

Design of a Buoyancy Compensation Device and Prosthetic Flipper for a Green Sea Turtle



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Design of a Buoyancy Compensation Device and Prosthetic Flipper for a Green Sea Turtle

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Table of Contents

Acknowledgements	4
Abstract.....	5
Chapter 1. Introduction.....	6
Chapter 2. Literature Review.....	7
2.1 Green Turtles.....	7
2.2 Kinematics of Swimming.....	7
2.2.1 Anatomy of a turtle	8
2.2.2 Lift Forces	8
2.2.3 Powerstroke.....	9
2.2.4 Routine Swimming.....	9
2.3 Causes of Flipper Amputation.....	9
2.4 Buoyancy Disorders in Sea Turtles	10
2.5 Potential Solutions to Buoyancy Disorder.....	11
2.6 Problems Encountered in Past MQPs.....	12
2.7 Rocky the Sea Turtle	13
Chapter 3: Methodology	14
3.1 Flipper Procedure	14
3.1.1 Step 1: Modifying CAD model	14
3.1.2 Step 2: Making Mold	15
3.1.3 Step 3: Making flipper prosthetic.....	16
3.1.4 Step 4: Designing Flipper Attachment	16
3.2 Buoyancy Device Procedure	17
Section 3.2.1 Preliminary Designs	17
Section 3.2.2 Selecting and Testing Material.....	19
Section 3.3.3 Calculations for Weight	19
Section 3.3.4 Making the Device	20
Chapter 4: Results and Discussion	21
4.1 Flipper	21
4.2 Buoyancy Device	22
4.3 Generalized Process	23
Chapter 5: Conclusion	24
Bibliography	25
Appendix A - Pamphlet Contents	27

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Abstract

This project focuses on Rocky, a green sea turtle located at the Key West Aquarium, who lost his front right flipper in a boating accident. In addition to a missing flipper, Rocky has a buoyancy disorder in the rear of his shell, which inhibits him from diving for food, swimming in a straight line, and breathing properly. This project aims to develop a floatation device to counteract Rocky's buoyancy disorders as well as a prosthetic flipper to imitate his healthy flipper. The flipper was fabricated using 3D printing and molding processes. Adapting from previous projects' calculations, a flipper was developed that will work as effectively as a healthy fin. The attachment mechanisms were designed by the project team and will be developed in collaboration with Hanger Prosthetics in Orlando, Florida. The team also created a generalized process, demonstrated in an instructional pamphlet and video, that can be used to assist in making prosthetics for other sea turtles.

Chapter 1. Introduction

Green sea turtles are one of the seven sea turtle species that still exist today. They are currently accepted as an endangered species, which negatively impacts the marine ecosystem. These endangered sea turtles are also at risk of becoming hurt or ill. One of the main injuries to a sea turtle is the amputation of a flipper. This is most commonly caused by debris in the water, boating accidents and predator attacks. Other problems green sea turtles face are diseases and disorders. A relatively common disorder, is a buoyancy disorder, or bubble butt syndrome, which inhibits the turtle from diving and resurfacing in water naturally. This disorder is often caused by trapped intestinal gas, which occurs from the ingestion of plastic debris, or spinal cord injuries.

Rocky, a green sea turtle at the Key West Aquarium in Florida suffers from both an amputated front right flipper, and a buoyancy disorder toward the back right of his shell after being struck by a boat. The buoyancy disorder is a result of spine damage from the accident. Because of these injuries, Rocky struggles to swim in a straight line, to dive and resurface in water naturally, and breathe comfortably. He is in need of a prosthetic flipper and a new buoyancy compensation device so that he can live a normal life within the aquarium.

Previous WPI project teams have worked with a different sea turtle at the Key West Aquarium, Lola, to create a prosthetic and a prosthetic attachment piece for her. The aquarium reached out to WPI in hopes that Rocky, who is much larger than Lola, could receive a prosthetic, while considering previous complications with the old projects. They also hoped that a project team could assist them in designing and developing a weighted device to allow him to swim normally. This is where this project stems from.

We set our project goals to successfully create a prosthetic flipper for Rocky, to design and manufacture a buoyancy compensation device for Rocky, and to create a generalized process for creating a prosthetic for a sea turtle so that others around the world can recreate this process.

Chapter 2. Literature Review

2.1 Green Turtles

Green turtles, scientifically known as *Chelonia mydas*, inhabit the tropical and subtropical waters of the world. They are currently considered an endangered species, due to overharvesting, habitat loss and disease [1]. In the 1980s, seagrass beds in Florida began to die off; similar events happened in Australia. Scientists researched why this was happening, and concluded it was the diminishing population of the green sea turtle species. Green sea turtles groom the seagrass beds in which they live, keeping them healthy and able to sustain many other marine animals, including manatees, sharks, rays and several fish. Without the green turtles eating the seagrass, the long blades of grass block the natural flow of the current and block the sun from hitting the ocean floor, potentially leading to the seagrass dying [2]. The survival of the green turtle species is crucial to maintaining the current marine habitat.

Their survival is not only important to the marine habitat, but also to the human population. Green turtles are culturally and economically significant to many people and play a large role in ecotourism. The turtles have a unique habitat history, where they often migrate to inshore waters at the age of 3 to 5 years and then remain there for their whole lives. The species' only time away from these shallow waters, near seagrass beds, is during their breeding times, when the females migrate away. [3]

No matter where the turtles are living, they are always at risk of injury or illness. They are typically very strong and independent. However; disease and accidents can hurt the turtle and require them to get treatment outside of the dangers of the ocean to survive. Sea turtles', including the green species, immune defenses allow them to survive severe flipper amputations that would kill most mammals [4]. This flipper damage is the most common injury for sea turtles to encounter, and although they can survive it, it keeps them from living a normal life.

2.2 Kinematics of Swimming

To best fit a prosthetic, it is imperative to understand the kinematics of the natural movement of a turtle. There are two basic modes of transportation for a turtle; terrestrial and aquatic locomotion. Understanding the strokes, thrust and other forces acting during this time will help create a prosthetic designed specifically for those movements. Because the green sea turtle spends most of its time in the water, aquatic locomotion will be the focus.

There are four things known to be true in the aquatic locomotion of a swimming turtle. The first is the swimming speed increases with an increasing stroke rate. Second, the stroke amplitude and force produced per stroke are directly proportional. Third, during both the up and down phases of a stroke the turtle is still producing a forward thrust carrying him ahead. Finally,

the maximum thrust of a stroke is reached at the end of the downstroke cycle [5]. All four of these things need to be analyzed to fully understand the motion of the flipper.

2.2.1 Anatomy of a turtle

The first thing to consider is the anatomy in relation to aquatic locomotion. It is determined a turtle's body is 94.2% of its mass while its proximal flippers are only 2.3% and the distal flippers a mere 3.5% [6]. Despite the flippers being less than 6% of its mass, turtles rely on these flippers to keep them alive. These flippers are dense connective tissue, so the bones can move the flipper as a single unit [7]. The proximal flippers provide most of the movement serving as semi-rigid wings while the distal flippers act as a rudder, controlling the direction while occasionally providing thrust. Sea turtles use their front flippers as both wings and paddles. This results in lift being generated from the convex surfaces of the limbs [7].

Most measurements of thrust production have been made when the sea turtles are hatchlings [5]. When they are hatchlings, they depend more on drag and have a unique paddling technique similar to a dog paddling. By doing this, they use their back flippers as paddles. However; once they are adult turtles they grow into a lift and propulsion-based mechanism. This allows them to travel longer distances and be more efficient with each stroke [7].

2.2.2 Lift Forces

Turtles flippers serve a similar role as wings on a plane when controlling the depth of the turtle. A lift is developed along the flippers resulting in the turtle swimming up or down. The angle of the "wing" determines the direction the turtle travels in. The lift forces determine the fluid flow and drag of the turtle moving through the water. These forces are always perpendicular to the fluid flow and drag. During the downward stroke of the flipper, the lift produced can act as thrust. When the flipper is at a greater angle and starts to be more perpendicular to the flow, the flipper produces higher drag [7].

2.2.3 Powerstroke

When swimming, a sea turtle gets the most thrust from the powerstroke. It is the strongest stroke and allows for powerful swimming. During this stroke, the angles and locations of the flipper are different than a routine swim. The difference between the two strokes can be seen below in Figure 1.

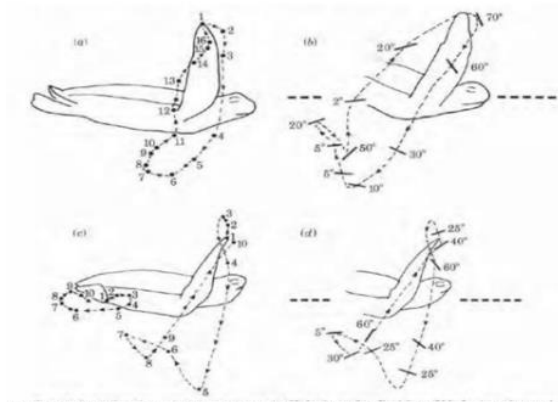


Figure 1. Flipper tip locations and angles of the flipper during swimming [20]

The upper schematics represent the flipper tip location during regular swimming (a), and the angles of the flipper during regular swimming (b). The bottom two drawings depict the motion of the flipper during a powerstroke. Figure c is the location of the tip of the flipper while figure d is the angle of the flipper. These differences of angles and locations determine the power and thrust that is produced with each stroke. However; turtles in captivity do not powerstroke as there is no need to and no threat causing them to react in fear.

2.2.4 Routine Swimming

On a day to day basis, a sea turtle will swim routinely, maintaining a speed between one and three miles per hour [8]. Routine swimming for a turtle in captivity is different that of a wild sea turtle. In the wild, turtles can reach speeds of up 20 mph to escape predators. In captivity this burst of speed is not needed. There will be other stresses acting on the flipper that only turtles in captivity experience, such as running into the sides of a tank.

2.3 Causes of Flipper Amputation

There are a few causes behind sea turtle flipper amputation; first is human interference such as fishing or boating accident, second is environmental causes such as a predator attack, which can leave the sea turtle severely injured. Seriously injured sea turtle flippers can have their circulatory system impaired. Some of these injuries can lead to open wounds that are difficult to heal. The healing process takes an extensive amount of time and can cause infection anywhere in the surrounding tissue of the open wound or the limb. Blood clots in wounds result in reduced

blood circulation. This leads to a lack of oxygenation and transportation of vital nutrients to the flipper's tissues. With a lack of oxygen and nutrients to the tissue, the tissue will die, and the limb will have to be amputated. Human interference or environmental cause can lead to a flipper being amputated if the open wound is not treated properly. [7]

2.4 Buoyancy Disorders in Sea Turtles

Sea Turtles demonstrate their buoyancy when they dive and swim under water and return to the surface to breathe. They control their buoyancy through changing the volumes in their lungs and their cloaca, which is the posterior orifice of an animal that serves as the only opening for the digestive, reproductive, and urinary tracts. They regulate this volume by breathing in oxygen (for a lighter weight) and allowing water in their cloaca, which is at the rear end of the turtle (for a heavier weight). The neutral buoyancy of a turtle under normal conditions is achieved with a lung volume of about 14% of its body volume. Through an experiment performed on fresh water sea turtles, Jackson (2011) discovered that turtles will overinflate or underinflate their lungs to adjust to any added or subtracted weight on their body. The experiment concluded that sea turtles are capable of returning their buoyancy to normal after it has been altered. [9]

Many sea turtles have buoyancy, or floating, problems. When a turtle suffers from a buoyancy disorder it is difficult for them to dive into and resurface in the water naturally. During one study, tests were performed on sea turtles that had buoyancy disorders. They found that turtles with positive buoyancy had a much greater metabolic cost of breathing than that of normal sea turtles. The turtles affected had a gasping-like breathing pattern, which can negatively affect their long-term survival. [10]

There are many causes to buoyancy problems in sea turtles. Many captive sea turtles are found having foreign matter, such as plastic debris, stuck in their digestive tracts. Intestinal foreign bodies can harm the turtle both directly and indirectly. Indirectly, it can affect the turtle's lipid metabolism, which can lead to the accumulation of intestinal gas and floating [11]. This gas or air accumulation in body organs, specifically the intestinal tract is the most prominent cause of buoyancy problems. Trapped intracoelomic gas can get stuck in different locations of the sea turtle and can move, once inside. One of the many ways, along with the ingestion of plastic debris, that sea turtles accumulate gas in their GI tract is through spinal injury. Caudal carapace fractures, which involve the spinal cord, are a common cause of floatation of the hind end of the turtle and are particularly common in the green turtle species [12]. A case study focusing on sea turtles in rehabilitation centers in Australia, proved further the correlation between floating problems and fractures. The study showed that many of the turtles who had buoyancy disorders also showed signs of both fractures and diseases [13].

2.5 Potential Solutions to Buoyancy Disorder

Buoyancy disorder is a common ailment for sea turtles in captivity. Since buoyant turtles are not considered releasable, aquariums have developed a few different ways to treat their sea turtles [14]. There are many different causes for buoyancy disorder, so treatment depends on the root cause of the buoyancy. For example, the Marine Savers, a government endorsed sea turtle conservation program, has three sea turtles suffering from extended buoyancy disorder. The program decided the best treatment for the turtles was to remove air out of the turtles' coelom, fluid-filled body cavity. The vet inserts a syringe between the rear flippers and the underside of the shell and extracts the air. The Marine Savers were able to extract between 1.4 and 2.5 liters of air from each of the turtles and are already seeing improvements in their condition [15].

However; if no improvements come from treatment, aquariums are forced to resort to other buoyancy solutions to remedy the buoyancy problem rather than treat the cause. For example, a green sea turtle was hit by a boat, causing an air pocket to develop under her shell. The turtle was taken to the Mall of America aquarium for treatment. After examination the aquarist determined that because of the way the shell was healing the air trapped could not be removed without disturbing the turtle's internal organs [16]. Unfortunately, buoyancy syndrome deems a turtle unfit for release so as a temporary solution the aquarium has attached weights to mitigate the turtle's buoyancy problem. This solution is only temporary because when the turtle sheds its shell, the balancing weight will fall off.

A group of students at the University of Minnesota are currently focusing on the same buoyancy problem affecting the green sea turtle residing at the Mall of America mentioned earlier. CT scans were taken of the turtle's shell to help the university students develop a better way to attach weights to the shell. Currently, the aquarium attaches the weights to the shell's scutes, the outer layer of the turtle's shell. This method is a temporary solution since the weights fall off when the turtle sheds the scutes off its shell. The prosthetic that the students hope to design would create a permanent attachment system for the weights [17].

Other examples of buoyancy compensation devices provide different potential solutions for the buoyancy disorder in sea turtles. The first example of a potential solution is the buoyancy compensator used by scuba divers. A buoyancy compensator, or a buoyancy control device (BCD), is worn by divers to provide neutral buoyancy underwater and positive buoyancy at the surface. It is comprised of an air bladder that is inflated orally or by compressed gas and straps to connect to a diver. When the diver rises in the water the air bladder is filled with gas and when the diver needs to sink the gas is expelled from the air bladder [18]. Weights are attached to the BCD to aid the buoyancy control of the diver [19].

2.6 Problems Encountered in Past MQPs

The WPI project group from last year worked to make a lighter prosthetic flipper for Lola, the sea turtle, and to make it easier to attach. They brainstormed by looking at different types of human prosthetics. From their research they discovered the best method to ensure a secure fit is to use liners. The liner is a thin sleeve that fits under the prosthetic and over the remaining limb. There are different types of materials that can be used as a liner such as silicone, polyurethane, copolymer and WinteresGel. Silicone is a very popular material for human prosthetics. This is because it provides good stability and adhesion, it is a soft, protective material and distributes the pressure evenly over the surface of the remaining limb. Polyurethane is another common sleeve used for prosthetics. Polyurethane flows away from high pressure, this is good for prosthetic sleeves because the pressure in the socket of the prosthetic gets distributed across the whole sleeve. Copolymer is a material that has a high longevity, this is because it does not have seams. In addition, copolymers are more elastic which allowed the sleeve to fit on an unevenly distributed residual limb. Finally, WinteresGel is a sleeve designed for a dolphin. The material was made for the intent of dolphins, but it is used for some human sleeves as well. The WinteresGel sleeve can survive saltwater conditions.

The MQP project team last year worked with a company called Hanger Prosthetics in Worcester, MA. The company sent the project team two types of sleeves. One sleeve was made of silicon, and the other was a combination of rubber and waterproof fabric.

The project team evaluated performance, ease of attachment, safety, durability, manufacturability, and cost as the criteria when coming up with potential prosthetic flipper designs. The first design was a jacket design made of neoprene. The jacket fastened around the turtle and the prosthesis was permanently attached to the jacket. The positive attributes of the design were its ability to distribute the pressure and its ease of attachment. However; due to the concern of the turtle's acceptance the jacket design was abandoned. The second design was the glove design where the prosthetic flipper was fastened to an attachment glove. The prosthetic flipper was attached by a pushpin lock securement method. The positives to this design include customization and past success with pushpin lock designs. The third design was a loop and plate design that involved the prosthetic flipper riveted into a flat plate. With neoprene straps, the flat plate was looped over the limb and the straps were pulled tight. The positives of this design included its applicability to many different turtles with few modifications. The fourth option was the vacuum design which involved dual sleeves and a one-way valve that used a vacuum suction to attach the prosthetic flipper. The positives to this design included the flipper being customizable to the turtle's stump, however; one concern is the one-way valve did not react well with seawater and the depths of the ocean. [8]

After coming up with the prototypes for all the prosthetic flipper designs, the project team sent them to the aquarium to get tested. The loop and plate design worked great, however; a major complaint was the flipper's weight and length. The aquarium staff also did not find the prosthesis easy to attach. The shuttle lock design worked well, however; much like the loop and plate design the prosthetic flipper was too long and heavy. This caused problems for the turtle to move in the water. The aquarium staff did not have any problems attaching the flipper to the turtle's stump. After receiving feedback from the aquarium, the project team adjusted the material and the attachment method. With a lighter material and the lock design, the flipper was easier to use in the water and the aquarium was able to attach the flipper with ease. [8]

The project group decided to use a material called Feather Lite, which had a much lower density than the Smooth Cast 325 which was the material they had used in their first trial. The Feather Lite proved to maintain a suitable durability, while being lighter and easier to use. [8]

2.7 Rocky the Sea Turtle

The Key West Aquarium in Florida is home to many different aquatic animals. One of their main exhibits features sea turtles that they have rescued from the wild, all experiencing various unique situations that could be harmful to their health or lifestyle. One of the turtles in this exhibit is a green sea turtle named Rocky. Rocky is missing his front right flipper after being injured in a boating accident. He has a difficult time swimming in a direct path because of this injury, often leaving him to make circles with his motion. Rocky also suffers from a buoyancy disorder, which the aquarium describes as his "floating" problem. Rocky's right back side sticks, or floats, out of the water, making it difficult for him to comfortably swim, to come up to the surface of the water to breathe, and to dive correctly and easily. Currently, the aquarium is attaching weights to Rocky's backside and a float to his front left side, for him to swim properly, however; they and the rest of the sea turtle community is hoping to find a better solution to this problem. The Key West Aquarium has asked for help in both creating a prosthetic flipper and a new device to combat floating so that Rocky can swim freely within his tank.

Chapter 3: Methodology

3.1 Flipper Procedure

To create a prosthetic flipper for Rocky the sea turtle, we had to take the steps outlined in this chapter. These steps were also recorded in a pamphlet (Appendix A) that will be made available for people looking to do similar work in the future.

3.1.1 Step 1: Modifying CAD model

Using previous CAD designs, a modified prototype was designed to be 3D printed. The previous flipper was designed for a sea kemp turtle. This type of turtle is significantly smaller than a green sea turtle like Rocky. To account for this, a scale was used to properly adjust the size of the new flipper. Using dimensions given for Rocky and the dimensions previously used, a general scale of the width and length was determined. This scale was determined to be 8:13. This was used in the scaling feature in SolidWorks. The final product was a 3D flipper fit for Rocky's flipper. Once designed, the flipper was printed and used to make a mold for the final prosthetic. Below are the steps that were taken.

1. Measurements were taken of the healthy flipper.
 - a. Length, Width, and Thickness.
2. The flipper was scaled to match the measurements of the healthy flipper, using a previous CAD file.
3. Noted the volume of the flipper (in CAD) to get an estimate on how much material would be needed
4. The new flipper in CAD was 3D printed. The file was sent in two parts because of the printer's dimension abilities. The parts were then glued together to make the full flipper.

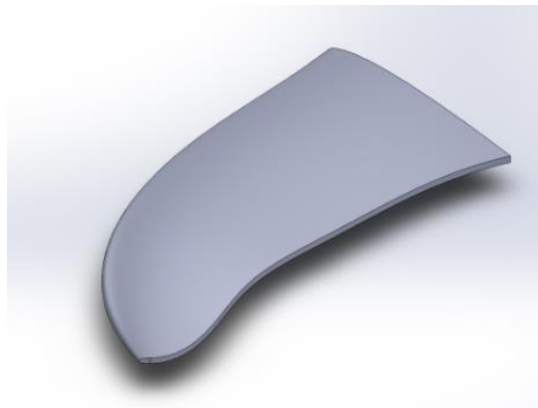


Figure 2. CAD model of the prosthetic flipper

3.1.2 Step 2: Making Mold

The materials used for the flipper and the mold were purchased from Smooth-On, a molding and prosthetics company. Below are the steps to make the mold.

1. A container was created to make the mold in. It is recommended wood be used for this box even though sheet metal was used in this project. A wooden box can be easily taken apart and reused if needed.
 - a. Each dimension was two inches larger than the greatest dimensions of the flipper (flipper dimension = 13x7x2 in. -> Box dimension = 15x9x4 in.)
2. Once the container was made, the 3D printed flipper and inside of the container were coated with a release spray, Universal Mold Release, from SmoothOn. This release spray helped remove the mold and flipper. This was left to dry for a day.
3. Next, materials used to make the green mold of the 3D printed flipper were prepared.
4. Using Mold Star 15 SLOW, the two materials used for the mold of the flipper were mixed.
 - a. This was a 1A:1B by volume ratio.
5. The Mold Star Mixture was poured into the container around the flipper.
 - a. The tip of the flipper was placed at the bottom of the box, and the wider, medial end of the flipper at the top
 - b. The flipper began to float and move. It was held in place until the silicone mixture completely surrounded the 3D flipper
 - c. A piece of sheet metal was placed on top of the container as a cap to keep the flipper in place once the mixture had completely surrounded the flipper.
6. After 24 hours, the mold was removed from the container.
7. To remove the flipper, the mold was cut down the middle
 - a. This cut was glued tightly after, so the mold could be used to make the prosthetic.

3.1.3 Step 3: Making flipper prosthetic

The materials used for making the flipper were also purchased from Smooth-On, a molding and prosthetics company.

1. The inside of the mold was sprayed thoroughly, multiple times, letting it sit for at least 24 hours
2. The material Smooth-Sil 950 was mixed.
 - a. Part A was poured into a small container.
 - b. Part B was poured into the container in a ratio of 10:100 to part A.
 - c. The mixture was stirred thoroughly.
3. The mixture was then poured into the mold, until it was filled to the top.
4. After waiting 24 hours, the flipper was cut out of the mold.

3.1.4 Step 4: Designing Flipper Attachment

During this step, the team had to test many different approaches to generate a model of Rocky's remaining stump. In the past, teams have used CT scans converted to CAD models, however; due to an unforeseen hurricane, the facilities at the Key West Aquarium were unable to produce a CT scan of Rocky.

The aquarium sent 2D pictures from specific angles and the team converted them into a 3D model. To do this, the files were imported into SolidWorks and traced onto different planes. The sketches were then blended together. The team found that this model was not very accurate, and because of the friction between the sleeve and Rocky's remaining stump, the team felt this model would not be worth moving forward with.

Next, the aquarium was able to create a mold of Rocky's stump, with Luna Bean molding material. The students did not receive the mold with enough time to completely build the attachment piece before the completion of the project.

The final attachment piece is in the process of being built in collaboration with Hanger Prosthetics in Orlando, Florida. The team was in contact with Hanger and the aquarium to plan a future for the project. Hanger Prosthetics is currently working on creating an attachment piece based off the mold of the residual limb to connect the flipper, made by the project team, to Rocky.

3.2 Buoyancy Device Procedure

Section 3.2.1 Preliminary Designs

To successfully design a buoyancy compensation device for Rocky, we first had to brainstorm multiple preliminary designs and analyze their strengths and weaknesses. Along with our own analysis, we looked to the Key West aquarium staff for their suggestions. The staff will deal with the device every day and they have the best understanding of how Rocky will respond to and live with the different devices. We developed multiple designs before picking the final.

First, after some collaboration with a team working on a similar project in Minnesota, we thought about making a shell cover that could clip on underneath Rocky and allow for small weights to be added and removed based on his needs. The piece had two different options for attaching to the underneath backside of the shell. The first was through a hinge mechanism, which would distribute the pressure on Rocky's shell. The second attachment was smaller and hooked on between the two hind flippers. This allowed the attachment to be one piece. After receiving feedback from the aquarium on their concern in attaching the piece to Rocky, and the possibility of it collecting unwanted materials from the water, we decided to not move forward with this design.

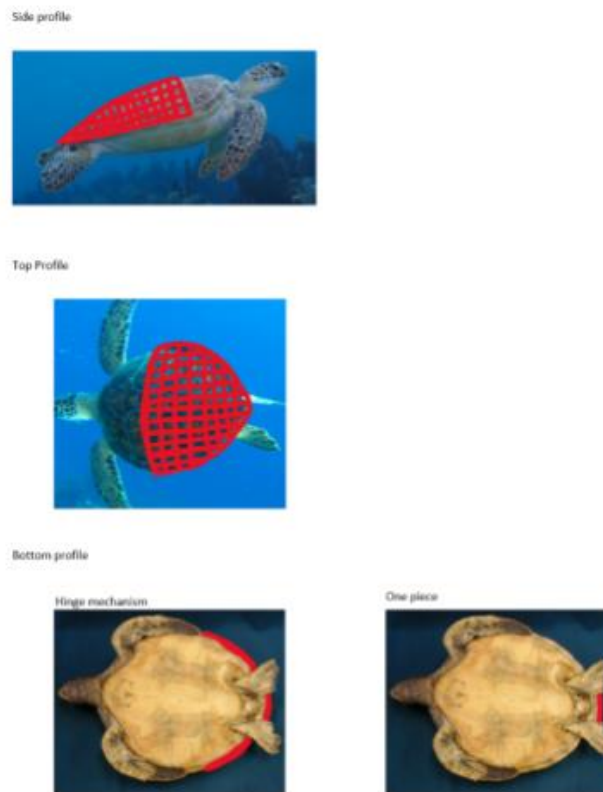


Figure 3. Preliminary Design Idea 1

Second, we had a design that resembled a pool noodle. It would only be placed on the back-right side of the shell of Rocky, since that is the portion that floats above the water. It would have been specifically designed for Rocky's shape and the exact weight that he needs to swim normally. It would have attached using magnets. This design wasn't rejected by the aquarium, however; they preferred other design ideas.

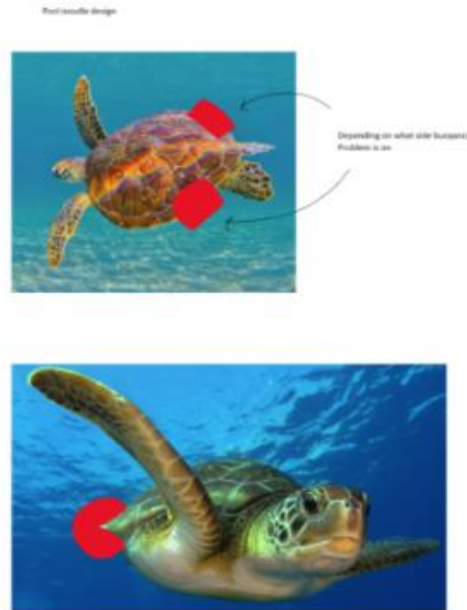


Figure 4. Preliminary Design Idea 2

Third, we presented a design that would be made from a stretchy material. It would be easy to manufacture and could be adjusted for other sea turtles. The design would be a strap across Rocky's shell and would be weighted more heavily on his back-right side. This design would be attached using magnets as well, so that it could be removed relatively easily. This design was received best by the aquarium, and they offered suggestions on pieces to add and materials to consider.



Figure 5. Preliminary Design Idea 3

The final design is a modified version of our third preliminary design. It uses a neoprene sheeted material that will stretch over Rocky's back, held down by magnets. The neoprene will contain pockets so that the weights can be adjusted depending on how much Rocky needs. The specific measurements and logistics of this design is shown below.

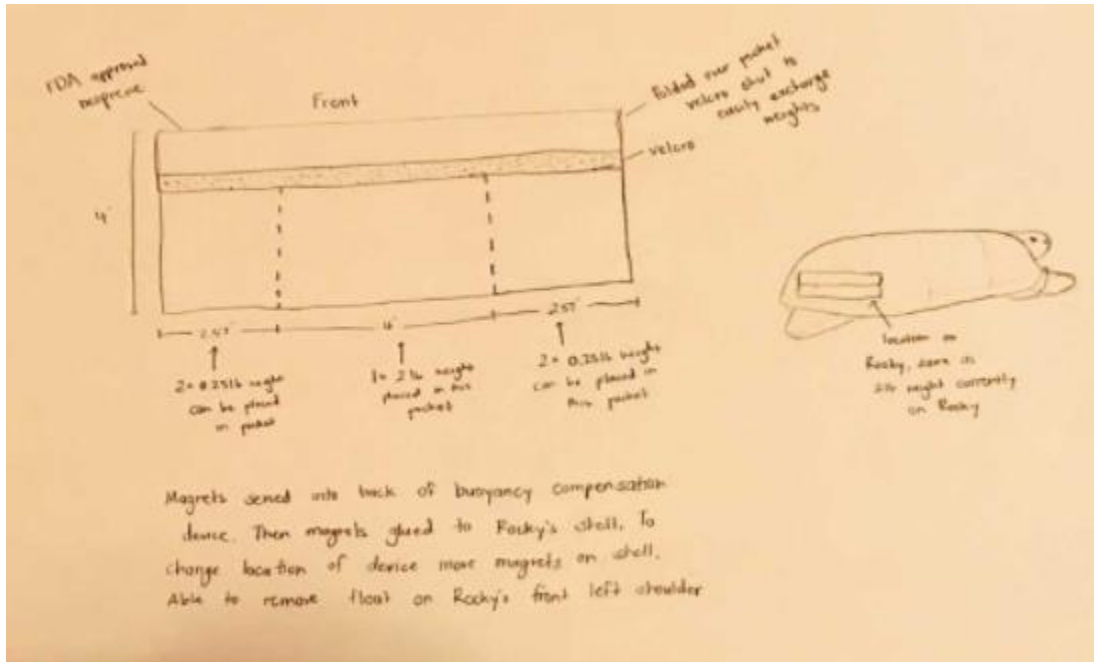


Figure 6. Final Design

Section 3.2.2 Selecting and Testing Material

We selected an FDA approved neoprene material, because of its use in wetsuits for scuba divers. This proves its ability to withstand salt water and other things that may be found in the ocean. We ordered a large sheet of this material and tested it. To test it we created a salt water solution and submerged the material in it. Letting the material soak in the water, we observed the changes that took place. We then removed the material from the water and again, observed changes. The material was then left to dry and observed again. Minimal changes were recorded, and the material was found to be effective in salt water.

Section 3.3.3 Calculations for Weight

To calculate the weight needed to rectify Rocky's buoyancy disorder we estimated the volume of Rocky and the approximate locations of his center of mass. To estimate the volume of Rocky, the aquarium took two dimensional scaled pictures on 3 planes, then we meshed those pictures into a 3-dimensional model of Rocky's carapace and used that CAD model to obtain an approximate volume of his shell. Calculations were performed to find the weight that needed to

be added to Rocky and the distance at which it should be placed. These calculations with our approximations is shown in figure 7.

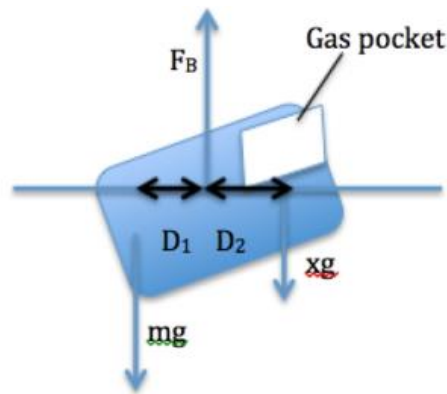


Figure 7. Free Body Diagram of Rocky

F_b = buoyancy force
 mg = weight force of turtle
 xg = weight force of added weights
 Neglect F_{gas}
 $m = 45.3592 \text{ kg}$
 $V_{submerged} = \frac{7}{8}(V_{shell})$
 $V_{shell} = 0.05157193 \text{ m}^3$
 $D_1 = 0.005 \text{ m}$
 $F_b = mg + xg$
 $F_b = \rho_{sw} * g * V_{submerged}$
 $F_b = (1.03 * 10^3 \frac{\text{kg}}{\text{m}^3})(0.0441441 \text{ m}^3)(9.81 \frac{\text{m}}{\text{s}^2})$
 $F_b = 455.961\text{N}$
 $455.961\text{N} = (45.3592 \text{ kg})(9.81 \frac{\text{m}}{\text{s}^2}) + (x)(9.81 \frac{\text{m}}{\text{s}^2})$
 $x = 1.12 \text{ kg}$
 $\tau = 0$
 $mg * D_1 = x * D_2$
 $(45.359\text{kg})(0.005\text{m}) = (1.12 \text{ kg})(D_2)$
 $D_2 = 0.2145\text{m}$

Section 3.3.4 Making the Device

An FDA approved neoprene material was used to make the buoyancy compensation device, following the design approved by the aquarium. The material performed satisfactorily in salt water. The material was cut using a shearing machine to 12 x 12 inches. The material was then folded in half and sewed using a speedy stitcher sewing awl. Velcro was placed across the top of the material to secure the weights in the pockets. This will allow the 2 lb. weight along with the .25 lb. weights to be adjusted, based on the performance of the buoyancy compensation device and the changing location of Rocky's buoyancy disorder.

Chapter 4: Results and Discussion

4.1 Flipper

When trying to manufacture the flipper, the team ran into many problems. The first challenge was that Rocky was much larger than the previous sea turtles that prosthetics have been made for. Rocky's large size made the molding process difficult, however; it was still possible and successfully completed. The team also faced many challenges when creating the attachment piece, which attaches the prosthetic flipper to the sea turtle's remaining stump. Previous groups who have successfully made an attachment piece designed it using a CT scan of the turtle. Due to an unforeseen hurricane that affected the aquarium's facilities, the team could not get CT scans of Rocky. Many attempts were made to find a new way to produce an attachment design.



Figure 8. Final Flipper

The team tried to convert 2D pictures into a 3D model, using SolidWorks. This method did not work due to a lack of precision. Without knowing the exact curves of Rocky's remaining stump there would be too little friction between the stump and the attachment piece. The next method attempted was making a mold of Rocky's remaining stump and using that model to create an attachment piece that would perfectly fit over the stump. This method is recommended by the team; however. Due to time restrictions, the team could not take these molds themselves, or use the molds to make an attachment piece. The team scheduled a meeting between Hanger Prosthetics of Orlando and the Key West aquarium to take the molds. Hanger Prosthetics has

agreed to use the molds to continue the project and create an attachment piece to connect the project team's flipper to Rocky's remaining stump.



Figure 9. Staff from Hanger Prosthetics and the Key West Aquarium molding Rocky's remaining stump.

During this project the team discovered that it is possible to build a prosthetic flipper from data that can be gathered by any aquarium staff, however; the quality of the prosthetic is much lower than one made using industrial grade equipment such as an MRI machine, and 3-D printer.

4.2 Buoyancy Device

The final buoyancy compensation device is a neoprene sleeve that allows weights to be dispersed and interchanged depending on where the gas is located at the time. This design was chosen because the weights can be easily changed and shifted as needed. The device itself weighs one pound when no weights are inserted. The maximum capacity is three and a half pounds, so the max weight is four and half pounds. This provides a large enough weight range to allow for changes in the amount of gas trapped. The team provided the aquarium with 8 quarter-pound weights and one two-pound weight.

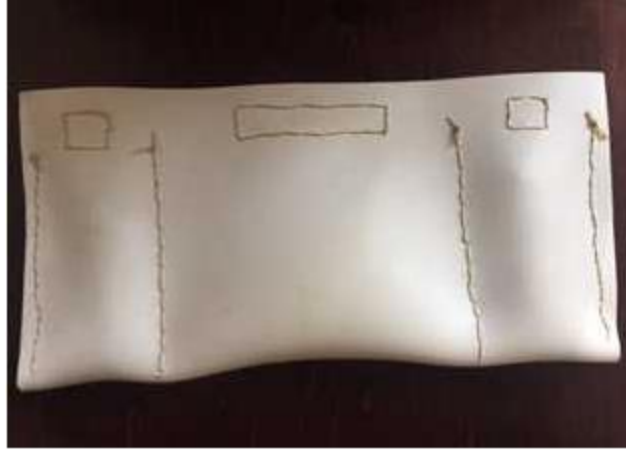


Figure 10. Final Buoyancy Compensation Device

The team was challenged when trying to find suitable weights for the device as well as finding a method to sew the fabric together to create the pockets. These problems were solved by finding weights used in aquatic aerobics and utilizing the speedy stitcher sewing awl. Using these methods, the design can easily be replicated should another device be needed. The device will be attached to Rocky's shell using cement putty. This is the method currently used by the aquarium and the buoyancy device in place. The putty is semi-permanent, so the device can be removed if needed.

4.3 Generalized Process

One of the goals of this project was to create a generalized process for creating a prosthetic flipper for a sea turtle. To do this, the team recorded pictures and videos and documented the steps they took in creating the flipper. The steps along with pictures were then recorded in a pamphlet which can be found in Appendix A. An instructional video was also created to aid anyone who is interested in manufacturing a prosthetic flipper for a sea turtle. This video can be found on YouTube (<https://youtu.be/25Wq7NdLGJk>). The team suggests that as of now, the best way to attach the prosthetic is through commercial products that can be either donated or purchased through a prosthetic company.

Chapter 5: Conclusion

The goal of this project was to manufacture a prosthetic flipper and a buoyancy compensation device for a green sea turtle at the Key West Aquarium, along with generalize the process for building a prosthetic flipper for a sea turtle. During this project the team discovered that it is possible to build a prosthetic flipper from data that can be gathered by any aquarium staff, however; the quality of the prosthetic is much lower than one made using industrial grade equipment such as an MRI machine, and 3-D printer. This project also produced the physical deliverables of a prosthetic flipper and buoyancy compensation device, to be tested and assembled by Hanger Prosthetics.

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Appendix A - Pamphlet Contents

Goal

The purpose of this booklet is to provide an easy to follow, step-by-step procedure to produce a prosthetic flipper for a sea turtle amputee. This is a recommended method used for a Capstone project at Worcester Polytechnic Institute. There are suggestions throughout, but the user is free to adjust the procedure if needed.



Figure 1: Lola, the ridley sea turtle, swimming with her custom fit prosthetic flipper.

Flipper Preparation

1. Get measurements of the healthy flipper.
 - a. Length, Width, and Thickness.
2. With attached CAD file (SolidWorks), scale flipper to match the measurements of the healthy flipper.
 - a. This is done through the scaling function in SolidWorks.
 - b. For this particular flipper, the scale was 8:13 inches because this is ratio of the previous turtle's flipper size to the turtle currently in need of a prosthetic.
3. Look at the volume of the flipper (in CAD file) to get an estimate on how much material you will need.
4. 3D print CAD model of new flipper. File may have to be sent in two parts depending on the dimension abilities of the 3D printer. If the file is printed in two pieces, glue them together to create a full flipper.
5. Order material (all materials listed on Materials page)
 - a. Smooth-Sil 950
 - b. Mold Star Platinum Cure Silicone Rubber (Part B)
6. Find a container large enough for the flipper to stand upright with sufficient space around the flipper (recommended 1-2 inches on each side). If no container is available, build a wooden box to make a mold for the flipper*.
 - a. The box should be made to be two inches bigger than each dimension of the flipper

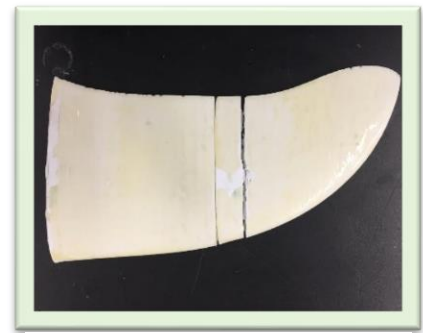


Figure 2: 3D printed flipper. Printed in 2 pieces that must be glued together.



Figure 3: Metal box created to make mold of 3D flipper in.

**Step 6 is a recommended method. When making our mold, we welded sheet metal to make a box. We reviewed our process and found that a wooden box would be more convenient. This is because it can be screwed together and easily taken apart to release the mold. This makes it reusable if another mold is needed.*

Making the Flipper

1. First the outer mold is made using the Mold Star 15 Slow series. Follow the instructions written on the material container to create the silicone mixture.
 - a. The instructions will tell what ratio of each material should be mixed.
 - b. For this mold, the ratio is 1A:1B by volume

2. Pour the silicone mixture into the wooden box around the 3D printed flipper.
 - a. Have the tip of the flipper at the bottom of the box, and the wider, medial end of the flipper at the top
 - b. The flipper will begin to float and move as the mold mixture is added. Be sure to hold the flipper in place until the silicone mixture surrounds the 3D flipper



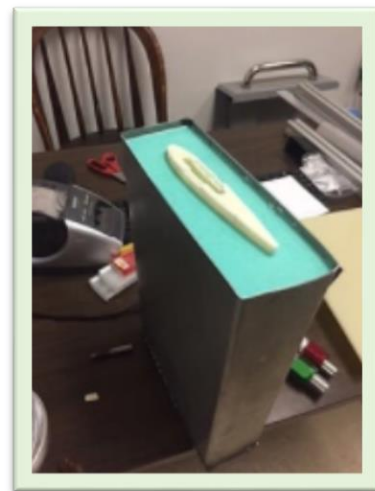
Figure 4: Holding the 3D printed flipper in place while the mold mixture is poured around the flipper.

3. Once the box is full and the flipper is completely covered besides the very top, cover the box with a lid.
 - a. This step is done so the end of the flipper is seen at the surface of the mold but does not float too far out of the box, changing the flippers position in the box.



Figure 5 (Left): Covered box to keep flipper in place and weighted down to prevent floating.

Figure 6 (Right): How the flipper should look once the mold hardens. Approximately 1/2 inch should be showing.



4. After 24 hours, remove the mold from the container. Then remove the 3D flipper from the mold*.
 - a. Depending on the size of your flipper, the mold may have to be cut open to remove the 3D model. If this is the case, make a straight cut down the side of the mold. Once the flipper is removed, glue the mold back together using superglue.
 - b. Spray the inside of the mold with SmoothOn Universal Mold Release (price and information in materials section of pamphlet). Let the spray dry for at least 24 hours.

**We recommend the mold be sprayed multiple times over the course of 3-4 days. This will make the removal of the prosthetic flipper significantly easier.*

5. Next, the material for the new flipper is to be mixed using Smooth-Sil 950 (ordering information in materials section). Follow the written instructions on the material container to create the mixture.
 - a. This ratio is 100A:10B by weight.

6. Pour the mixture into the mold
7. Let this sit for at least 12 hours



Figure 7: Pouring the Smooth-Sil 950 into the mold



Figure 8: Final prosthetic flipper removed from mold.

8. Cut the mold so the final flipper can be removed
9. Sand down the flipper to ensure it has a smooth surface
10. Create 3D model of the remaining damaged fin using CT scans or casting

Products Used

SMOOTHON MOLD STAR 15 SLOW

Both A and B parts are included. Mixing ratios are explained in instructions. Used for mold of 3D printed flipper.

Price: \$185.05

Type: Gallon



<https://www.smooth-on.com/products/mold-star-15-slow/>

SMOOTHON SMOOTH-SIL 950

Both A and B parts are included. Mixing ratios are explained in instructions. Used for prosthetic flipper.

Price: \$138.94

Type: Gallon



<https://www.smooth-on.com/products/smooth-sil-950/>

SMOOTHON UNIVERSAL MOLD RELEASE

Spray used to release mold from container as well as to release new prosthetic from inside of mold.

Price: \$13.94

Type: 12 oz can



<https://www.smooth-on.com/products/universal-mold-release/>