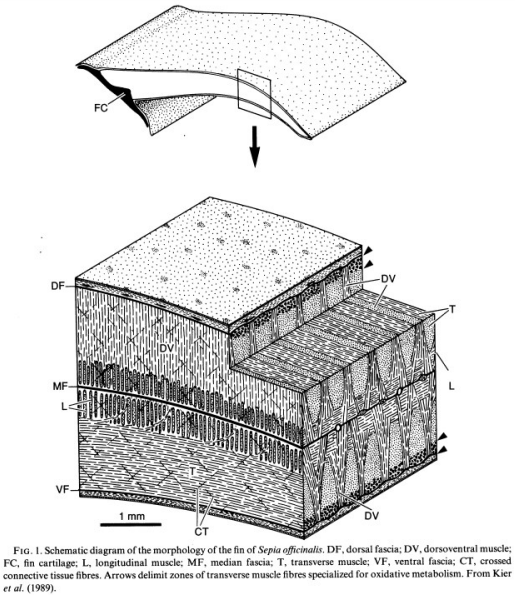


FIG. 1. Schematic diagram of the morphology of the fin of *Sepia officinalis*. DF, dorsal fascia; DV, dorsoventral muscle; FC, fin cartilage; L, longitudinal muscle; MF, median fascia; T, transverse muscle; VF, ventral fascia; CT, crossed connective tissue fibres. Arrows delimit zones of transverse muscle fibres specialized for oxidative metabolism. From Kier *et al.* (1989).

Fig 2: cutout diagram of cuttlefish fin muscle, courtesy of Dr. William Kier et al. [(2)]

The musculature of a cuttlefish is a muscular hydrostat which explains its flexible nature and lack of bone structure. Dr Kier et al. created a helpful muscle cross-section diagram that allows the breakdown of the various tissue layers [(2)]. The section labeled DF is the dorsal fascia which acts as the protective fiber surrounding the fin muscle as well as a connective tissue to maintain fin structure. The next layer is the dorsoventral muscle (DV) which alters the thickness in the opposing dorsoventral direction of the transverse muscle. The transverse muscle (T) acts as the primary contraction mechanism for fin bending, this is also the only muscle group in the cuttlefish fin to be aerobic. The longitudinal muscles (L) are the only muscle to work in the lateral medial direction and prevents longitudinal extension due to DV muscle fibers. The median fascia (MF) is the main connective tissue for the muscular hydrostat and has mirrored muscle groups on either side for dorsal or ventral bending.

In an example anerobic bending motion in the ventral direction of the fin starts with the transverse muscles bending the fin in the ventral direction. To assist the transverse muscles the dorsoventral muscles activate on the dorsal side to decrease the thickness and therefore ease the bending in the ventral direction. The longitudinal muscles then react to the transverse and dorsoventral muscles and try and maintain the same length in the lateral medial direction. For an anerobic bending motion in the dorsal direction simply reverse the dorsoventral and transverse muscle contraction directions.

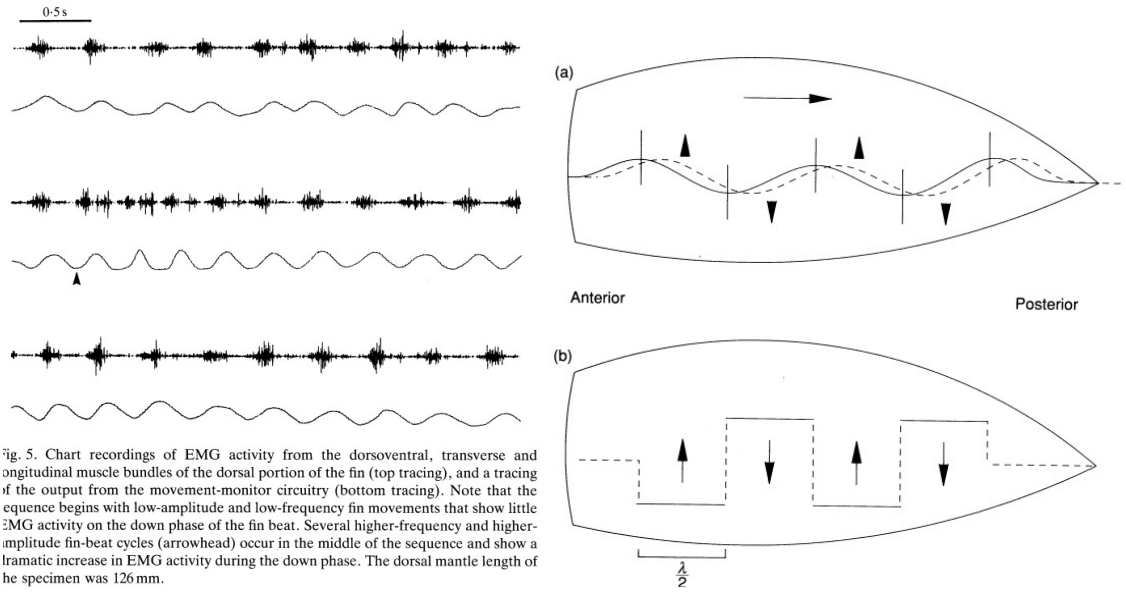


Fig. 5. Chart recordings of EMG activity from the dorsoventral, transverse and ongitudinal muscle bundles of the dorsal portion of the fin (top tracing), and a tracing of the output from the movement-monitor circuitry (bottom tracing). Note that the equence begins with low-amplitude and low-frequency fin movements that show little EMG activity on the down phase of the fin beat. Several higher-frequency and higher-amplitude fin-beat cycles (arrowhead) occur in the middle of the sequence and show a dramatic increase in EMG activity during the down phase. The dorsal mantle length of he specimen was 126 mm.

Fig 3: EMG data taken from a cuttlefish using electrodes and wavelength diagram, courtesy of Kier et al. [5]

The activation of muscles also follows a sinusoidal motion to accelerate water in the posterior direction and the cuttlefish in the anterior direction. This is proven by Kier et al. who inserted tungsten wire electrodes into the fin musculature to measure muscle action potentials. The cuttlefish was then placed into a tank with variable water velocity to control the speed that the cuttlefish was travelling at. What was found was a distinct pattern of muscles turning on and off in a pattern that coincided with a sinusoidal wave in the dorsoventral direction. The frequency and amplitude were also found to be correlated to each other as if one is increased the other must also increase at a similar rate. The large the frequency or amplitude the larger the amount of water displaced is and therefore the amount of force produced by the fin.

What was found is that cuttlefish have two distinct fin activity modes: gentle and vigorous [4]. Gentle beating was used when the cuttlefish was hovering or slowly moving and is the primary way the cuttlefish moves. As gentle beating is aerobic for energy efficiency only the transverse muscles are active during this beating mode. Vigorous beating is used when capturing prey or evasive maneuvers [4] but due to it being anerobic it is used sparingly. During vigorous beating though all three muscle groups are active, and a large amount of force can be produced.

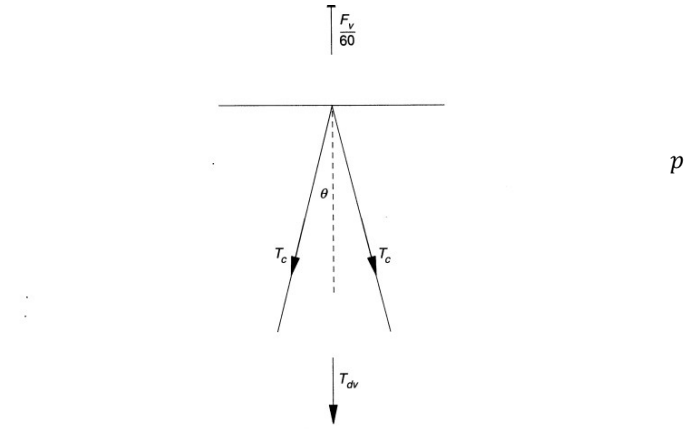


FIG. 4. Schematic diagram of the forces acting on one-sixtieth of the dorsal surface of the fin. The horizontal line is the dorsal surface. The two obliquely oriented lines are connective tissue fibres.

$$p = \frac{F_h}{yt} \qquad F_v = \frac{F_h x^2}{A_0} \qquad F_h = A_{tm} s_{tm}$$

$$F_{v,tot} = 120 T_c \cos(\theta) + 60 T_{dv}$$

$$T = EA\varepsilon$$

$$\varepsilon_c = \frac{\sqrt{\left(\frac{x}{30}^2 + \frac{900 A_0^2}{x^2}\right)}}{x_0\sqrt{2}} - 1$$

$$\varepsilon_{dv} = \frac{A_0}{(x x_0) - 1}$$

Fig 4: Force diagram and equations for dorsoventral and lateromedial fin, courtesy of Johnsen et al. (2)

A system of equations based on experimental data found by Johnsen et al. analyzes the dorsoventral and lateromedial forces a cuttlefish can produced. There are approximate twenty unique variables in the system of equations but depending on assumptions and found values it proves valuable for finding stress, strain, forces, area, position, or other unknowns. This system of equations also helps equate the stress and strain put upon the fin due to forces applied. This is important later for energy calculations as due to elastic characteristics of muscular hydrostats.

$$\begin{cases} F_T(t) = \int_S p(t)(n_x \cdot dS), \\ F_{D(t)} = \mu \int_S \left(\frac{\partial v(t)}{\partial \delta} \cdot n_x \right)\Big|_{\delta=0} dS, \\ \rho \frac{dV}{dt} = F - \nabla p + \mu \nabla^2 V, \\ \nabla \cdot V = 0 \\ \sigma_{ij,i} + F_j = \rho_s \frac{\partial^2 u_j}{\partial t^2}, \\ \varepsilon_{i,j} = \frac{1}{2}(u_{i,j} + u_{j,i}), \\ \varepsilon_{ij} = \frac{1}{E}\left[(1+v)\sigma_{ij} - v\sigma_{kk}\delta_{i,j}\right. \end{cases} \qquad (i,j,k = x,y,z),$$

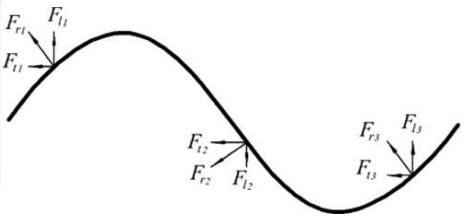


Fig 5: Robotic Cuttlefish sinusoidal dynamic analysis, courtesy of Su et Al. (8)

Fig 6: dorsoventral and posteroanterior force equations for simplified robot model (8)

Due to their being no current research on the posterior thrust mechanics of a cuttlefish a synthesized model was made from robotic and biological models. This allows a system of equations to be set up with the assumption that if the robotic model proposed by Su et al. (8) is the same size and shape as the cuttlefish, its mechanical equations will match the biological model proposed by Kier et al. (5). This is done finding the change in velocities for a time segment and solving for acceleration to find the difference between thrust and drag. Then by finding the drag force by using a point velocity a point thrust force can be found to complete our 3D force equations for the biomechanic benchmark.

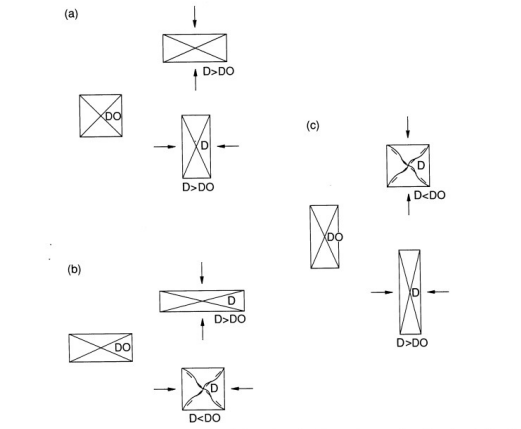


FIG. 3. Schematic diagram showing the strains of diagonal tension elements in rectangles subjected to horizontal compression or elongation. (a) Diagonals are originally oriented at 45°. Both horizontal and vertical compression strain the tension elements. (b) Diagonals are originally oriented at less than 45° to the horizontal. Horizontal compression of the rectangle results in shorter diagonals. Therefore the tension elements buckle. (c) Diagonals are originally oriented at greater than 45° to the horizontal. Vertical compression buckles the tension elements.

Fig 7: Diagram of tension, stress, and strain in cuttlefish fins, courtesy Johnsen et al. [(2)]

Due to the nature of the cuttlefish fin being a muscular hydrostat there is a small amount of stress and strain energy that is stored in the elastic fin. This can be calculated using the equations in fig 5 and then by combining them with elasticity to energy charts in figure c the energy expended to stretch the fin can be calculated. This energy can then be recuperated with small energy losses and must be included in calculations for overall efficiency.

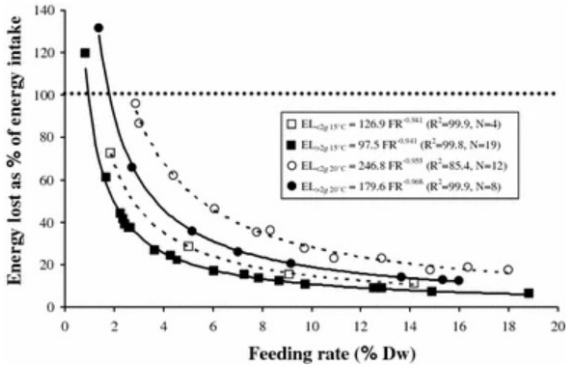


Fig 8: energy loss due to energy intake compared to feeding rate [(9)]

Due to the variable characteristics of a cuttlefish being a living being an exact energy efficiency of energy intake to energy produced is extremely difficult to calculate without experimental data. As such, no experimental data has been found to directly correlate energy intake vs energy expelled or lost by a cuttlefish due to just fin propulsion. However, only energy produced is profoundly important for our biomimetic benchmark so using the work produced equation (E = F*d) is a good estimator of how much energy a cuttlefish can produce.

The overall energy efficiency of a cuttlefish can be understood thanks to Grigoriou et al. [9] who measured the correlation between: energy lost percent of energy intake versus feeding rate. What is seen is that as the feeding rate increases (fed +x% of dry body weight) the energy lost from intake decreases at a reciprocal rate. This means that cuttlefish are good at reserving energy at low feeding rates until a point where too little is fed to maintain homeostasis. This is valuable to know for a biomechanical benchmark as the feedback loop of a cuttlefish increasing energy efficiency as less food is eaten must be considered when using this benchmark as a comparison to other creatures or robotics who have different, or no, energy efficiency systems built in.

Results

Experimental tests were not done for this research project due to lack of resources. Nevertheless, an example experimental application of the cuttlefish model can still be proposed using a theoretical biomimetic cuttlefish robot.

Experimental Setup:

1. Robot Design Specifications:
    - The robot mimics the shape and fin musculature of a real cuttlefish, with flexible hydrostatic fins actuated by soft materials simulating transverse, dorsoventral, and longitudinal muscle activity.
    - The fins produce sinusoidal beating of varying frequencies and amplitudes, powered by programmable soft actuators.
    - Sensors onboard include force transducers to measure thrust and accelerometers to track motion.
2. Test Environment:
    - A controlled water tank equipped with an adjustable flow pump to simulate varying underwater conditions with a flow meter to measure water velocity.
    - Cameras and laser-based particle image velocimetry (PIV) systems to visualize and measure fluid dynamics around the robot.

Procedure:

1. Initial Calibration:
    - Measure the mass, dimensions, and resting buoyancy of the robot in water to ensure neutral buoyancy.
    - Assess actuator responsiveness to sinusoidal input signals for amplitude, frequency, and phase.

2. Baseline Measurements:
    - Operate the robot in still water, programming the fins to produce gentle and vigorous beating modes as described in the biological benchmark.
    - Record thrust force, forward acceleration, and energy consumption for each mode.
3. Dynamic Testing:
    - Gradually increase the water flow velocity to evaluate how the robot adapts its propulsion under environmental drag.
    - Use the robot's sensors and external measurements to calculate thrust (using F=ma), drag forces, and net acceleration in different flow conditions.
4. Energy Efficiency Evaluation:
    - Calculate energy expenditure using power input to the actuators (P=IV).
    - Determine work output using work-force equation (W=F*d)
    - Compare energy efficiency by evaluating the ratio of work output to energy input across various fin frequencies and amplitudes.
5. Stress and Strain Analysis:
    - Incorporate elastic properties into the fin design to mimic real cuttlefish energy recuperation from strain.
    - Use embedded strain gauges to measure stress and strain in the fin material during motion.
    - Calculate the energy stored and recovered during elastic deformation to assess efficiency improvements.

Data Analysis:

- Compare robot performance with biological benchmark, focusing on thrust force, acceleration, and energy efficiency.
- Evaluate the validity of the biomimetic design by analyzing discrepancies in thrust or drag equations.
- Assess the hypothesis that incorporating soft hydrostatic fin properties enhances performance over rigid fin designs.

Potential Outcomes:

- Validation of the biomechanical benchmark for robotic application, proving that sinusoidal fin motion achieves energy-efficient underwater propulsion.
- Identification of mechanical or material constraints in the robotic model that deviate from biological efficiency.
- Insights into improving actuator programming or material selection to further mimic real cuttlefish dynamics.

Discussion

The largest flaw of this synthesized model is the assumption that a cuttlefish fin and robotic sinusoidal fin match perfectly according to size and energy production. This assumption is not completely true but is the best model available from modern experimental data. The posterior and anterior thrust and force have not yet been analyzed for a cuttlefish and should be researched for a more complete zoological understanding of the cuttlefish.

A research experiment to evaluate the posterior thrust of a cuttlefish with a biomechanical model in mind follows. The cuttlefish should be placed into a tank with variable water pump to accelerate the water in a certain direction. Before placing the cuttlefish into the water, the wet weight of the cuttlefish should be taken to find its mass. Once placed in the tank the water should be slowly accelerated until a maximum velocity is met (maximum should be around where cuttlefish is a maximum vigorous beating but does not significantly move anteriorly or posteriorly). The mass, water velocity, and cuttlefish acceleration should then be able to be used to determine the force the fin produces according to newtons second law. Better data could be achieved with the addition of EMG mapping and force sensors.

Additionally, the synthesized biomechanical benchmark given is very viable for a biomimetic robot to use cuttlefish fin motion as a mode of propulsion. This has already been recreated in multiple robots and experiments but the replacement of soft actuation in the find movement may allow the robot to reach greater depths with higher energy efficiency. Additionally, all cuttlefish robots involve a hard shell and hard components as part of the fin. By using only soft materials a more accurate biomimetic robot can be created that can also survive deeper depths due to the high plastic deformation range of soft materials.

Much more research is needed to assess this biomechanical model for accuracy and missing information. But more research into the validity of its assumptions,

Conclusions

Cuttlefish fin propulsion highlights an unexplored method of underwater propulsion, making it an ideal subject for biomechanic analysis. It’s muscular hydrostat structure uses sinusoidal wave motions, providing a highly efficient mode of underwater movement, balancing aerobic and anaerobic energy expenditures based on environmental demands. The unique mechanics of cuttlefish fins underscores the evolutionary optimization of this species for stealth and adaptability in aquatic environments.

The biomechanical benchmark synthesized in this study highlights the potential to use cuttlefish-inspired mechanisms in robotic design, particularly for soft robotics. While current robotic models offer valuable approximations, they often do not fully replicate the energy efficiency and flexibility seen in living cuttlefish. Future research should refine this benchmark through experimental validation, such as measuring real-time thrust and force dynamics of live cuttlefish in controlled environments. This data would allow for more accurate modeling and improved biomimetic applications.

This research not only deepens our understanding of cephalopod biomechanics but also lays the groundwork for innovations in underwater robotics. The adaptability, efficiency, and precision of cuttlefish motion holds promise for technologies that mimic its propulsion mechanisms. As these benchmarks evolve, they will bridge the gap between biological models and robotic models, advancing the possibility of new way of underwater movement.

Appendices:

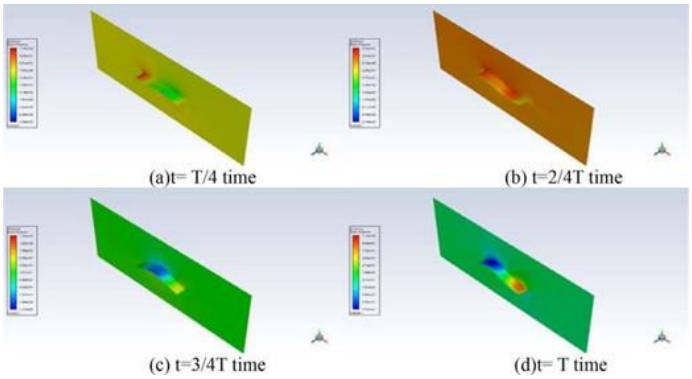


Fig A: pressure calculations at timepoints of sinusoidal motion [8]

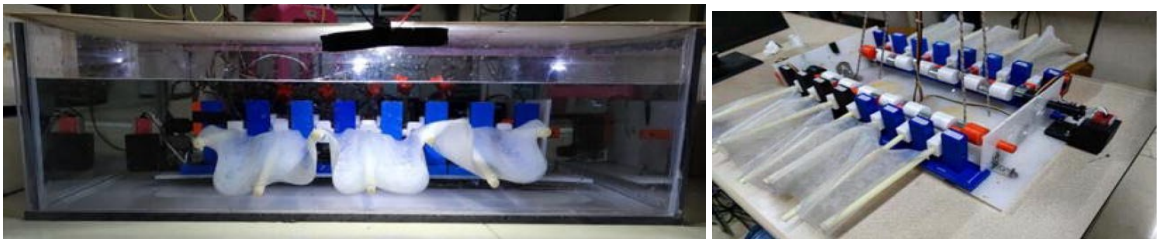


Fig B: images of robotic cuttlefish fin model [8]

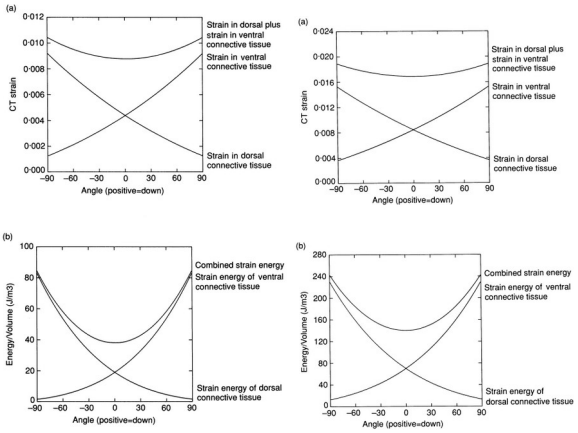


Fig C: energy, stress, and strain tabulated comparisons, courtesy of Johnsen et al. [(2)]

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Citations:

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