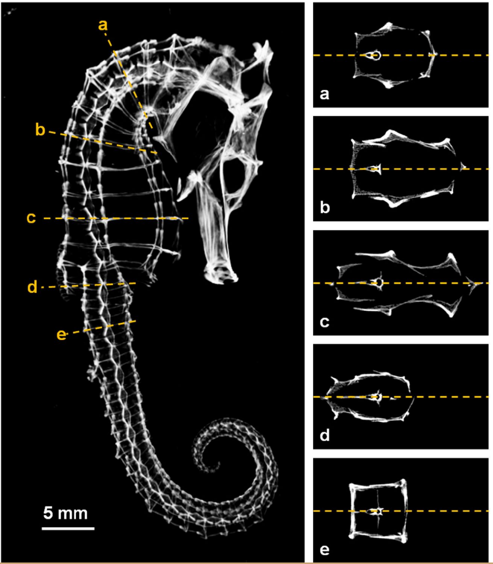
Seahorse Kinetic Interlocking Plate System (SKIPS)

Ostentatious Octopi

Project Overview

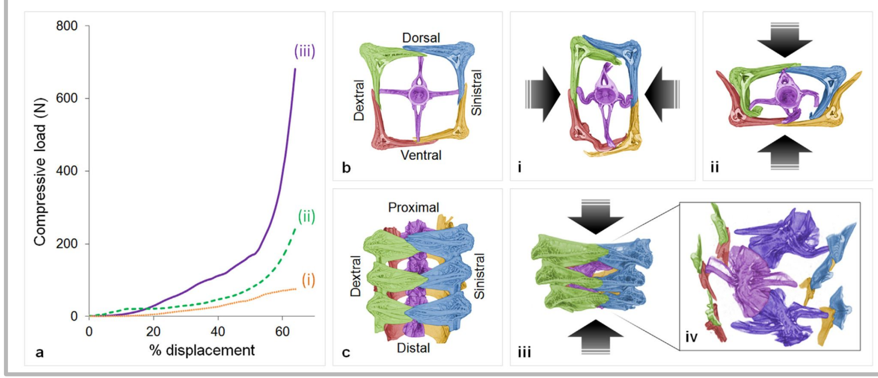
Seahorses have a variety of unique features that are worth examining, such as equiline features, vertical swimming position, and ability to camouflage. This project focuses on the skeletal structure of the seahorse tail, which allows it to bend and compress and helps give the tail its prehensile properties.



The objective of this project is to modify the Kamigami hexapod robot with a new central skeletal structure that is inspired by the structure of the seahorse tail. By modifying the robot's structure, the team aims to partially replicate the flexibility and compressibility of the seahorse tail and improve the robot's ability to navigate winding pathways and tight spaces.

Hippocampus Kuda: Spotted Seahorse

Summary of Objectives



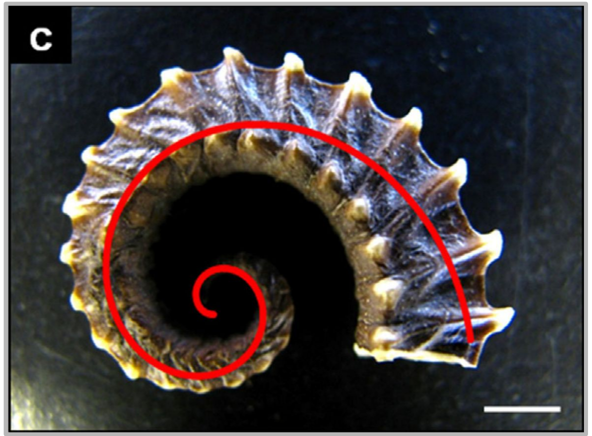
* Porter et al. 3D rendering for the compression of the skeletal structure

Hypothesis being tested:

A bio-inspired design derived from a seahorse armor bone configuration can provide a flexible and compressible body for a robot structure.

Novel biological principle being translated:

As discussed in the paper *Highly deformable bones: Unusual deformation mechanisms of seahorse armor*, Porter et al. it has been known that a “seahorse tail is composed of subdermal bony plates arranged in articulating ring-like segments that overlap for controlled ventral bending and twisting. The bony plates are highly deformable materials designed to slide past one another and buckle when compressed.” The paper shows that the “complex plate and segment motion, along with the unique hardness distribution and structural hierarchy of each plate, provide seahorses with joint flexibility while shielding them against impact and crushing.”



* Example of the flexibility given the bone structure and bone material composition

Literature Review: Discovery Decomposition

Highly deformable bones: Unusual deformation mechanisms of seahorse armor

[Michael M. Porter, Ekaterina Novitskaya, Ana Bertha Castro-Ceseña, Marc A. Meyers, Joanna McKittrick]

Background & Hypothesis

Seahorse tail structure consists overlaping segments of subdermal bony plates

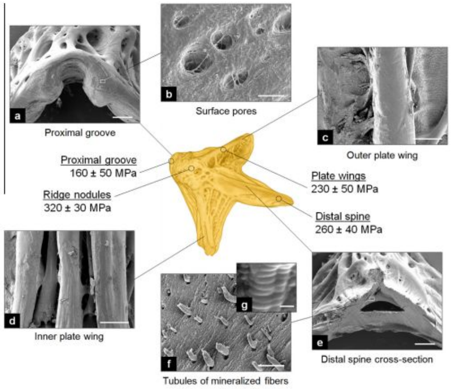
Unlike most fish, seahorse tails can bend and twist ventrally and have prehensile capabilities

Hypothesis: A seahorse tail's ability to flex and compress, while also being strong and resilient against external forces, is a product of the structure, arrangement, and composition of bones in the tail

Seahorses' subdermal armour helps protect against natural predators which capture their prey by crushing

Seahorses' bony plates are dfferent from from the scales, shells, and exoskeletons that serve as armor in most fish, crustaceans, and mollusks

Methods



Deproteinization: Skin removed on seahorse tail to visualize and study arrangement of overlapping subdermal plates

Microcomputed tomography and scanning electron microscopy: Scans of tail sections and individual plates used to render models of skeletal structure

Compression testing: Test machine used to compress tail sections by 60% of original height in three orthogonal directions (lateral, ventral-dorsal, and distal-proximal)

Mineral Composition: Water, mineral, and organic fractions of seahorse bones measured by comparing weights after cleaning, drying, and extreme heating

Microhardness Testing: Bony plates indented in four locations using hardness testing machine

Results

Tail consists of 36 square-like segments; a combination of gliding (1 DOF) and ball-and-socket (3 DOF) joints within and between segments allow for flexibility and compression

Tail could be compressed by nearly 50% in all three orthogonal directions without permanent damage; plates slide past each other and lateral struts buckle to accomodate compression

Bony plate material is itself highly deformable

Bony plates are organic/inorganic composites with a composition of 40 ± 5 % mineral (calcium phosphate), 27 ± 4 wt.% organic, and 33 ± 5 wt.% water

Proximal grove hardness (160 ± 50 MPa) is nearly 40% softer than distal spine (260 ± 40 MPa)

Conclusions

Structure, joints, and arrangement of bony plates allow tail to flex ventrally and compress without permanent damage

Bony plates are energy absorbant and resistant to crack propogation like many animals' bones, teeth, and horns

Hardness distribution is functional; hard outer surface provides protection while softer material at joints allows for mobility and stress absorption

Test Hypothesis

Tail's flexibility and resilience to external forces is a product of bone structure and arrangement - supported

Test Hypothesis

Tail's flexibility and resilience to external forces is a product of bone composition and material properties - supported

Analogy Check

Design Solution	Analogy Check	Design Problem
Hippocampus Kuda		**Seahorse Kinetic Interlocking Plate System (SKIPS)**
Behaviors	(What does the system do)	**Behaviors**
Has a flexible, deformable tail structure made out of overlapping bony armor plates	Similar	A flexible and compressible overlapping segmented system for passage through curved confined spaces
The tail can also be used for prehension	Not present	Prehension is not present
Structural Components	(What is the structure of the system)	**Structural Components**
The external square ring like structure of bone plates supported by a single vertebra. Each ring overlaps its anterior neighbor for axial bending.	Similar 90%	An external ring structure will of 6 segments overlap their adjacent neighbours connected by elastic bands. An internal cylindrical segment will be connected to the outer ring structure using elastic bands.
Neighboring segments are connected by four gliding joints where the distal spines of the anterior plates insert into the proximal grooves of the posterior plates.	Different 20%	The anterior and posterior neighbors will be connected by glue along extended interior pipe
Each vertebra is joined to the bony plates by connective tissue attached to the vertebral struts at the dorsal, ventral and lateral midlines. The plate–vertebra junctions are extremely flexible joints with nearly six degrees of freedom.	Similar 90%	An internal cylindrical segment will be connected to the outer ring structure using springs. Each internal cylindrical segment will be connected to its adjacent one with a ball and socket joint
Uses dorsal fin for movement	Different	Six uncoupled origami legs will be used for movement
Size	(Does it scale)	**Size**
The measured dimensions of the tail sections were approximately 7 x 7 x 10 mm^3 with the overall length of around 5-8 cms.	Different 20%	The body needs to be larger, with enough surface area on the top for electronics and any additional payload. (initial measurements of segments 30 x 30 x 30 mm^3).
The size of each tail section decreases linearly in size along the length of the tail.	Different 20%	The dimensions will be constant along its length.
Prehensile tail has about 36 bony square like segments	Different 20%	The body will be composed of 6 segments in total.
Operating Environment	(Where?)	**Operating Environment**
Sea horses are marine species, typically found in corals, mangrove roots and seagrass beds	Different	Tunnel like environments with solid footing.
Functional Mechanisms	(How does the system work?)	**Functional Mechanisms**
The overlapping bony plates slide past each other allowing for compression. Each tail segment has gliding and pivoting joints. The connecting tissue holds the structure together.	Similar 50%	The elastic bands are used to emulate the connecting tissue. Segments will be glued together via the interior flexible NijaFlex

Analogy Check

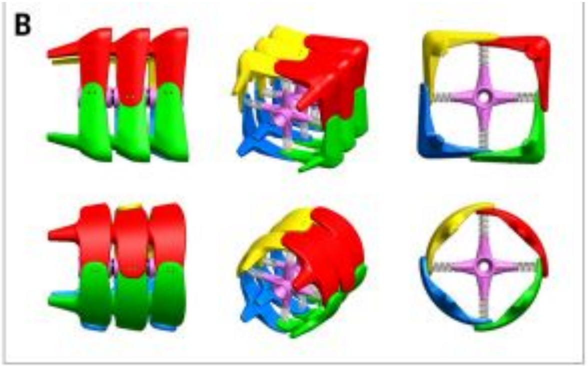
Characteristics/Specifications	(Which are distinguishing?)	Characteristics/Specifications
The tail sections were compressed to a displacement of 60% of the original specimen in one of the three orthogonal directions (i) lateral (dextral–sinistral), (ii) ventral–dorsal and (iii) distal-proximal. While ventral bending is highly possible, lateral bending is limited.	Unsure 50%	Some amount of compressibility is possible due to using flexible materials and elastic bands. The design is symmetrical and this will allow for bending in both ventral and lateral directions individually.
Bone hardness level: 80–320 MPa	Similar 90%	PLA/ABS 3D printing material hardness: 132.45 MPa
Material composition of bones (Calcium phosphate, proteins and water)	Different 10%	PLA/ABS 3D printing material, elastic bands linking between plates, layer cardboard, plastic sheet, super glue, 80 grit sandpaper
Bones are deformable	Different	PLA structure not deformable
Performance Criteria	(How well does system work?)	**Performance Criteria**
This deformation behavior protects the tail segments from fracture as the majority of seahorse predators capture their prey by crushing.	Similar 90%	Deformable and flexible behavior in the structure aims to protect inner components.
Overlapping bony plates allow for nearly 50% compression before buckling occurs	SImilar 60%	Compression to a particular level (goal 30% compression before buckling) actual measurements 23.4% compression
Flexibility in the ventral direction to create a spiral formation in the tail	Similar 50%	Flexibility in both ventral and lateral directions.

Arguments for viability despite differences:

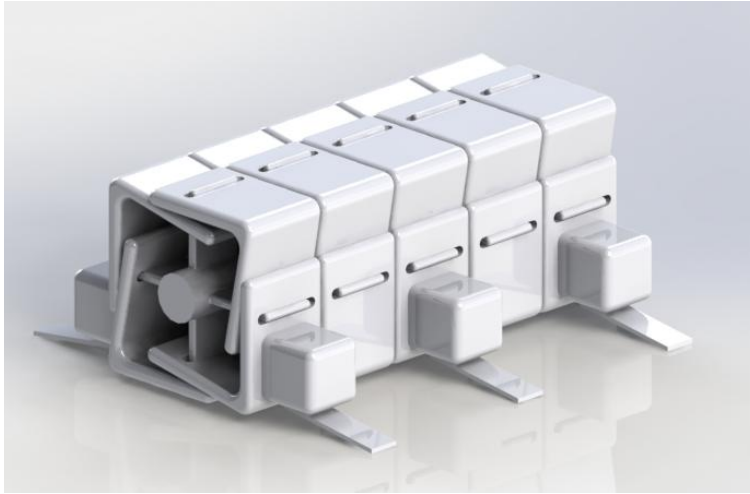
- **Behavior:** The robot does not have the prehensile capabilities of the seahorse as prehension is not a design goal. The seahorse structure is being imitated in the robot design for flexibility and compressibility.
- **Operating Environment:** The robot operates on ground or floor surfaces surrounded by air, instead of in the water. Unlike a seahorse, the robot will have legs for crawling over the ground, and air should provide similar or less resistance to bending and compression versus water.
- **Size:** The robot is being scaled up almost proportionally to retain the structural behaviour while allowing for practical use. The size of tail segments reduces linearly in a seahorse, this allows for more bending at the caudal end of the tail for prehension. Prehension is not the focus of this project.
- **Material:** The robot skeleton is 3D printed from synthetic materials (PLA and NinjaFlex) instead of organic material. While it is not possible to exactly match the material properties of the seahorse skeleton, PLA and NinjaFlex should provide a close enough approximation of the hard and soft skeletal materials of the seahorse, respectively, to partially replicate the skeleton’s flexibility and compressibility.

Initial Prototype - Body Design

Initial prototype of robot structural segment inspired by seahorse tail.



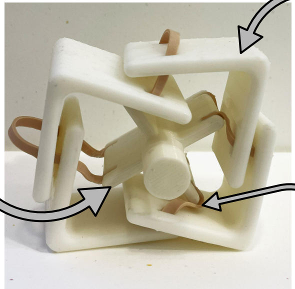
Inspiration from
Why the seahorse tail is square
Porter et al.



Initial CAD model of Seahorse Kinetic Interlocking Plate System (SKIPS)

Design Iterations - Body Design

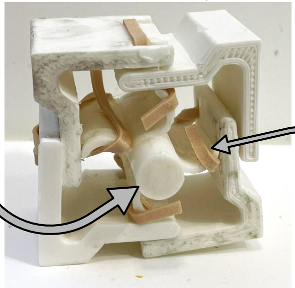
NinjaFlex
Internal Cross



4 External
Armor Plates

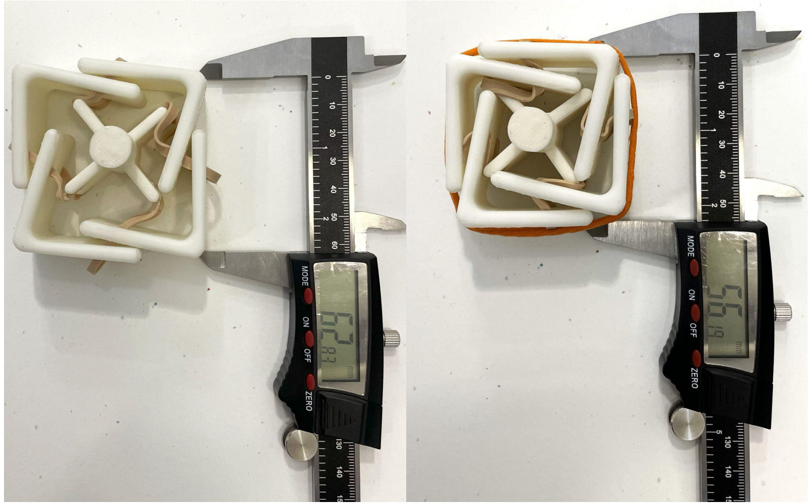
Rubber Band
joints

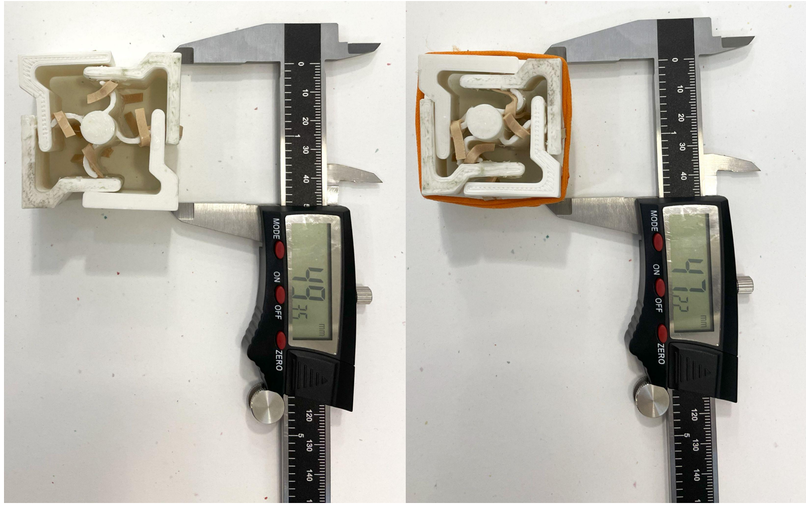
NinjaFlex
Internal Fan



4 PLA External
Armor Plates

Rubber Band
joints





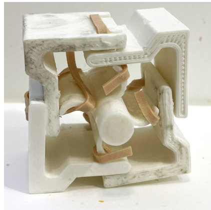
Design Iterations - Body Design

Shown here is a different iteration with peg-socket type joints that prevent the structure from over bending leading to failure.

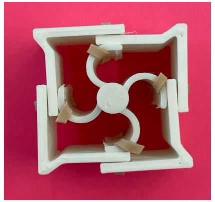
This has not been implemented due to the poor accuracy of the 3D printer and due to time constraints.

Design Iterations - Body Design

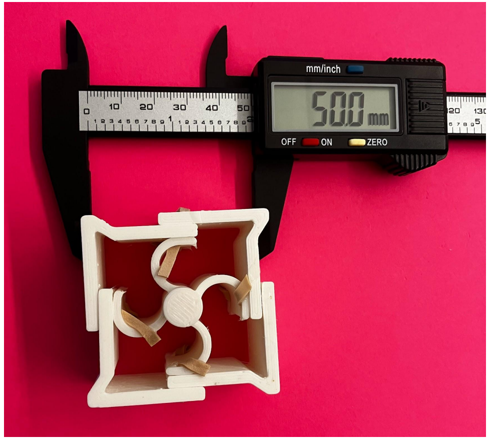
First Skeleton Armor Inspired Design



Second Skeleton Armor Inspired Design



Final Skeleton Armor Inspired Design



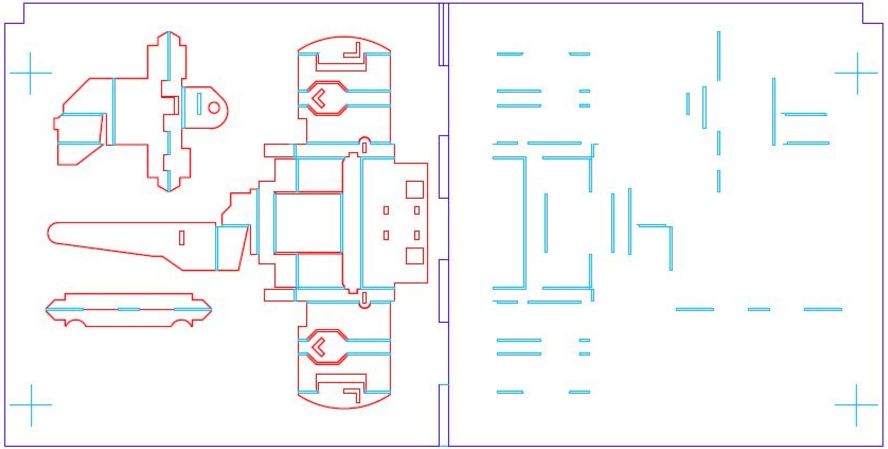
Relaxed State

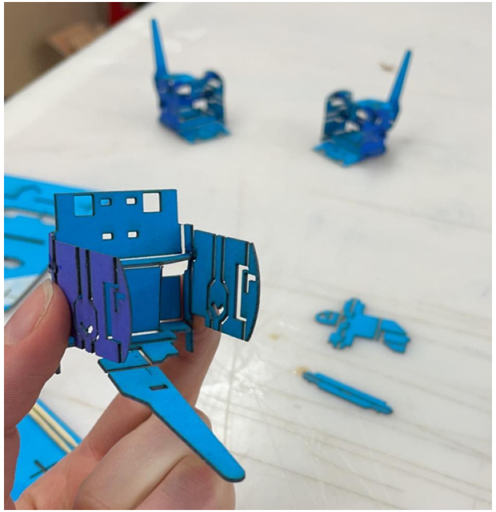
Full Compression

Final Seahorse Skeleton Armor Inspired Design:
23.4 % change in cross section height

Initial Prototypes - Leg Design

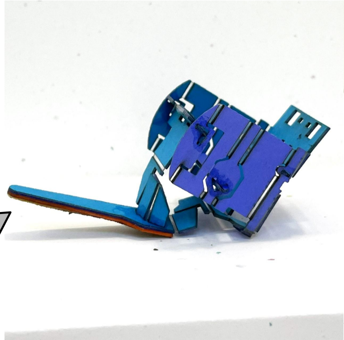
Layers:
Card Paper
Plastic
Card Paper
Card Paper

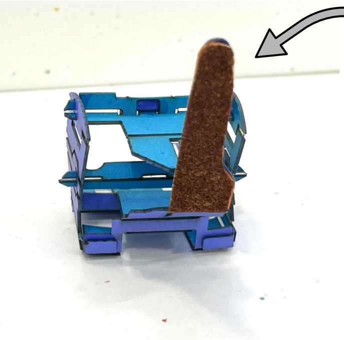




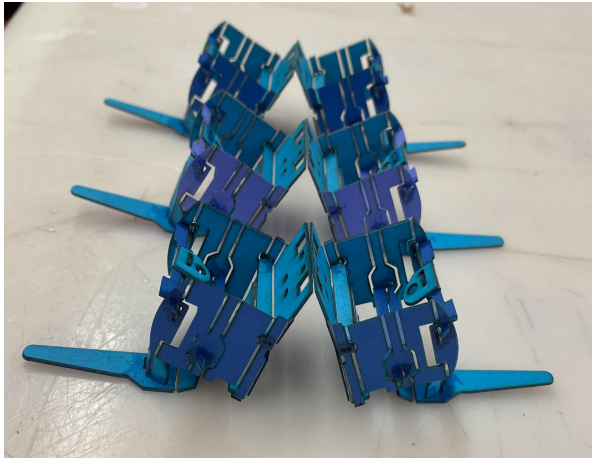
Single Leg Design
Clari-Mega Leg
Module 1

Added 3 more layers of card paper to foot for strength

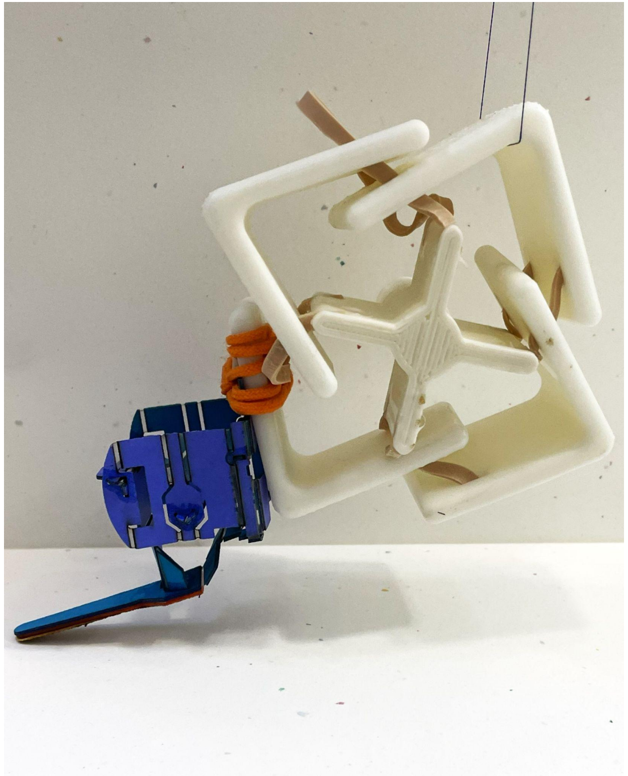


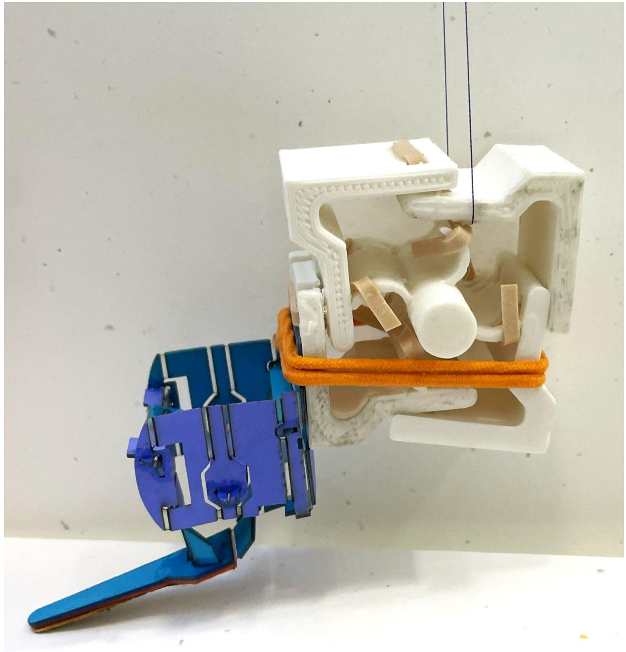


Added sandpaper layer for friction

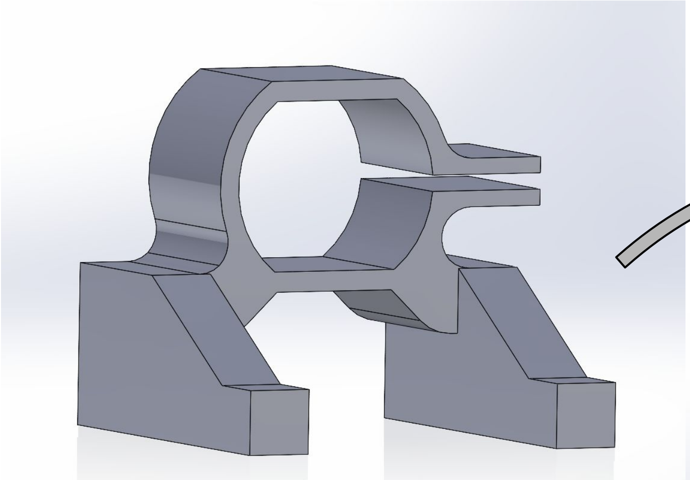


Initial Prototypes - Leg Design with Body

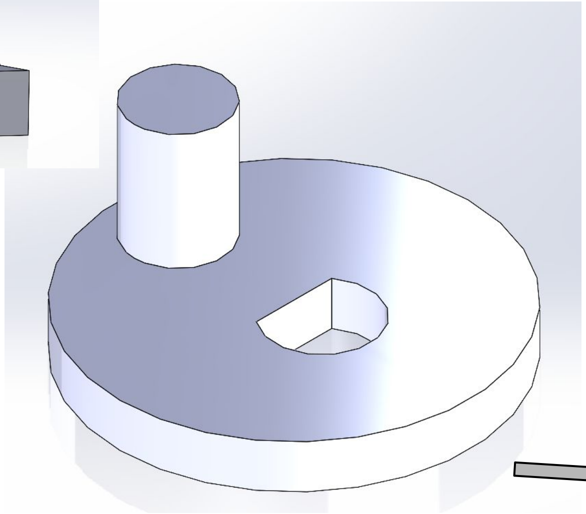




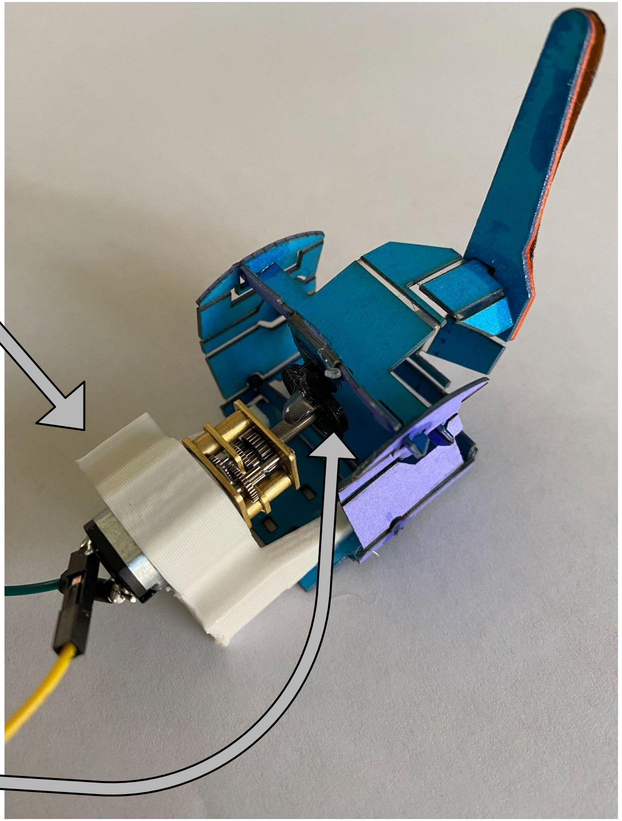
Motor Mounts and Linkage System



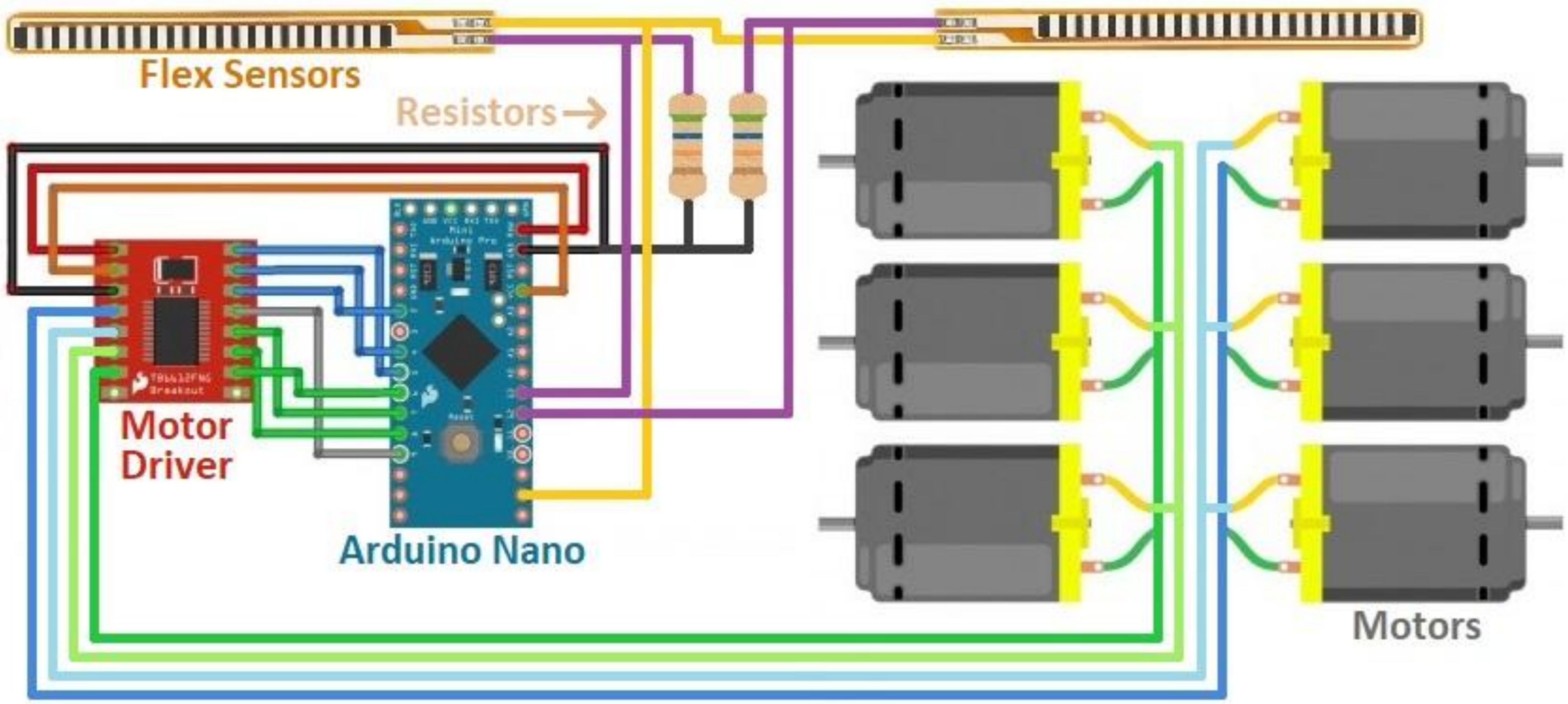
Motor Mount



Motor-to-Foot Linkage

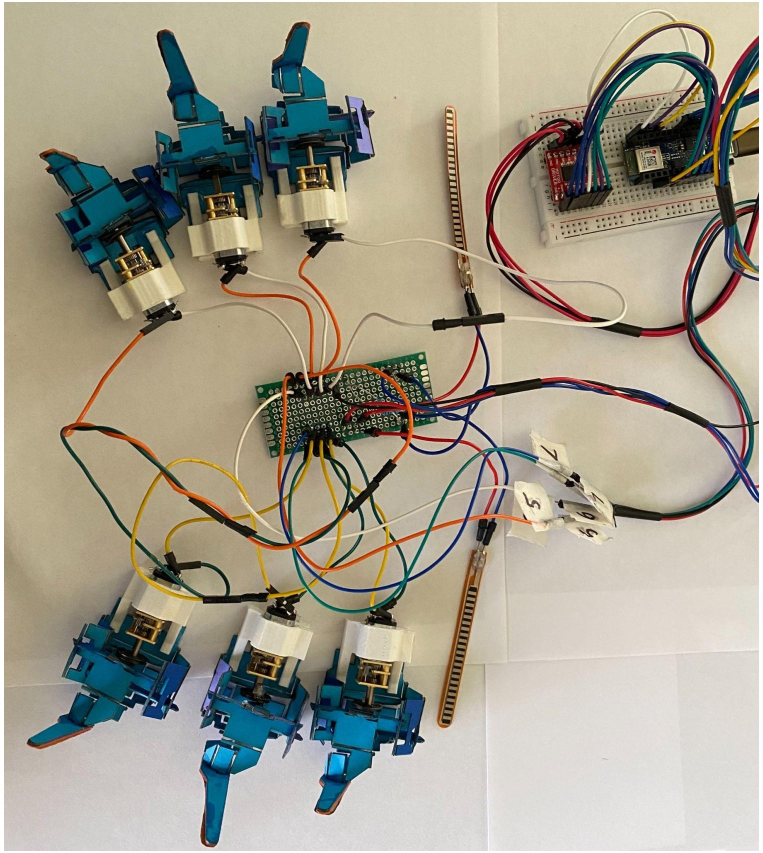


Electronics - Wiring Diagram



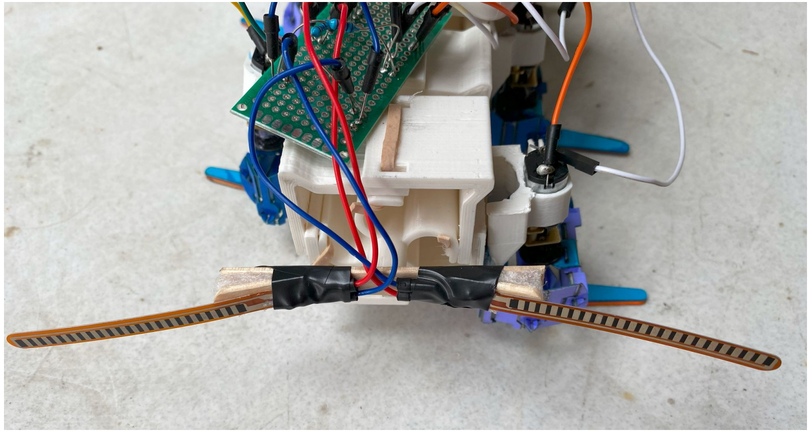
Electronic Components

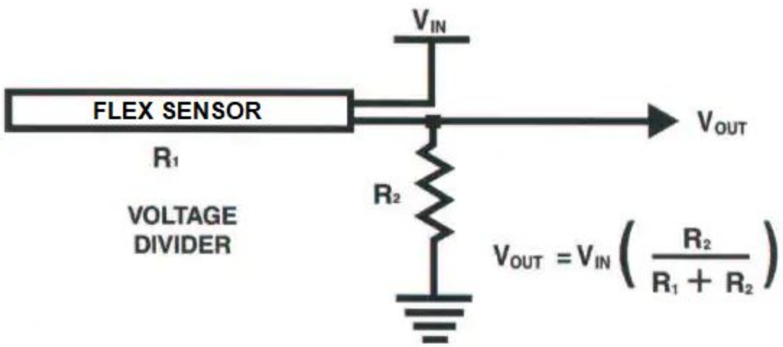
- Arduino Nano microcontroller is used to control robot
- Six geared DC motors are used to actuate robot legs individually
    - Initially non-geared lightweight motors were used but they failed to provide enough torque to actuate legs consistently
- SparkFun TB6612FNG motor driver regulates power to motors
- Power supplied by portable battery
- Arduino program enables control of robot via smartphone by Bluetooth Low Energy (BLE) using LightBlue App
- Spectra Symbol flex sensors used to simulate antennae to direct robot away from walls.
    - More information about sensors given on following slide
- Soldered circuit board on robot used to organize motor and sensor wiring



Bioinspired Sensors

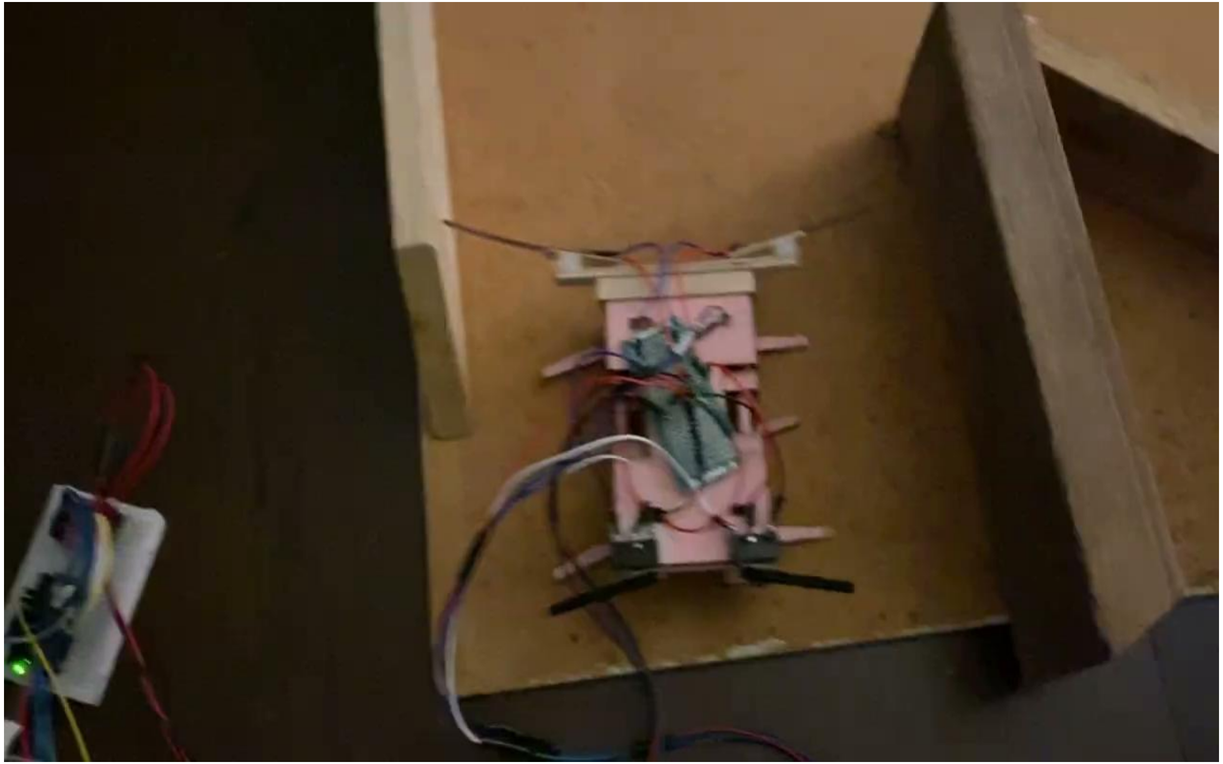
- Two Spectra Symbol flex sensors mounted to front of robot to mimic functionality of insect antennae
- Resistance between two sensor pins increases as sensor is flexed
- Wired in series with static 100 kΩ resistor to form voltage divider (see diagram)
  - For constant input voltage, output voltage changes as sensor resistance changes
  - Output voltage read by arduino to determine sensor flex
- While sensors provide analog data, they are used for binary feedback here
  - Voltage change past a certain threshold indicates sensor has been flexed by encountered obstacle
- Arduino program reacts to obstacles encountered on one side by turning robot in opposite direction until sensor no longer detects obstacle, at which point forward motion is continued





Initial Prototypes - Sensors

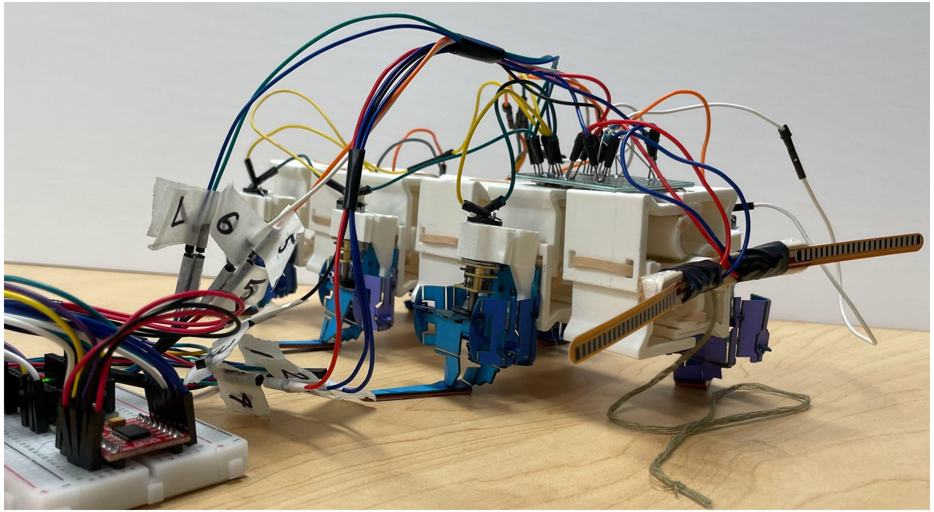
The video below shows successful flex sensor implementation on the previous version of the DASH robot



Final Prototype

Seahorse Kinetic Interlocking Plate System (SKIPS)

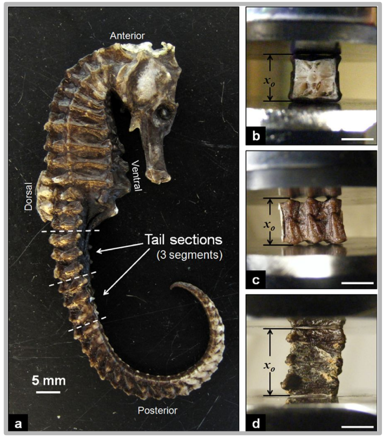
Final Seahorse Kinetic Interlocking Plate System (SKIPS) Body

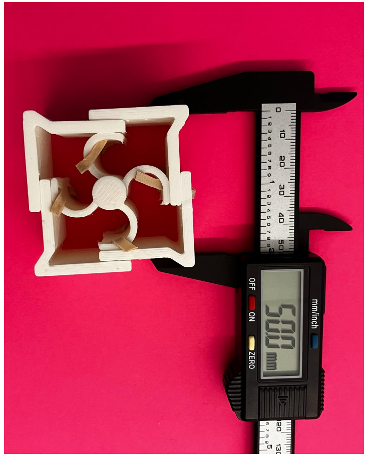


Experiments - Compressibility

One of the major bio-inspired principles that we wished to achieve with our design is the compressibility of the seahorse armor plates. With the final design we were able to achieve a 23.4% compressibility, whereas Porter et al. measured the seahorse skeleton compressibility at 50% before bone breakage.

Compression Testing on seahorse skeletons performed by Porter et al.



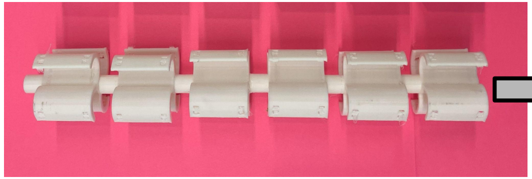


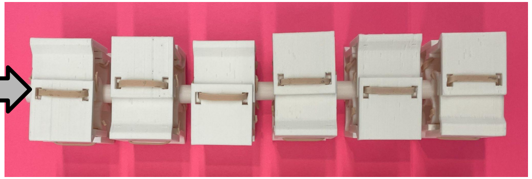


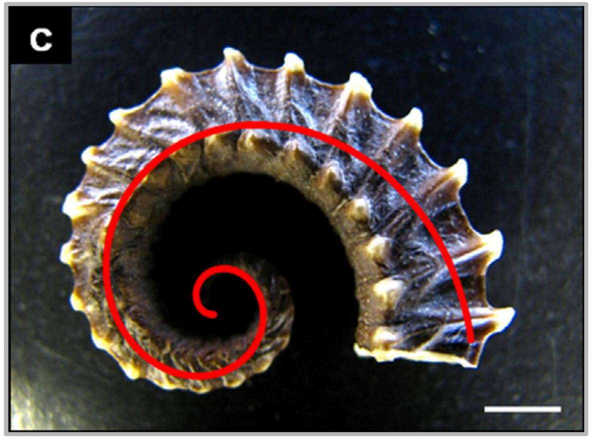
Relaxed to Max Compression

Experiments - Flexibility

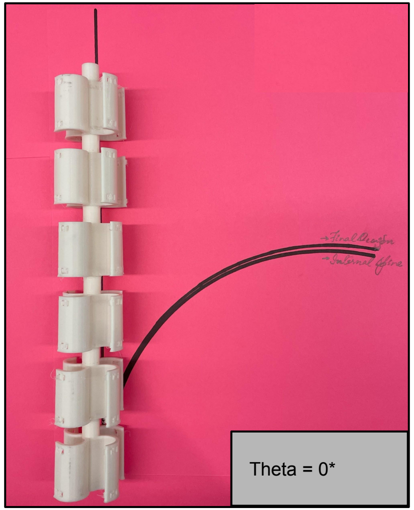
Flexibility seen in a seahorse skeleton tail, Porter et al.



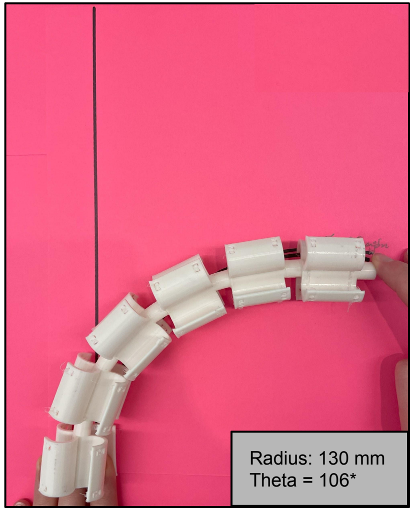




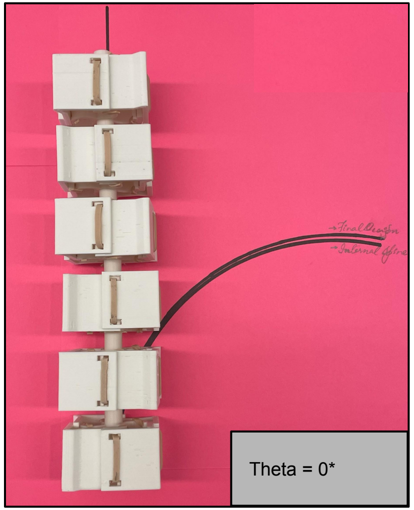
Inner Fan relaxed state



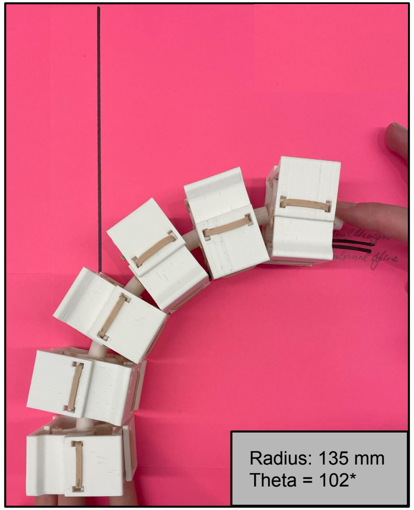
Inner Fan 106 degree flex



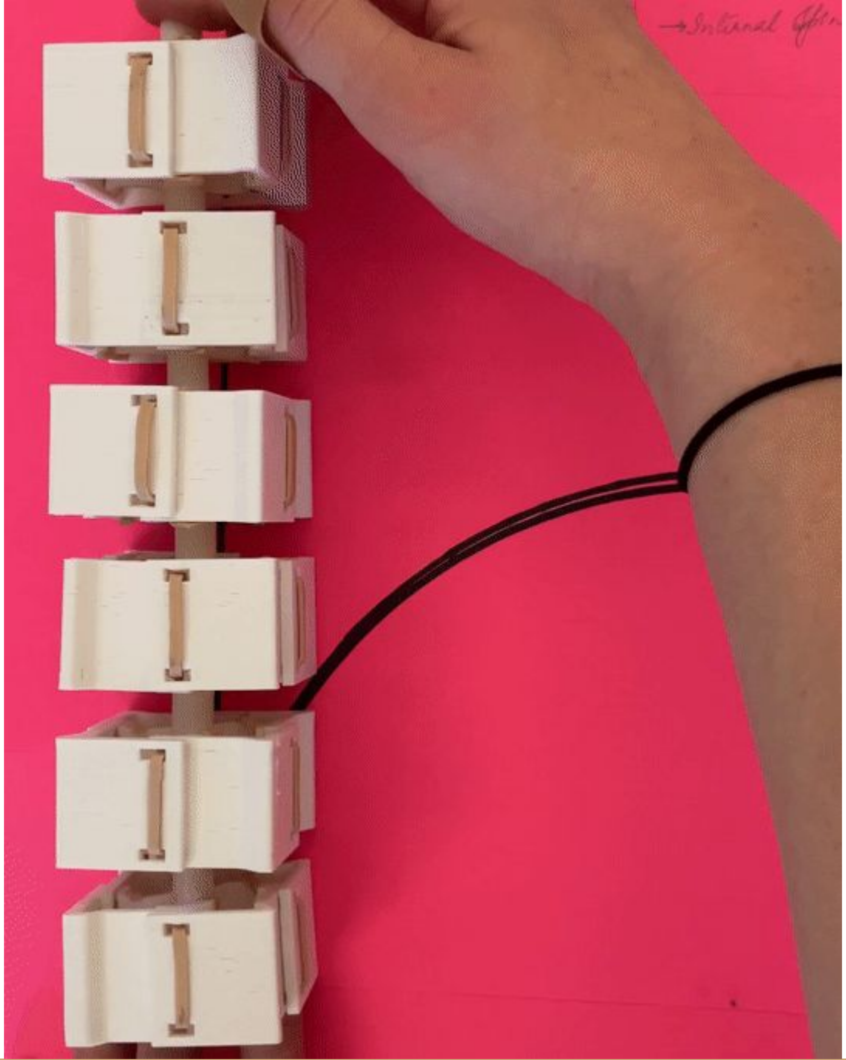
Final Design relaxed state



Final Design 102 degree flex



Experiments - Flexibility



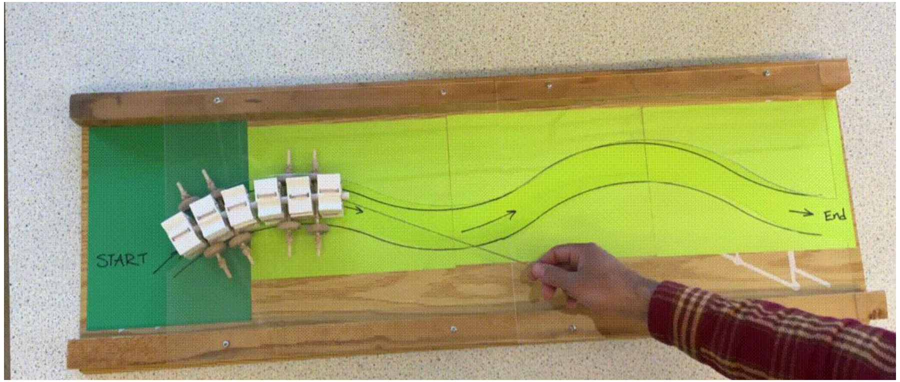
Evolutionary Morphology of Vertebrates UGent

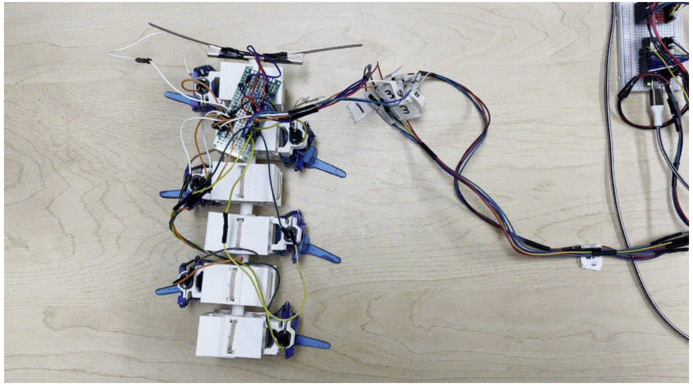
Seahorse tail grasping

Detail of a seahorse (Hippocampus reidi) grasping onto a dowel with its highly flexible and controllable tail.

Experiments - Maneuverability

914 mm long track with curves built with a circular radius of 240 mm.
57 degree angle for skeleton design.





Maneuverability Test:

isolating the Seahorse Kinetic Interlocking Plate System (SKIPS) main body structure

Body is supported on rubber bands connected to wooden dowels with wooden wheels.
Track raised to line up with center of structure and not interact with the wheels.

Seahorse Kinetic Interlocking Plate System (SKIPS)

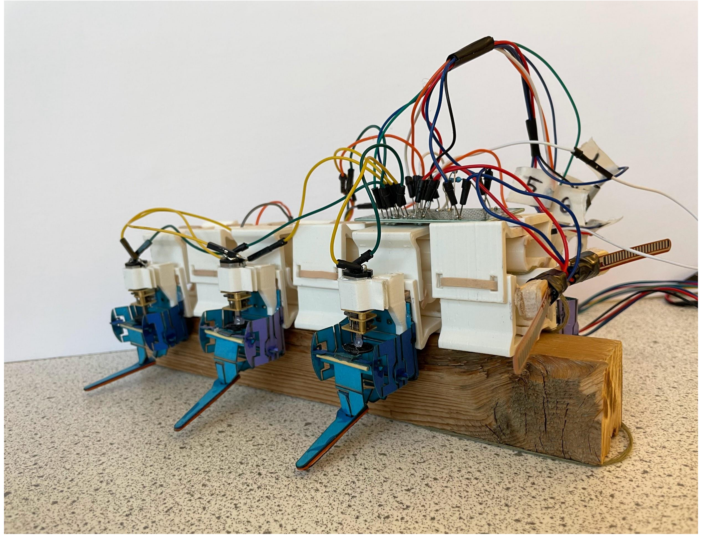
Walking test with SKIPS

Difficulties arose with weight of the central body compared to the strength of the legs. The weight of the central body pressed down until the feet laid flat and the feet no longer had ability to move the robot a significant distance.

Summary of Results

Compression Testing Results

Relaxed state	50 mms (no compression)
100 gms weight	50 mms (no compression)
500 gms weight	48 mms (2 mms, 4% compression)
1000 gms weight	44.9 mms (5.1 mms, 10.2% compression)
Max compression	38.3 mms (11.7 mms, 23.4% compression)

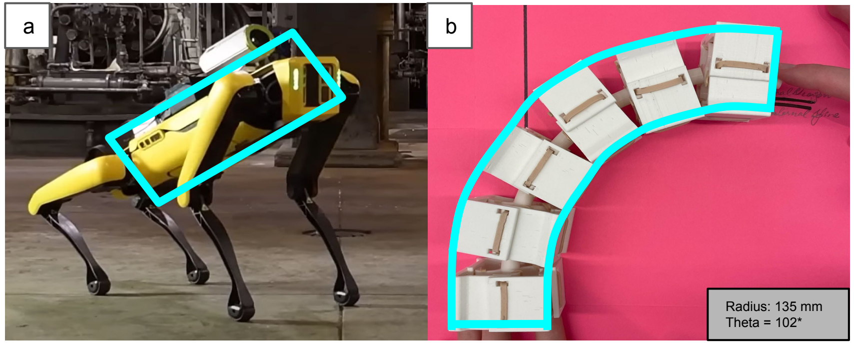


Maximum Flexibility Testing Results

	Radius of curvature	Internal arc angle
Inner fan	130 mms	106°
SKIPS	135 mms	102°

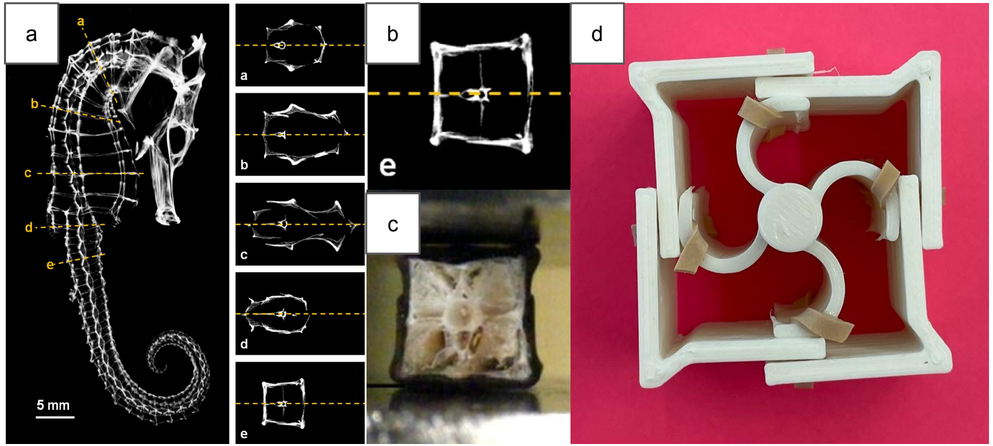
Conclusions

This design is inspired by the distinctive features of the seahorse tail, including its arrangement, structure, and the combination of a hard exterior and soft interior. In the figures below it shows the similarities in the design choices based on the original organic design of a seahorse skeleton interlocking plates. The design choice differences have been made in light of the limitations imposed by the building materials. It is most important to point out the similarities of the hard exterior plates that form a square cross section as seen in (b - d). The interlocking plates present in the bone structure of the seahorse and in the model of SKIPS provides exceptional strength and rigidity, while simultaneously facilitating deformation in response to external forces.



Boston Dynamics Spot compared to Seahorse Kinetic Interlocking Plate System (SKIPS).
(a) Spot from the Boston Dynamics promotional video of “See Spot Work” [7].
(b) SKIPS demonstrating flexibility in its maximum flexibility test.

The Spot robot from Boston Dynamics is a remarkable demonstration of the latest advancements in robotic technology, and it has this rigid structure for its central body. The findings of this study represent a significant contribution to the field of robotics, as it highlights the potential of bioinspired designs in future flexible and compressible robotics.

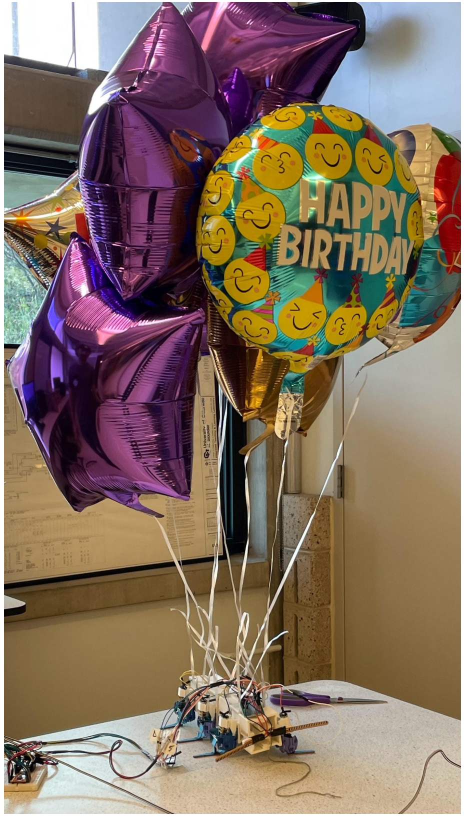


Comparison Segment of Seahorse tail [4] and Seahorse Kinetic Interlocking Plate System (SKIPS) segment. (a) μCT scan of a juvenile seahorse skeleton (Hippocampus kuda) illustrating the cross-sections of several different segments along the length of the fish [4] (b) zoomed in image of (a) looking at the cross section of the tail segment. (c) preserved skeleton segment from a Hippocampus kuda [4]. (d) cross section photo of final design of SKIPS central body segment.

Future Work

Given the opportunity to continue research into the design of SKIPS we would want to focus on different ways to improve compressibility and decrease the weight of the central body. One initial thought is to look into kirigami techniques to build the central body out of paper instead of 3D Printing of PLA. A major hurdle we would need to overcome is the hard exterior and soft interior nature we want based on the finding in *Highly deformable bones: Unusual deformation mechanisms of seahorse armor* Porter et al.

Given the opportunity we would be honored to be able to work with Dr. Dominique Adriaens. To be able to learn from his expertise on seahorses and other similar fish would greatly help in our develop of future iterations. Dr. Adriaens would be able to explain limitations and constraints that seahorses face and provide a detailed background of similar research.



Failed attempt to reduce weight on the kirigami legs

Thank you

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