MODELING NON-INVASIVE ATTACHMENT MECHANISMS FOR CETACEAN BIOLOGGING TAGS

FINAL REPORT

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Abstract

In order to better understand marine mammals like dolphins and whales, researchers obtain physiological and acoustic data for analysis. Attaching biologging tags to the mammals is one method to obtain this data without perturbing the animals. These tags use suction cups to affix to the skin. The purpose of our project was to design a suction cup that will withstand twice as much normal loading than the previous cups used in our sponsor's lab. To support this, our team created a systematic approach using finite element analysis (FEA) and performed experiments in the lab to verify our model.

Executive Summary

Biologging tags aid in conservation efforts, help scientists gain a greater understanding of marine life as oceans are largely unexplored and unobservable, and help determine ocean regulations for humans as we encroach on marine spaces more and more [1]. Recently, biologging tags have been attached to animals via suction cups using a pressure differential to minimize the pain caused to the animals and the risk of infection that comes from puncture wounds. Biologging tags attached via suction cups are also easily recovered after they detach from the animals. Professor Alex Shorter and his team are working on the design and fabrication of these cups. Oftentimes, biologging tags will lose suction on the animal before the desired release. To combat this, Professor Shorter asked us to design a suction cup that will withstand twice the normal loading force that their previous cups endured. The designs of their cups were heuristic whereas the evaluation of the cups tended to be performed experimentally, which was expensive and inefficient. Thus, Professor Shorter also asked us to create a systematic approach using finite element analysis to identify key design parameters and predict forces exerted by a suction cup for the cetacean biologging tags.

We developed a FEA model consistent with the needs of our stakeholders [2]. To do this, we compiled a list of requirements and specifications. Our stakeholders asked that our model was able to change a parameter, run with a reasonable simulation time, and match with experimental values. From this, we specified that our model must be able to model the force versus displacement for a suction cup with normal loading conditions. It also must allow for stiffness to be varied from 250 N/m to 7500 N/m, and eventually allow for size to be scalable based on diameter between 1 and 10 cm as well as friction between the cup and surface to be altered. The simulation must also run in less than 30 minutes and generate values within 15% of experimental data. Further explanation of our requirements and specifications can be seen in Table 1 of this report.

In order to be successful with our project, we planned to deliver results for our stronger suction cup design, FEA model, and experimental results. With three different aspects of our project happening concurrently, we expected the possibility of some bottlenecks during our work. Since we have multiple facets to our work, one area of concern was being able to continuously progress all areas in parallel. To help this, we proposed timelines for the project and delegated team members to certain areas of the project. With the cup design, we saw some bottlenecks in calculating the force of the cup for our complex cup design with two different materials. For the FEA model, we were all fairly new to FEA modeling, and expected the suction cup model to be very complicated. We determined that if we could not deliver the perfect model, we would like to at least come up with something that was helpful to model the different elastic materials. For the experimental aspects, we needed to be trained on molding and using the Instron, which came with some expected hiccups as we learned these new skills. By allowing ourselves enough time and being well planned and organized, we were able to overcome these potential bottlenecks.

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Project Background

Biologging tags are devices commonly used to take measurements on free-ranging animals without disturbing them in their natural environment [1]. Biologging tags can record a broad range of data, such as physiological factors like body temperature, heart rate, and oxygen utilization [3]. They can even be used to record acoustic data, such as the amplitude and frequency of whale calls [4]. There are many reasons why we use biologging tags. First, we can gain a greater understanding of marine life because the oceans are largely unexplored and unobservable. They have also been used to aid in conservation efforts and to determine ocean regulations as humans progressively encroach on sea habitats more and more. One example of the way biologging tags have been used to study marine life is the analysis of basking sharks during breaching. The graphs below capture the kinematics of a basking shark during breaching by measuring the depth of the shark, its tail beat amplitude, vector of dynamic body acceleration, and the speed of the shark [5].

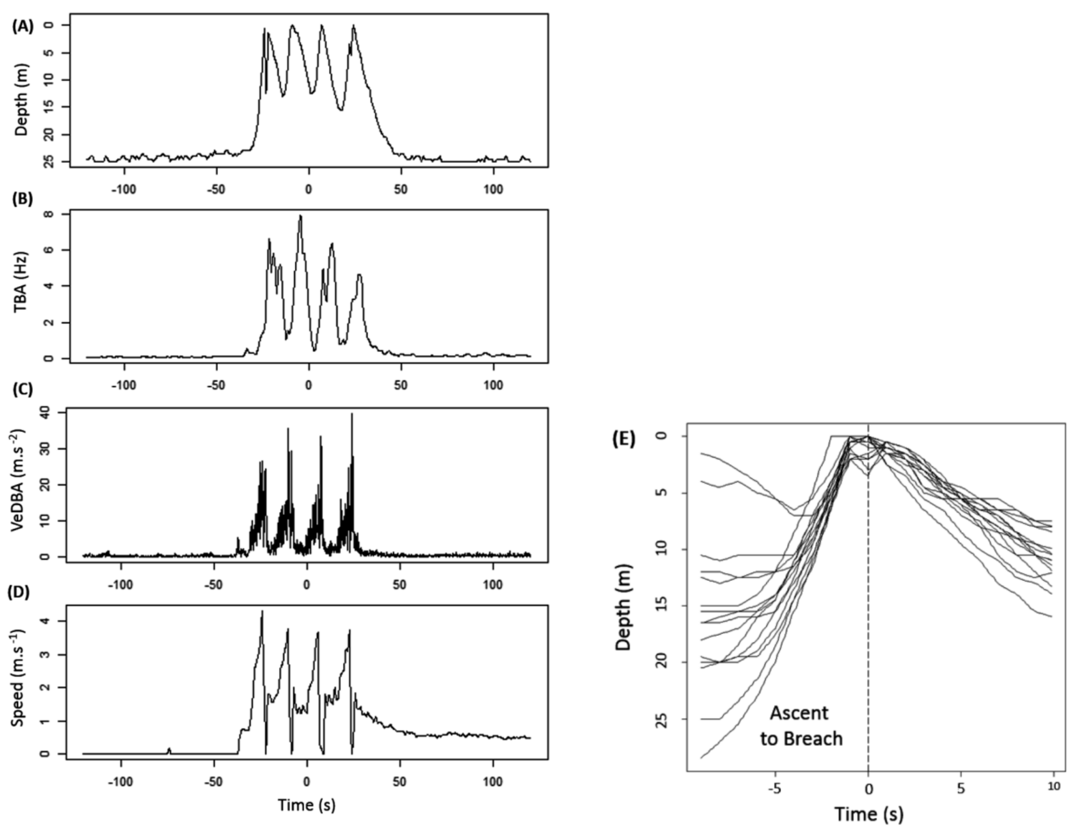


Figure 1. "Characteristics of breaching. (A–D) A quadruple breach by a six-meter basking shark over 47 s showing changes in depth (A), tail beat amplitude (B), VeDBA (C) and speed (D) over the series of breaches. (E) Depth profiles of 16 single breaching events performed by a single shark, with time (in seconds) centered on the breach, overlaid on a common timescale showing repeatability of ascent angle and subsequent descent after breaching." [5]

It is currently unknown what the biological function of breaching is for basking sharks. Their diet consists of plankton, so unlike great white sharks, they do not need to break the surface of the ocean to catch prey. The authors of this study set out to investigate and record what happens when a basking shark breaches for further insight into the behavior of these animals.

The data from biologging tags have also spurred the establishment of ocean regulations to protect endangered marine species and aid in conservation efforts of ocean habitats. In Baja California, Mexico, fishermen were unknowingly catching endangered loggerhead sea turtles and contributing to the decrease in their population. In order to better understand why these turtles kept being accidentally caught, biologists outfitted 6 turtles with biologging tags that were able to record a number of parameters, including satellite tracking location and water temperature [6].

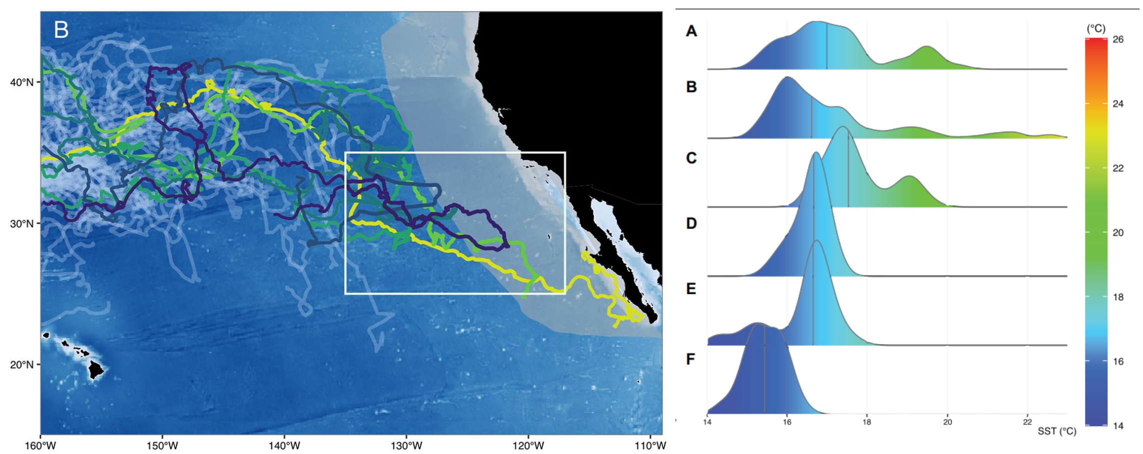


Figure 2. Location tracking map of the 6 tagged loggerhead turtles and their corresponding temperature distributions [6]

Using the data collected from the biologging tags, they were able to trace the migratory patterns of the turtles and discover that the turtles used thermal cues to both select or avoid habitats and initiate long-distance movements. While at first there seemed to be no reason for their migratory patterns, the thermal distributions shown for each turtle (A,B, … F) in Figure 2 suggested that the turtles preferred to swim in thermal corridors that were around the favored temperature of about 18 degrees Celsius. Using this information and the satellite-tracked locations of the turtles, they were able to estimate where these thermal corridors existed. This led to permitting that required fishermen to change to only hook-and-line fishing and keep the discovered thermal corridors open for the loggerhead turtles, thus protecting them from endangerment and helping conservationist efforts [6].

Biologging tags similar to those in the given examples are often attached to whales and dolphins by using suction cups, and the tags are attached to the whales using a long hand-held carbon fiber pole. Within 24 to 48 hours, tags lose suction or are purposefully detached then float to the surface where they are tracked and recovered [1]. The suction cup sticks to the animal using a pressure differential; the atmospheric pressure on the outside of the cups presses down on the low pressure area inside of the cup. The basic normal loading equation that governs a suction cup is F=PA, where P is surrounding pressure and A is suction cup area [7]. One of the most common causes of failure is air leakage of the suction cup, which is heavily influenced by cup volume, elastic modulus, and stiffness [8].

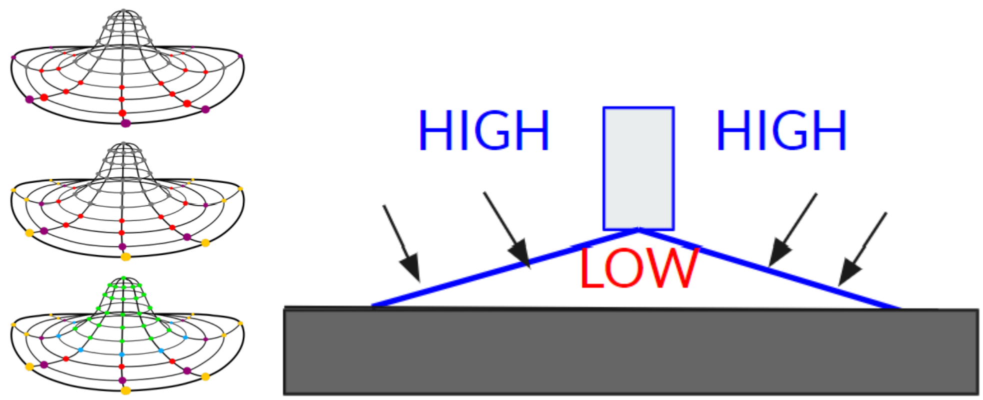


Figure 3. Left, elastomeric shell that undergoes deformation when compressed onto the skin. [7] Right, diagram of pressure differential forces acting on a compressed suction cup, simplified without friction for clarity purposes.

To understand the forces acting on a suction cup in more detail, it is helpful to break down the operation of a suction cup into four different phases: initial phase, pushing phase, attached phase and detached phase, illustrated in Figure 4. [9].

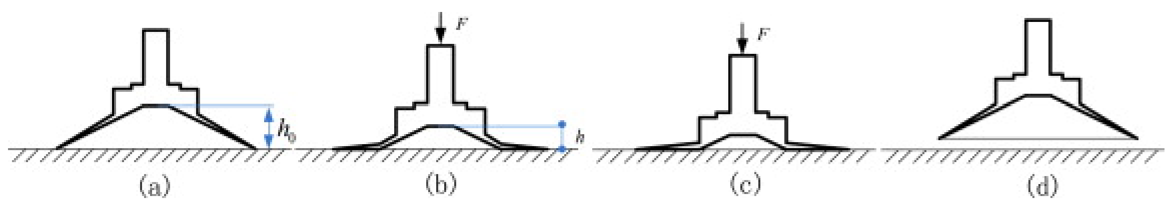


Figure 4. Phases of the suction cup: (a) initial phase, (b) pushing phase, (c) attached phase, and (d) detached phase.[9]

The pushing phase and attached phase are the two phases relevant to failure of a suction cup. The force exerted during the pushing phase determines how much air is expelled from the cup and the volume of air underneath the suction cup [9]. After the suction cup is completely attached, the pushing phase is over and the cup can no longer deform more to expel more air [9]. The cup enters the attached phase, where the forces on the cup consist of the atmospheric pressure force, the internal contact air pressure force, and the internal cavity air pressure force, illustrated below in Figure 5 in green, blue, and magenta respectively [9].

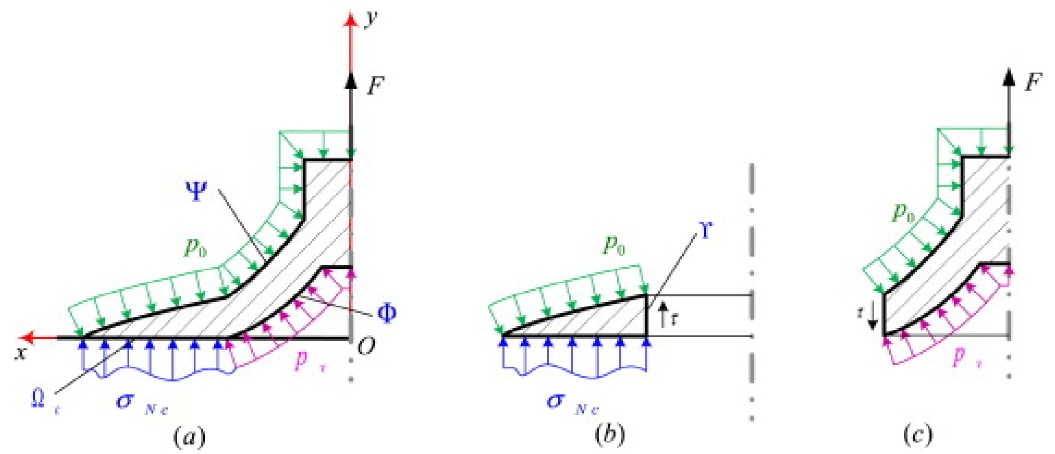


Figure 5. (a) Force equilibrium of the suction cup in the attached phase, (b) free-body diagram of the contact part of the suction cup, and (c) free-body diagram of the vacuum part of the suction cup. The upward force F is an applied payload force. [9]

Professor Alex Shorter's research group studies marine mammals (whales and dolphins) using biologging tags attached to the animals using suction cups. A major challenge for these tags is how best to design the elastomeric suction cups. The cups need to generate enough force to secure the tag to the animal, but not too much that the animal is perturbed by the suction. Their current design strategy involves tedious trial and error testing in the lab and field. In order to make this process faster and reduce wasted material, they desire a more systematic approach using finite element analysis to design the elastomeric shell that undergoes large deformation when compressed onto the skin.

It is for these reasons that the problem statement for this project is to design a suction cup for cetacean biologging tags that is twice as strong as the current suction cups used in Professor Shorter's lab. To accomplish this goal, we want to have a heavy emphasis on prediction and verification of the resulting force and performance of the cups. To do this, we want to create a finite element analysis model of the cup and verify the success of the model by comparing it to experimental results [2]. FEA is the simulation of any given physical phenomenon using a numerical technique. It is used to reduce the number of physical prototypes and experiments and optimize components in their design to save time and money [10]. Because the silicone rubber used for the suction cup is an elastomeric material, this makes the FEA modeling more complex. However, FEA has been used to evaluate elastomers, but more material behavior is required for modeling because of the nonlinearity of elastomers [11].

Our first objective is to create an FEA model of a suction cup with the ability to change a few key parameters (such as stiffness, size, and material) and predict the resulting forces and cup geometries created by those forces. We also aim to experimentally verify our model using real suction cups and perform a tensile test to compare with our model's results. Our second objective is to design a new suction cup to be used on the biologging tags that is two times better than the current suction cups used on the tags.

Design Process

Following the ME Capstone Design Process Framework, we went back and forth through many of the blocks (sometimes revisiting them multiple times) to create the solution we are working on now. Starting with need identification, we talked with our sponsor and other stakeholders to learn more about the needs of this project. We learned that the way they were modeling suction cups was completely trial and error based. From there we developed a rough problem definition that our stakeholders needed a better way to model suction cups rather than having to physically create the suction cups and then model them via real world testing. We came up with an idea to create a systematic approach using finite element analysis to identify key design parameters and predict forces exerted by a suction cup for cetacean biologging tag. With our problem statement created we then went back to the stakeholders to learn more about their specific needs of our model. We learned about the specific parameters that they wanted to model as well as what they didn't need. Additionally, we began to think about the solution verification for our project. We then started drafting ideas about how to verify our model. Luckily for us, we found that there had already been established procedures and data taken from real world suction cup tests. We decided to create our model one parameter at a time alongside the real world suction cup testing. We wanted to do this so that we could verify our model against the real world testing, and then add on additional parameters which bring additional complexity. However, we believe that this additive process will create more accurate and reliable results from our model.

After completing our first design review, we updated our problem statement to include an additional goal. This goal is to design a new suction cup capable of withstanding twice the normal force of the current suction cups being used on the biologging tags. With the change in our problem statement, we also needed to update our requirements and specifications, so we met with our sponsor once again to develop this list. We added several requirements related to the geometry of the suction cup and its performance as shown below in Table 1. We still intend to address the initial problem statement we developed and create an FEA model of the suction cups verified by experimental data, but now we have the additional goal of fabricating our own cup that is two-times better. After changing our problem statement, we moved into the concept generation stage of the design process, using guidance from the learning block. Our process of concept generation and subsequent screening are described below on page 12 in greater detail.

Design Context

The main stakeholders for this project are Professor Shorter and his team, biologists, conservationists, and even the marine wildlife that is wearing the biologging tags. While Professor Shorter has a very high interest in the problem, the societal aspect of the problem that is driving the work to be done is very broad and spans across the globe as a passion for wildlife conservation and understanding. The stakeholders that are likely to be affected positively by our project include biologists, conservationists, and Professor Shorter with his team because of the information they will gain from the success of the biologging tags attached to the animals. The users (whales and dolphins) in this case may experience any of the main negative effects, mainly consisting of slight discomfort from the suction cups pulling the skin. Other stakeholders that may be considered adversaries to the project include fishermen and shipping companies that may have to alter their routes due to permitting resulting from the information gained by using biologging tags. An additional stakeholder we will be working with is Professor Hulbert, who will be helping us work with FEA software. While he does not have a direct interest in marine life, he will have a large influence on the FEA side of our project. Our stakeholder map summarizing all of this information is shown below in Figure 6 [12].

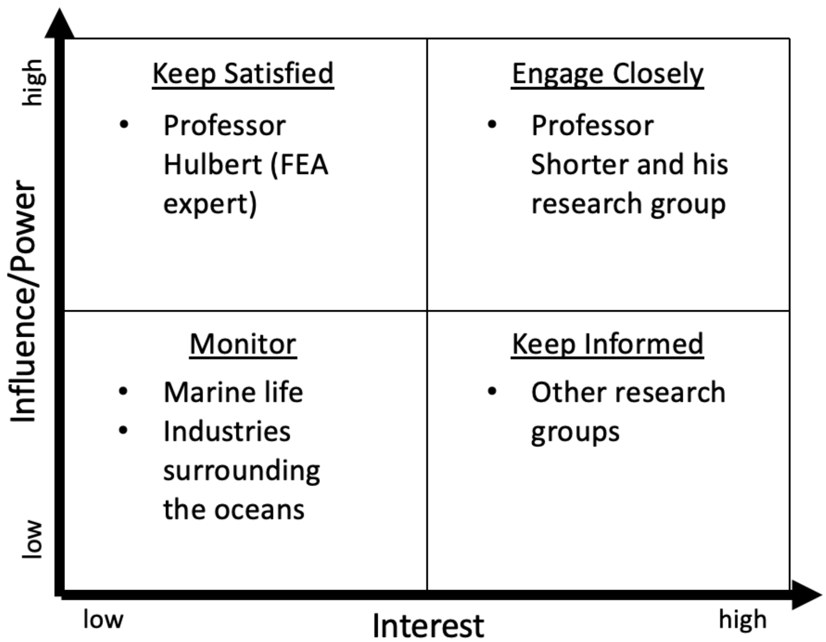


Figure 6. Stakeholder map displaying the stakeholders involved in our project. Each stakeholder is placed in a quadrant depending on their level of interest and influence on our project. Each quadrant has an underlined task for the stakeholders as well.

We believe that our sponsor ranks the social impact of our project only secondary to the environmental impact of the design, since this impact forms the backbone reason for trying to gain more data from these ocean animals. The order of these priorities may affect our design since we may be more concerned about the health of the animals, not sacrificing the safety of the users to ensure information is being gathered for the societal stakeholders. We do not expect to face any ethical dilemmas in the design of our project because the motivation for the project is rooted in making positive environmental change and the design implementation is meant to benefit animals. We think that our personal ethics align well with the professional ethics that are upheld by the University of Michigan, especially after completing the learning blocks that emphasize analysis of the impact of our design on stakeholders and other groups that are not immediately obvious.

The manufacturing of the suction cups is reasonably sustainable since the suction cups are small, and only relatively small quantities of these cups need to be fabricated. Due to their small nature, they contribute only a tiny fraction of the waste in the global landfills. Pollutant emissions are limited since they are made by pouring a melted material into a suction cup mold, and these cups last for a while before needing to be discarded. The use of the suction cups in the ocean is potentially less sustainable if the cups either detach from the biologging tags or the whole tag sinks. This would increase ocean pollution, which is already a massive global concern. To make this aspect of the design more sustainable, we could prioritize the mass requirement of the suction cup to ensure a new design will not cause the biologging tags to sink once they detach from the animal. We plan to prioritize this requirement anyways, because if a tag sinks, the data from it is lost and the entire purpose of using the biologging tag is defeated. Therefore, the consequences of prioritizing this requirement do not add any additional constraints that we did not already anticipate. The impact of creating a usable FEA suction cup model is actually reducing the amount of the suction cups that need to be manufactured for testing as well.

The only ethical dilemmas we perceive encountering are the issues surrounding animal safety and wanting to not discomfort the animal while still generating enough force for the tag to be able to stay on for a day or two. The attachment of a bio logging tag can affect the behavior and maneuverability of an animal due to the increased load [13]. According to one study, dolphins with tags swam 11% slower than they did without a tag due to the increased drag associated with wearing a tag [14]. To manage these problems, we will counter our force measurements with literature stating safety limits for suction cup force. Since we are creating a simulated model, it will ultimately be up to the team to choose their desired suction cup parameters which will ultimately affect the user, but we will be sure to list any warnings related to large forces on the skin for user safety. Since the animals have no say in the matter, the power dynamics in this case are definitely highest on the human side of the project, with the sponsor guiding our team with authoritative power. This is why we must all work together to create a solution that is not harmful and beneficial to everyone. We believe our personal ethics align with those upheld by the University of Michigan, and we strive to design with safety and wellbeing at the forefront of our focus.

Requirements and Engineering Specifications

The overarching goal of our project is to improve suction cup design by understanding the key cup parameters that are responsible for performance. We accomplish this by analyzing cup properties that contribute to its forces and by developing a model for suction cups using FEA software [2]. Through meeting with Professor Shorter and his team, we were given requirements to meet as we solve our design problem. Using the FEA software, we would like to be able to change cup parameters, run at a reasonable time, and imitate the current physical experiments that Professor Shorter and his team currently perform in the lab [15][16]. The cups must be able to attach to the biologging tags and function properly. To begin this analysis, we will perform the physical tests and FEA modeling using dogbone samples made of the suction cup materials. By meeting with Professor Hulbert, we were able to discuss the challenges and what may be feasible for us using FEA software. We found that it may be too complex for our skills and limited time to develop a model of a suction cup against normal loading, but we may be able to better model the cup under compression to find cup characteristics [17].

The requirements gained from our stakeholder interviews were transformed into engineering specifications by using our literature review to assign appropriate values to quantify the objectives of our model and experimental verification. The order of the requirements are in order of their importance to the success of our project, determined by responses from our sponsor and his team. All of the requirements must be met, besides the shorter simulation time being more of a strongly desired wish and the experimental validation being flexible depending on how much time we have [16]. We would like to at least experimentally validate some parameters in the beginning to make sure our mathematical model aligns with our predictions and calculations. The specification for the first requirement is difficult to express in quantifiable terms due to the mathematical complexity of the problem, but our stakeholders feel that is a paramount requirement.

Table 1. Requirements from project stakeholders and corresponding specifications, categorized by David Garvin's eight basic dimensions of product quality [18].

Category	Requirement	Specification
Performance	Create an FEA model of the suction cup	- FEA software must model the force versus displacement for a cup under compression - Additionally, model a dogbone specimen under tension
Features	Be able to change parameters in the FEA model	FEA software must allow variation for the following parameters: - Stiffness: 250 N/m to 7500 N/m - Size: scalable based on diameter between 1 cm to 10 cm - Friction: Must be able to alter friction between cup and surface
Aesthetics/ Perceived Quality	Reasonable simulation time, easy to use	Simulation time must be under 30 minutes Model should require no more than 3 inputs from user
Reliability	Match FEA model with experimental values	FEA creates models within 15% of experimental data including dogbone data
Features	Modeled and tested cups must be compatible with the existing cup systems	Geometry of suction cup head must stay the same for each tag attachment, cup diameter must be 1 in < D < 4in
Reliability	Cups must not affect the buoyancy of the tag	Must weigh < 10g
Conformance	Tags must minimize impact to animal	Pressure differential ≤ 4 psi
Performance	Cups material must allow deformation	Deformation of up to 2x original deformation amount; up to 17.98 mm
Reliability	Cups should not leak	Minimum gas permeability [19]
Performance	Elastomeric materials only	0 creep or relaxation

To match the FEA model with experimental values, we have come up with a simple, initial experimental design. We picked three different materials for the suction cups and dogbones, then modeled and tested them. For the physical experiments, we performed three of each specific test and averaged them out in order to get more accurate data. From there, we compared the results to the FEA simulation, then made adjustments to the model as necessary.

Concept Generation

To ideate potential concepts that would increase the force of a suction cup per our new stakeholder's new requirement, we pursued a concept generation process. This included brainstorming, using design heuristics to modify our existing solutions, and performing a functional decomposition that we also used to help score these concepts later in the concept selection process.

As per the rules of a successful brainstorming session, we first began with individual ideation sessions to bring into the group session. During the group session, we focused on postponing judgment, encouraging wild ideas, accepting quantity over quality, building on each other's ideas, and using sketches to better communicate our thoughts. We looked up different design heuristic cards to help switch up our thought processes and flip our assumptions about many concepts; this greatly helped expand our divergent thinking. A full list of our solutions can be found in Appendix A.

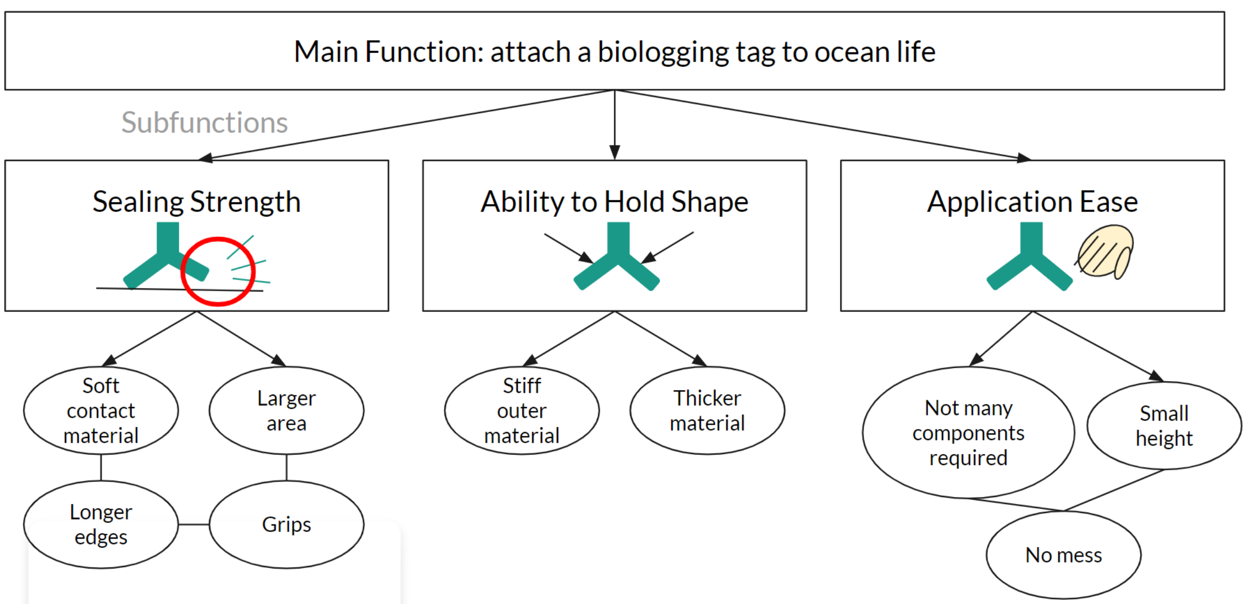


Figure 7. Diagram of our functional decomposition used in the concept generation phase.

We then performed a functional decomposition of our problem, as shown in Figure 7, and started with the main function of our solution which is to attach a biologging tag to ocean life. This was broken down into three subfunctions: sealing strength, ability to hold shape, and application ease. Some basic principles that would achieve these subfunctions were branched out from the subfunctions and used in our concept exploration process to come up with more valuable ideas. Our top six design concepts are shown below in Figure 8.

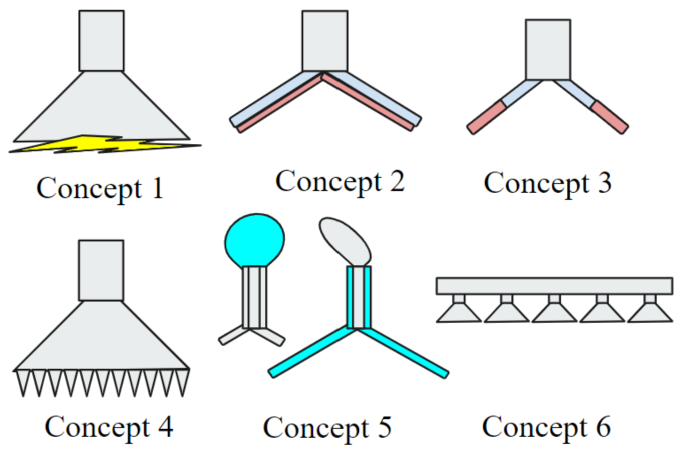


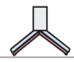
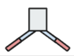
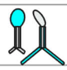
Figure 8. Top 6 design concepts with very differing solution styles.

These 6 concepts can be classified into a few major categories that we saw throughout our idea generation process. Concept 1 falls into the category of solutions using adhesives, concepts 2 and 3 fall into the category of having multi material properties, concept 4 falls into the category of small bodily inserts, concept 5 falls into the category of simple hydraulics, and lastly concept 6 falls into the category of numerical multiplication of suction cups. The selection of these six concepts will be discussed further in the next section of this report.

Concept Selection Process

The top 6 design concepts were selected by sorting through all of our solutions and ranking them on a 1-100 Likert scale based on which ones fulfilled our main three sub functions identified in our functional decomposition and how distinct they were from one another. The concepts that received the top scores are shown in Figure 8 and we will proceed to analyze their advantages and disadvantages, shown numerically in the pugh chart (Table 2).

Table 2. Pugh chart with weighted categories comparing the top 6 design concepts

Concept Number	Manufacturability (2)	Cost (1)	Durability (4)	Ease of Application (3)	Affect on Animal (5)	TOTAL SCORE
1 	0	0	0	0	0	0
2 	+1	-1	+1	0	0	5
3 	0	-1	+1	0	0	3
4 	-1	0	-1	-1	-1	-14
5 	-1	-1	-1	-1	+1	-15
6 	+1	-1	0	0	0	1

Concept 1 is a suction cup with an adhesive on the bottom of the cup. The advantage of this design is that it would have a higher sealing strength and time until failure, however the disadvantage is that there is potential for abrasion on the animal's skin. Concept 2 is a suction cup with two materials layered: one stiff on the outside and one soft on the inside. Its advantages are that its sealing strength, contact stiffness, and application ease are all very high. Its disadvantage is that if it is not properly manufactured, we could see some separation between the materials due to shear stress. Concept 3 is also a dual material cup but the softer material is only on the bottom half of the cup. The advantage is that the sealing strength would be much higher if there were any surface imperfections but the disadvantage is that it is much more likely to break and fail due to shear forces and the horizontal connection between the materials. Concept 4 is based on the remora fish [21] and is a cup that has many thin, toothlike projections on the bottom of it. The advantage is that it is easy to apply and grips to the whale skin very well, however we are worried that this may cause potential irritation and more invasive harm to the animal. Concept 5 is a suction cup design based on an urchin [22] with a simple hydraulic system which contracts a fluid sac to extend the cup (increasing area) then contracts to create pressure. The advantage of this design is that it will seal well and create a higher pressure, however it would be hard to apply and it would occupy a lot of space. Concept 6 uses multiple cups instead of just one; the advantage is that if a few cups fail then the device can still stay attached but the disadvantage is that there may be overall less force keeping the cups attached.

The first concepts that our team generated were very simple and included mostly changing the size, geometry, and single material. Unlike these very basic concepts, we have now ideated some very distinct and more divergent solutions that may prove to help our stakeholder's team thanks to the concept generation process. If we had not learned of another requirement from our stakeholders and performed a deeper exploration of concepts, we probably would have seen even more fixation on these earlier ideas.

From this analysis and the corresponding results shown in Table 2, we can conclude that design concept 2 is the most advantageous design. It culminates all three subfunction requirements efficiently with a disadvantage that can be easily fixed through experimental testing. This design best meets the stakeholder requirements and specifications identified in Table 1 and is the most promising for reasons that will be discussed in the next section.

Concept Description

As delineated in the previous section, our concept selection analysis chose design concept 2, shown in Figure 9. To reiterate, this suction cup is a dual material layered cup with a stiffer material outer layer and softer material on the bottom contact layer of the cup. The soft contact material increases the sealing strength of the cup while the rigid elastic outer shell increases the contact stiffness and thus the contact pressure in the sealed region. This achieves two of our subfunctions, sealing strength and ability to hold shape, as well as meeting our stakeholder requirement of increasing the suction force due to this increased pressure. Our third sub-function is also met by this design because the cup itself does not take up as much space as many of the other ideas, which will also make it easier to apply the biologging tag onto the animal.

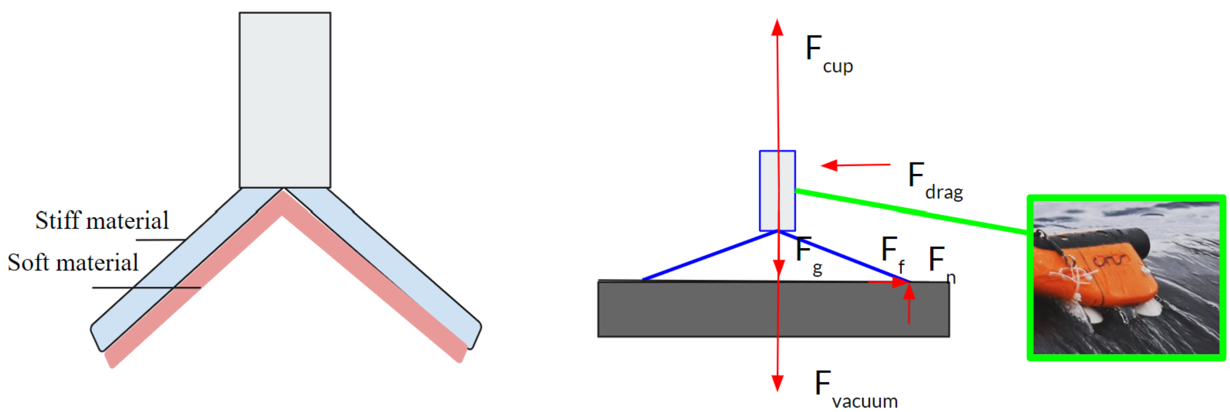


Figure 9. Left, “Alpha design” concept 2 with a dual material layer; Right, free body diagram of our suction cup labeling the relevant forces in our engineering analysis

A free body diagram shown in Figure 9 was used to analyze some of the most important forces acting on the suction cup. Leakage is one of the main modes of failure for these suction cups, so this softer material prevents that by making the suction cup able to seal on imperfect surfaces by increasing F_f. Higher stiffness is required for a longer lifetime before failure to maintain a higher pressure (F=PA) and thus a stronger suction force, increasing F_{cup} and F_{vacuum}. Thus, the suction cup is much more likely to stick tighter and not leak.

Another idea for improving the cups which was explored was increasing the area of the lip of the cup. This idea was investigated later on in the design process after pull tests were conducted using the instron and a clear image of the bottom of the cup before failure was examined. In

Figure 10 it can be seen that the lip of the cup lost its circular shape and suffered some deformation the moment before failure.

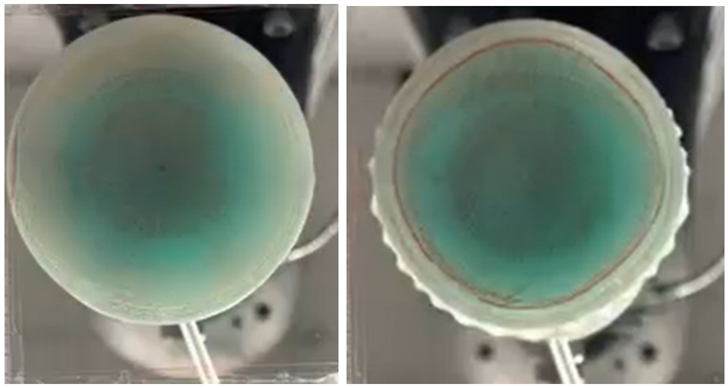


Figure 10. Fully compressed suction cup (left) and suction cup right before failure (right) during failure testing

We believe that increasing the area of the lip could lessen the stress on the lip of the cup. Due to time constraints, a cup with an increased lip area was not able to be tested, but our final design would have been a dual material cup with a larger lip area.

The second deliverable of our project was our FEA model. Within the model, we experimentally determined the material parameters and compared them to the data given on the manufacturer's data sheet. We then modeled the dogbone experiments to determine the material parameters and generate an output force vs. displacement curve for verification. Lastly, we modeled a suction cup when in compression without friction from the lip of the cup, similar to our suction cup stiffness compression tests. An example of this can be seen below in Figure 11.

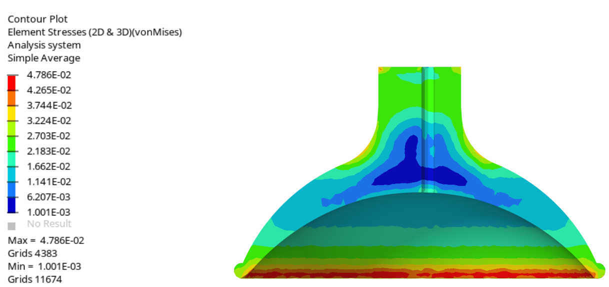


Figure 11. FEA model of the stresses on a suction cup in compression

Concept Analysis and Iteration

After selecting our alpha design, we attempted to physically create it with some members of Professor Shorter's team. We used the previous molds to help create our alpha prototype. Alongside of this, half of our team worked on creating relevant FEA models. With updated data driven advice via the FEA model and the real world testing, we would have liked to generate ways to improve our alpha design given more time on the project. We thought of ways to incorporate some of the other idea concepts into our design (such as additionally applying adhesive film to a dual material cup to increase strength without over increasing pressure differential). Given more time, we would have iterated through the whole process again, predicting the force via FEA, physically testing the cup, and then using those results to create a better data driven design.

Problem Domain Analysis and Reflection

The goal of our project is to design a suction cup for cetacean biologging tags that has twice the strength of the current suction cup used in Professor Shorter's. In addition to this goal, we wanted to heavily emphasize prediction and verification of the performance and forces within the cups via a finite element analysis model. We verified the finite element analysis (FEA) model by comparing its results to experimental data as well as data from previously existing literature. Essentially, our process was an iterative triangle. It started with designing a new suction cup that we predicted would have increased strength against a normal load. From there, we used FEA software to model how we believed each cup of different material would perform. Finally, we performed experimental verification to help refine our FEA model and actually test if our new suction cup has improved performance. This leads back to the top of the process again which was to look at how the cup performed and design a better one. The biggest change in our problem domain versus the problem previously expressed in design review reports is that we no longer delivered just an FEA model. The added problem statement clause was to design a cup that is twice as strong as previously existing designs, model the cup using FEA software, and then verify it using real world testing. In summary, we still had heavy emphasis on delivering an FEA model for predicting suction cup performance but the goal of creating a twice as strong suction cup as well predicting/verifying it using an interactive design process was added mid-semester.

Verification and Validation Approach

FEA and Experimental Data Relationship

In order to achieve our final goal of modeling a suction cup to predict performance, we decided to use experimental data as well as intermediate FEA modeling to verify parts of our final model and increase our confidence in the final model. First, we sought to experimentally determine the material parameters required for modeling and compare them to the manufacturer's material parameters listed on the data sheet. We then modeled the dogbone experiments we conducted to determine the material parameters and output a force vs. displacement curve. Finally, we compared the force vs. displacement graph from the dogbone FEA models with the force vs. displacement curve determined experimentally for verification. All of these steps are described in more detail below. By simultaneously running experiments on the materials used for suction cups and modeling these materials, we hoped to gain a greater understanding of the parameters that most directly affect performance of a suction cup.

Suction Cup Compression and Failure

Our first tasks were to learn about suction cup compression and failure. We started by compressing various suction cup samples onto a clear acrylic surface, as shown in Figure 12. We found that suction cups made out of a stiffer material resulted in a larger air pocket than those made out of a softer/more flexible material. This made sense because the stiffer cups had a greater force needed to cause failure and our hypothesis for calculating that force required was *Force = Area * Pressure Differential.*

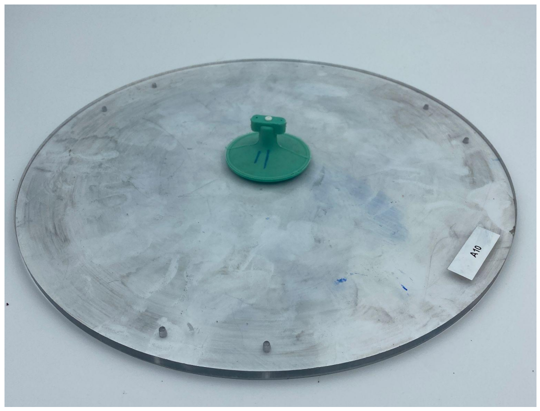


Figure 12. Suction cup compressed on acrylic plate

Following the compression tests, we pulled the suction cups off of the clear acrylic surface and recorded video underneath the surface, shown below in Figure 13. We saw that the outer brim of the suction cup that made contact with the acrylic surface grew smaller and smaller until one point of the brim would lose contact. This would cause an air leak to occur and thus would result in a loss of pressure differential and subsequently a loss of suction force. The largest takeaway from this experiment was that if we could somehow delay or prevent the outer rim from losing contact, we would likely make the suction cup resist a much larger force before failure.

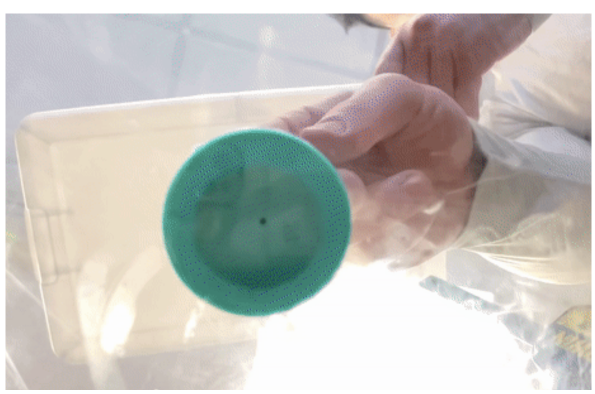


Figure 13. Suction cup pulled off of the acrylic plate.

Suction Cup Properties and Failure Tests

In order to test some basic suction force qualities of each of the three different material suction cups, we performed static tests of each compressed cup on a smooth acrylic surface. A manometer was attached to a top access hole to measure the pressure within the suction cup while it was compressed on the clear acrylic surface, and the inner cup area was measured with calipers. These measurements were used to calculate each cup's static suction force that it is theoretically producing, demonstrated by Eq. 1, where P is the pressure inside the cup and A is the inner area of the cup.

$$F = PA \qquad [1]$$

A demonstration of the experimental setup can be seen in Figure 14. The ring of the suction cup that is in full contact with the surface is seen by the darker outer ring from the bottom view, and the inner area is the lighter area in the middle that is the pressurized air pocket.

Figure 14. Static, compressed suction cup test. Left, bottom view of the compressed cup as seen through a clear acrylic surface. Right, a manometer measured the pressure within the cup.

The results of these measurements and calculations are shown in Table 3.

Table 3. Static suction cup compression qualities for each of the tested materials, Mold Max 20, 30, and 40.

Material	Cup Inner Area (m^2)	Pressure (-psi)	Force (N)
Mold Max 20	0.000586	0.4	1.617
Mold Max 30	0.000539	0.8	2.978
Mold Max 40	0.000777	1.4	7.508

These results matched our theoretical understanding of suction cup properties with the stiffest cup material, Mold Max 40, having the greatest suction force of the three cups with 7.508 N. We expect to compare these suction forces with the results from failure testing to see if the force as a cup is about to break off a surface is truly greater than the static suction force.

Pull to failure tests were also performed using the instron machine. Data was collected for each of the three suction cup materials and plotted in Figure 15. The moments of failure when the cup was pulled from the plate are marked by the black diamonds.

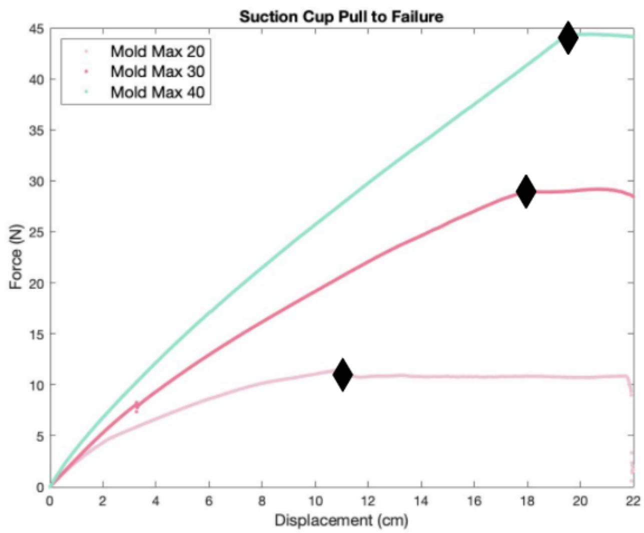


Figure 15. Force and displacement values for the pull to failure test. Failure marked by black diamonds on the graph. The stiffest material, Mold Max 40, required the greatest force and displaced the furthest.

Suction Cup Material Modeled with Dogbone Shape

To begin our iterative design process of creating a stronger suction cup, we wanted to begin by modeling the cup in FEA software. However, before we did this we needed to understand and model our material parameters. The easiest way to do this was to start with a shape that was easy to model. Thus we chose a dogbone sample to begin modeling in our FEA software. Half of the team began creating the FEA model of the dogbone sample while the other half of the team took to the lab to physically create the dogbone samples. These dogbone samples were all made out of different types of Smooth-On silicone with varying stiffness. Once created, tensile tests were run on the physical samples to determine stress-strain curves which would be later compared to our FEA models.

Tensile Test Procedure

Tensile tests were conducted on the dogbone specimens. For this test, a base and clamps were 3D printed and attached to the Instron. These clamps held the ends of the dogbone specimens in place while the Instron stretched the samples of 2 cm. The cross-sectional areas of the stretched samples were then measured and compared with the unstretched cross-sectional areas. An image of the tensile test setup with the dogbone specimens can be seen below in Figure 16.

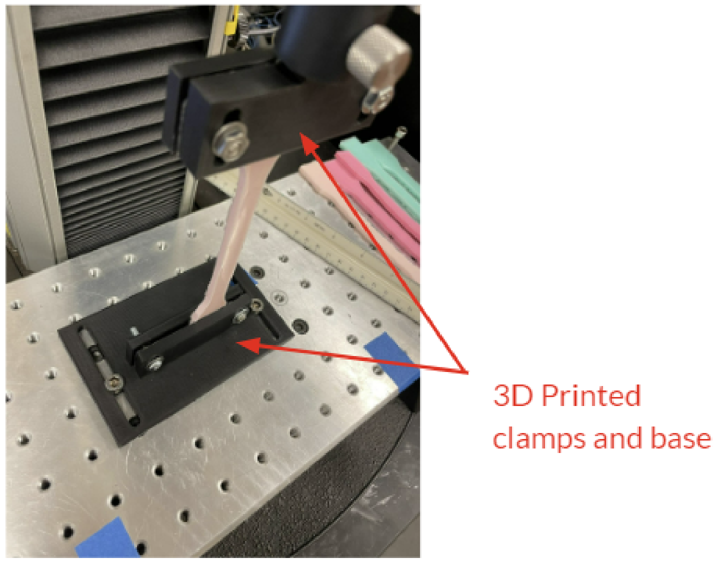


Figure 16. Our dogbone tensile test setup using the Instron machine. The dogbones were clamped on the ends using pieces we designed and 3D printed. Each dogbone was pulled 2 cm and the force was recorded.

Tensile Test Results

The tensile test recorded the force the instron used as it pulled each dogbone to our designated displacement of two centimeters. Each dogbone was tested three times. The data was averaged and plotted on the same graph to compare the results as seen below in Figure 17.

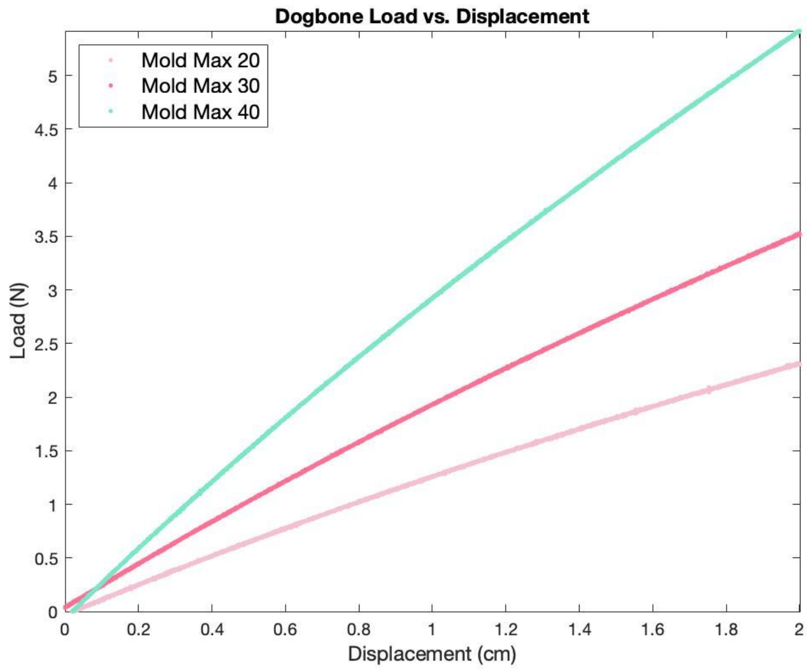


Figure 17. The load versus displacement data for each of the three different dogbones after being stretched 2 cm. The stiffest material, Mold Max 40, requires the greatest force to get to 2 cm.

The data shows results that we expected. The Mold Max 40 is the stiffest silicone solution, so it makes sense that it required the largest amount of force to stretch it two centimeters. Likewise, Mold Max 20 is the least stiff and required the smallest force, while Mold Max 30 required a force somewhere in between. The data is also very close to linear, which makes sense for elastic materials like silicone rubber. The data appears to be slightly curving in the downward sense, which may be due to impurities in the creation of the dogbone molds.

After these tensile tests were performed, the slope of the stress-strain curves were used to calculate Young's Modulus shown in Eq. 2 for each of the materials. The slope reflected Young's Modulus since

$$E = \frac{\sigma}{\epsilon}, \quad [2]$$

where σ is stress and ϵ is strain. Poisson's ratio was also calculated in Eq. 3 by using the change in longitudinal length and lateral length, as described by

$$Poisson's\ Ratio = \frac{Lateral\ Strain}{Longitudinal\ Strain}. \quad [3]$$

In order to calculate each of the strain values, the change in length was divided by the original length of both the longitudinal and lateral changes, respectively. For each material, the tests were performed three times and averaged to try to reduce any potential errors. The results of these calculations are shown in Table 4.

Table 4. Tensile test Young's modulus and Poisson's ratio results for Mold Max 20, 30, 40, averaged over 3 trials for each material.

Material	Young's Modulus (mPa)	Poisson's Ratio
Mold Max 20	0.055	0.637
Mold Max 30	0.083	0.597
Mold Max 40	0.131	0.543

Poisson's ratio for each of the materials was slightly higher than 0.5, which was of the same magnitude of the expected value of around -1.0 to 0.5. Poisson's ratio of greater than 0.5 is not normally physically possible due to the requirement that the shear modulus and bulk modulus of a stable material have positive values. Therefore, we know that there was systematic error at play as well as bias due to small imperfections like air bubbles within the dogbone samples.

Finite Element Analysis of Dogbone Materials

Finite Element Analysis was performed on the dogbone in efforts to correctly predict the experimental results. The geometry of the dogbone was created in Solidworks, and was uploaded to Hyperworks for the FEA modeling [24]. In Hyperworks, the dogbone was modeled to replicate the experimental setup, by constraining one side and pulling on the opposite end, as shown below in Figure 18.

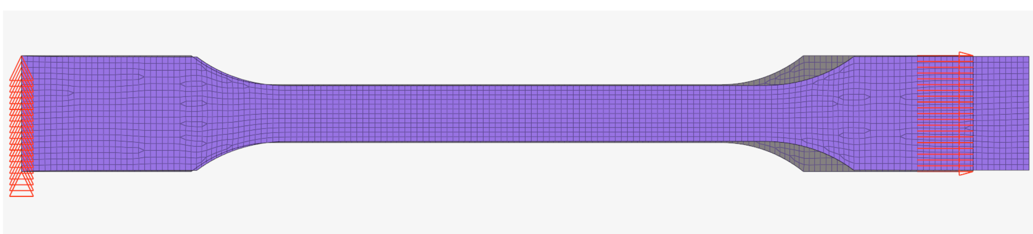


Figure 18. Model of the dogbone in Hyperworks after it has been stretched. The gray dogbone in the background is the resting dogbone. On the left of the dogbone are markers indicating constraints, and on the right are arrows indicating the force vectors representing the pull of the specimen.

The results of the FEA analysis were recorded and plotted against the experimental values as shown below in Figure 19.

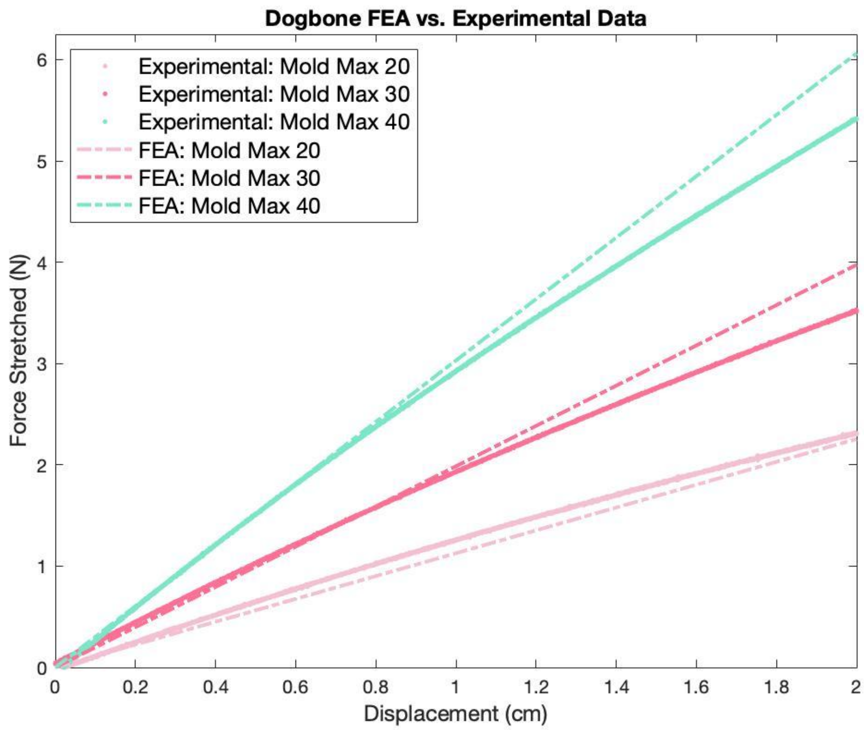


Figure 19. Comparison of the FEA model and experimental results.

Suction Cup Stiffness Compression Tests

Stiffness compression tests were performed on samples of Mold Max 20, 30, and 40 cups. The tops of the cups were sealed and attached to the Instron. The lips of the cups were fitted into the 3D printed base pictured below.

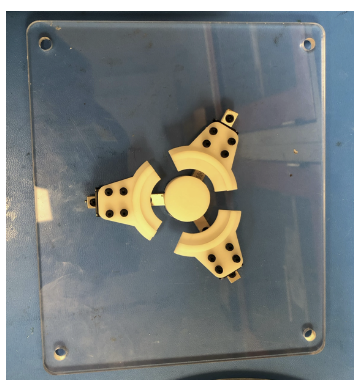


Figure 20. Compression test base, allowing only lateral movement of the suction cup

Each of the edges of the base can slide freely in the X-Y plane. This allows for the cup to push out the base as it is compressed. Each cup was compressed 1 cm. The graphs of the data gathered from these tests can be seen below in Figure 21.

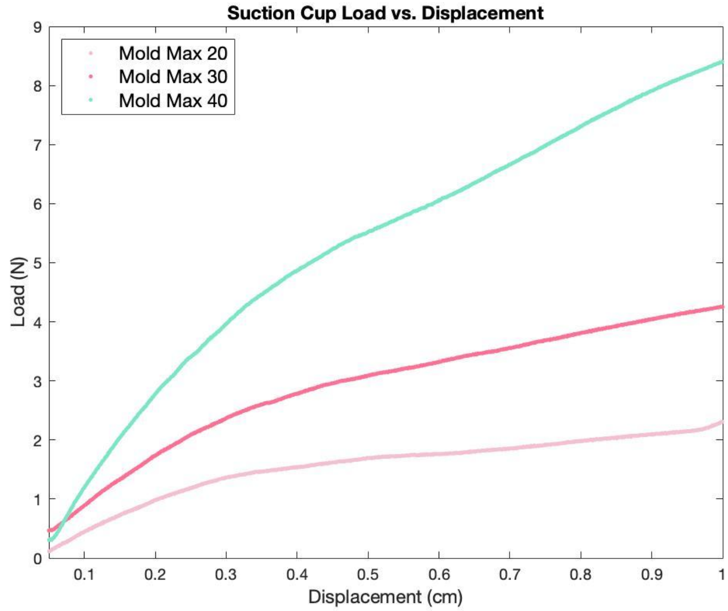


Figure 21. Suction cup load versus displacement plots for our three materials. The data appears to have two sections. It is initially fairly linear until about 0.35 cm. The slope of linearity decreases for the next section of about 0.35 cm to 1 cm.

Finite Element Analysis of Cup Compression

Similar to the dogbones, we modeled our suction cups in Hyperworks and used Finite Element Analysis to mimic the compression test, seen in Figure 22. The test was set up in the software with the cup constrained so that the lip could only move outwards when the top of the cup was pushed down.

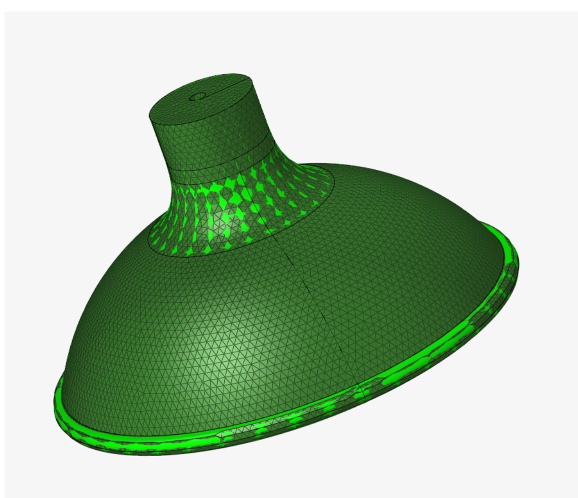


Figure 22. Meshed suction cup model in Hyperworks [24].

The data from the experiment was recorded and plotted against our experimental results. The results are below in Figure 23.

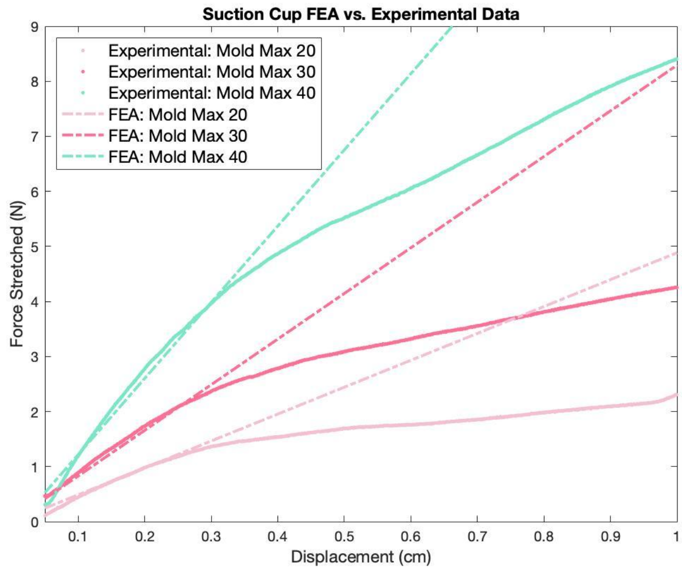


Figure 23. Comparison of the FEA data (dashed lines) and experimental data (solid lines) for the suction cup compression tests. FEA data matches experimental data well until around 0.35 cm where the experimental data linearity shifts.

As mentioned before, the experimental data from this test had two linear sections. Our FEA model captured strictly one section of linear data, so it did not agree completely with the experiment. With more time, this is something we would have liked to improve by creating a more complex model or tweaking the experimental setup. Additional data was collected in Hyperworks showing the stresses felt by the suction cup [24]. As shown before, these results can be seen in Figure 24. We see that the highest stress occurs in the lip of the suction cup.

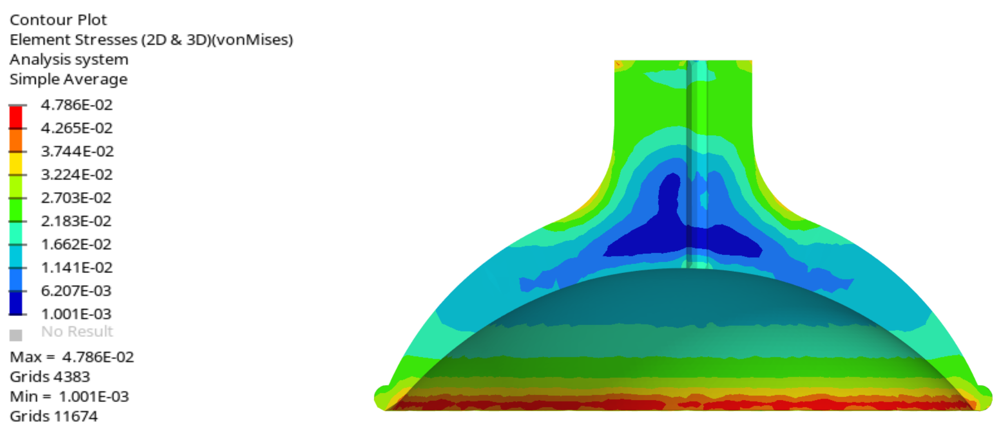


Figure 24. Contour plot showing the stresses felt in the suction cup. The highest amount of stress is found in the lip of the cup, as indicated by the orange and red colors.

Discussion

The strengths of our final design outcome are that the FEA-predicted performance of different materials matched real experimental results with decently good accordance. In the performance prediction for the dogbones of the three different materials tested, the results of the experimental tensile tests and FEA had a very strong agreement, with the force versus displacement plots matching their counterparts very well. Similarly, the stiffness compression testing FEA and experimental plots matched nearly identically in the earliest displacements up to around 0.3 cm. Our suction cup failure tests met our expectations that the cup with the stiffest material would endure the highest applied force before failing, while the softest material endured the least amount of normal loading. If given more time, we would have liked to plot the pressure differences and compare the suction cup force being pulled with a stationary suction cup. A deeper look into the radial forces acting within the cup during a failure test would also likely provide a better concept of suction cup performance. After seeing the non-circular shape of the bottom of the cup in contact with the surface, this idea of radial strain seems quite relevant to the problem at hand.

A weakness of our design outcome was that the stiffness compression experimental results showed a two-part plot of force and displacement with two different linear sections, the later of the two not matching with our FEA predictions. This raises the question of experimental error and bias versus incorrect reasoning in FEA modeling. We currently believe that this behavior may have been due to a combination of air bubbles in the silicone as well as the cups being overly compressed slightly during experimental testing, but these hypotheses have yet to be verified with more testing. Another weakness of the FEA modeling is that predicting performance of the cup including friction forces on a surface were too complex for the scope of this single-semester project, and should likely be further investigated in future work.

If more time and resources to collect data were available to our team as well as time to better define the problem for our project, a different outcome of the project would be likely. Some questions we would like to explore further would be how some different parameters, such as thickness, cup lip length, geometry, and size, could be modeled to predict cup performance in FEA software. Combining different parameters such as these together in one simulation would be highly beneficial to the research team and would be what we would have explored if given more time on the project. In order to experimentally verify these effects, we would use the testing methods of using different molds and performing force tests with the Instron to compare performance predictions, similarly to what was done for material comparisons in this work already. We would isolate a parameter to test by keeping all other cup qualities the same besides the one we were testing, for example making three cups of differing thicknesses but keep the material and geometry the same.

Reflection

For our final product, it was important for us to think about our suctions cups at both a micro and macro level. Our suction cups help attach biologging tags to marine life which aid scientists in understanding these animals and thus improve conservation efforts. As for social and economic impacts, our suction cups by themselves do not make a large impact due to their small batch size and the fact that they are not designed for large scale commercial or consumer use. If the improved suction cup design were used for commercial use there could be an impact in the global economy of improved suction cup technology for customers, but that is not the case. The big effect of our suction cups is aiding in the attachment of biologging tags. With the added data from biologging tags, conservation efforts could have a large impact in the global sphere of regulating shipping trade routes or confirming new offshore building sites. To help characterize and improve our design process and solutions, we made stakeholder maps which included Professor Shorter's lab, conservationists, and the marine life itself.

Throughout this entire process, we found that many of us in our team had relatively similar identities and thus similar ideas about solutions. To combat this, we made sure to use a variety of design differentiation processes and tools so that we could expand our net of possible design solutions. Our sponsor was fantastic in working with us and letting us have the freedom to come up with our own solutions and designs. This was likely due to intentionality and actively recognizing the power dynamic between us.

We were very fortunate that there was a very equal power dynamic between Professor Shorter's lab and ourselves. We were very comfortable asking for help and questions from the people who had more experience than us. We did have a mix of cultures and identities throughout our stakeholders and us and we believe that this added diversity helped improve the creativity and uniqueness of our designs and modelings. One unique thing about our project however was the power dynamic between the animals and us. The animals obviously do not have a voice so it was important for us to think about their needs. Therefore in our requirements and specifications we made sure to include that the suction pressure of the suction cup had to be under 4 psi due to the fact that any greater pressure differential would cause discomfort and irritation to the animal.

Recommendations

There are several recommendations we have for processes that we didn't have time to complete. First, it was very difficult to create a perfect 5 mm-thick dogbone due to its viscous nature, which skewed our model. We recommend creating more dogbone samples to verify the experimental results that we collected and more accurately calculate the Young's modulus and Poisson's ratio of the three materials. For the Poisson's ratio calculation, it would be beneficial to have an extensometer because our experimental procedure of measuring the width before and after stretching the sample left a lot of room for experimental error.

Additionally, with more time we would have liked to improve our FEA model of the cup and verify it experimentally. We created a linear static model of the pure compression of the cup with constraints modeling the stiffness compression tests we conducted in the lab. However, the experimental data from those tests were not purely linear. They appeared to consist of two linear portions of different slopes. We were able to fairly accurately model the first linear portion of the data, however this is not a complete prediction of the behavior. We recommend trying to fully model the behavior in these experiments by trying out a hyperelastic material model in Hyperworks or another FEA software. Furthermore, modeling the stiffness compression tests of the suction cups is just one way of predicting the performance of the cups. Ultimately, we would have liked to model the failure tests of the suction cups. This is a much more complex FEA problem due to the introduction of the rubber seal created when compressing the cups onto the surface. We recommend trying to model the conditions created in the failure testing since that data offers more insight into how and when the cups will fail.

As for future work on manufacturing new cups, we recommend creating a number of new cups and comparing them to the cups already used. From our FEA model of the stiffness compression testing, we found that the highest stresses in the cups occurred at the lip when a compressive force was applied. Therefore, we recommend printing a suction cup with a thicker lip using the new mold we designed. We also designed a second mold for a cup with twice the thickness of the current cups used. We recommend printing a cup using this mold to see how overall thickness impacts the behavior of the cup. Lastly, we recommend creating more dual-material cups based on the final design we chose for a cup two-times better than the current cups. We recommend testing the dual-material cups experimentally with the stiffness compression tests and failure tests.

Conclusion

Biologging tags aid in conservation efforts, help scientists gain a greater understanding of marine life as oceans are largely unexplored and unobservable, and help determine ocean regulations for humans as we encroach on marine spaces more and more. While it may seem invasive to put these tags on animals, the benefits greatly outweigh the costs. The amount of valuable data that can be translated into conservation efforts and a greater understanding of how these animals can coexist in a symbiotic relationship with humans is paramount. Without making an effort to stop the endangerment of many species, they will likely go extinct unless humans make the effort to understand how we are affecting them. Biologging tags have been attached to animals via suction cups using a pressure differential to minimize the pain caused to the animals and keep this big picture cost to the animals at a minimum. While Professor Shorter and his team are working on perfecting the design and fabrication of these cups, we strived to elevate the analysis and design of the suction cups from an approach informed by engineering analysis. We approached this by first analyzing the natural behavior of suction cups, followed by creating an FEA model. In the lab, we created three cups of varying stiffnesses and recorded data and images of suction cups in compression as well as pulling to failure. These tests gave us a better understanding of the suction cups, and we moved onto FEA modeling and verification. To verify feasibility, we started by modeling and experimenting with dogbone samples because of their simple geometry. A tensile test was performed for our dogbones to capture the linear force versus displacement. After comparing and analyzing the FEA and experimental results, we moved onto suction cup compression tests. In these tests, the vacuum or suction force was not involved. We pushed down on the suction cup and recorded force and displacement. Experimentally, we found the test was composed of two linear sections whereas the FEA model was simple linear data. This finding is something we wish we had more time to work through. The complexity of creating a perfect FEA model for a suction cup will require more effort and knowledge. However, we were pleased to initiate this complex system by supplying an FEA model that can predict aspects of experimental data and provide insight on how to improve the success of suction cups for biologging tags.

Acknowledgements
We would like to thank Professor Shorter for his insight and guidance throughout the design process as both our project sponsor as well as our ME 450 instructor. Additionally, thank you to Dory Yang and Ethan McMillan for teaching and helping us create the dogbone and suction cups and perform experiments in their lab. Finally, thank you to all of the ME 450 staff for supplying a great course that challenged our thinking and gave a great project experience.

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Appendix A. Brainstorming Details

We each brought our best concepts together for our brainstorming session and then combined some of these in our group brainstorming session. The results of this can be seen below in Figure 25.

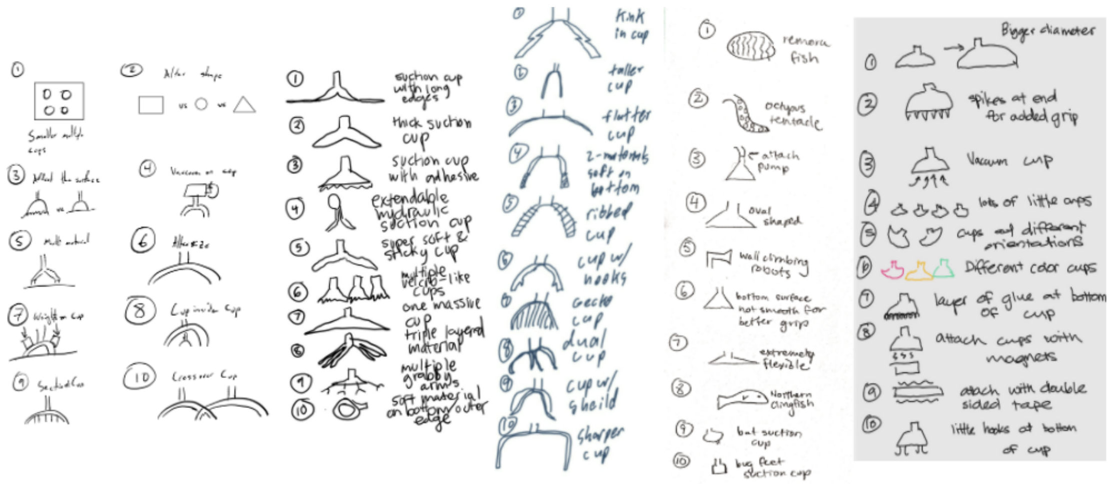

Figure 25. Brainstorming Session Results

The main categories of ideas and the number of ideas that fall into each category can be seen below in Table 5.

Table 5. Concept Categories

Category	Number of Ideas
Changing Cup Size	11
Changing Number of Cups	3
Adding Adhesive	10
Changing Material Properties	18
Other	8

Please note that the “other” portion of this table refers to ideas which fall outside of the realm of feasibility.

Appendix B. Bill of Materials and Manufacturing Plan

Table 6. Bill of materials for molding suction cups.

Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
Silicone Mold Max 20	1 trial unit	Smooth On	Mold Max™ 20	$34.95	(610) 252-5800	
Silicone Mold Max 30	1 trial unit	Smooth On	Mold Max™ 30	$34.95	(610) 252-5800	
Silicone Mold Max 40	1 trial unit	Smooth On	Mold Max™ 40	$34.95	(610) 252-5800	
3 Part Suction Cup Molde	1	Printed in house from SLA printer	N/A	<$5		This was printed in house. Thus SLA printer cost not included
Dobone Casting Molds	3	Printed in house from FDM printer	N/A	<$5		This was printed in house. Thus SLA printer cost not included

Manufacturing Plan

Begin by printing all three parts of the mold (side one, side two, and bottom) using an SLA printer. From there you can use common nuts and bolts to attach the three pieces together. However make sure to attach tubes and splitters in the mold before screwing it together.

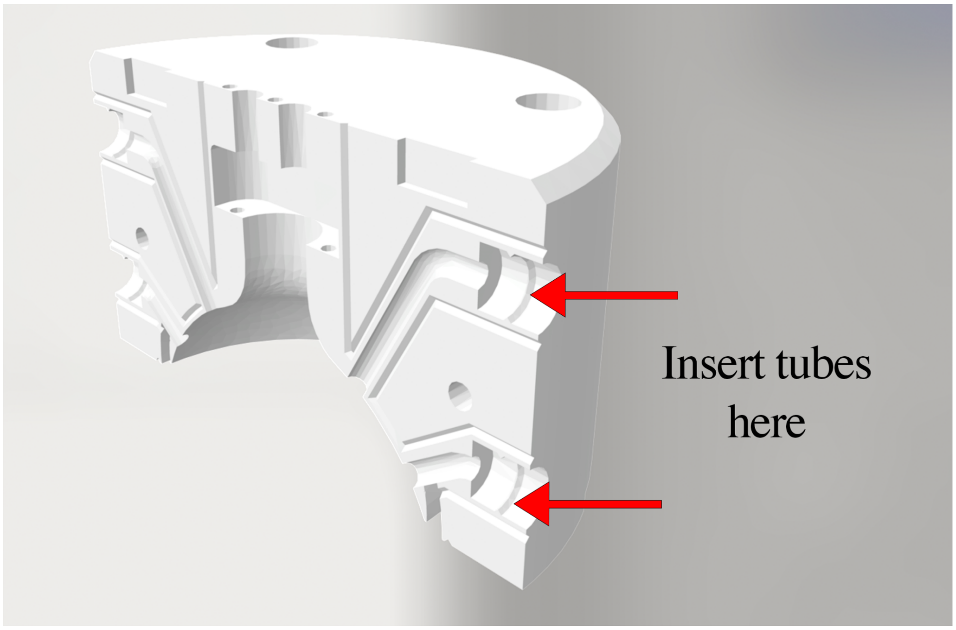

Figure 26. Mold for pouring a suction cup with tubes for inserting silicone called out.

Once the mold is assembled it is time to begin getting the silicone ready. You may use whatever Mold Max silicon you like but we recommend Mold Max™ 40 for the best results. Mix 100 mL of the Mold Max silicone in a stirring cup according to the manufacturer directions. Once thoroughly mixed, place the silicone (still in the stirring cup) into a pressure chamber of your liking. Activate the pressure chamber and wait 3+ minutes or at least until most of the bubbles from the silicone are gone. Then remove the silicone from the pressure chamber and pour it into two syringes. Attach tubes hanging out from the mold to the exit of the syringes. Then push the syringes slowly so that all of the silicone has entered the mold and that it is now filled to the top. Let it cure for 24hrs and then unscrew mold and remove the newly constructed suction cup.

Biographical Sketches

Name: Kayla Coalmer
Pronouns: she/her
Year: Senior
Major/Minor: Mechanical Engineering, Music minor
Hometown: Houston, Texas
Experience: I spent the last two summers working in the home appliance manufacturing industry, and the summer before that I was working with a company to evaluate new carbon capture technologies for a $1B investment fund. I have also been working in a research lab for the past two years with a mechanical engineering professor and PhD employee to create a device that diagnoses corneal infections through fluorescence and spectroscopy.

Relevant interests to the design project: I am passionate about animal welfare and have fostered kittens for a local rescue for over two years (17 kittens total now). I also am interested in ocean coral reef conservation and actually have 145 gallons worth of saltwater reef tanks in which I grow corals and take any rescue saltwater fish that cannot be taken care of by their owners anymore (due to people moving, deaths, no time, etc.).

Name: Jack Zeile
Pronouns: he/him
Year: Senior
Major/Minor: Mechanical Engineering
Hometown: Boulder, Colorado
Experience: Last year I started two distribution companies based in the e-commerce space. I have vast experience creating systems/funnels, training teams of offshore employees, and raising funding capital. Additionally last summer I worked at a real estate investment group that specialized in the trade of housing purchase contracts.

Relevant interests to the design project: I have always loved the ocean and its conservation efforts. As a kid I spent a lot of my summers in Florida and South Carolina. The ocean has always been a place of very fond memories for me and any work of keeping the ocean and its wildlife healthy and prospering is something I am very much interested in.

Name: Teddy McGregor
Pronouns: he/him
Year: Fifth Year
Major/Minor: Mechanical Engineering with a Computer Science Minor
Hometown: Wilmette, IL
Experience: Over the last year and a half I have had two internships working for two tier one automotive suppliers where I assisted in testing, change management, and warranty issues. Starting last semester, I have been involved in researching the computing capabilities of mechanical metastructures in the Structural Dynamics and Controls Lab on campus.

Relevant interests to the design project: I think that the ocean is fascinating because of how vast it is and how cool the animals that inhabit the ocean are. Learning more about the world we live in by examining the habits of whales and dolphins is something I do not know much about but would like to.

Name: Kerry Meade

Pronouns: she/her
Year: Senior
Major/Minor: Mechanical Engineering, Computer Science Minor
Hometown: Arlington, VA
Experience: The past two summers I interned at a large aerospace company where I was a manufacturing engineer involved in the building of wire harnesses for space satellites. I worked a lot on improving engineering processes and documentation as well as assessing models and drawings of wire harnesses to deliver feedback on manufacturability.

Relevant interests to the design project: I love animals and the idea of applying engineering skills and problem solving to aid in ocean conservation efforts and animal welfare is really exciting to me. I took a class last semester on tissue mechanics and it got me further interested in biomechanics. Whales and dolphins especially are some of the most fascinating animals, so the opportunity to work on a biomechanics-related project for this is a great intersection of my interests and skills.

Name: Emma DeRidder
Pronouns: they/them or ze/zir
Year: Fifth Year
Major/Minor: Mechanical Engineering
Hometown: Chicago, IL
Experience: I spent a summer working for the Department of Energy at their Savannah River National Laboratory site working with weapons-grade nuclear materials and modeling safe geometries for facility sumps to prevent unwanted fissions. This past summer I interned with Siemens and worked as a smart infrastructure engineer and designed and modeled sustainable buildings for commercial uses. I am currently working as a student researcher and experimentally evaluating the potential of an origami inspired phononic structure with metamaterial inclusions for wave steering in air medium in the Structural Dynamics and Controls Lab.

Relevant interests to the design project:
I have always loved the ocean and marine life. Before moving to Chicago in 2015, I spent my entire life in Papua New Guinea and Australia and really appreciated the oceans I grew up swimming in. I love scuba diving and have many amazing memories from interacting with marine life and would love to learn more about them.