Rowing Foot Stretcher Design

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Rowing Foot Stretcher Design

A Major Qualifying Project Report
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science
by
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Date: April 25, 2012

Approved:
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This report represents the work of WPI undergraduate students. It has been submitted to the faculty as evidence of completion of a degree requirement. WPI publishes these reports on its website without editorial or peer review.
Abstract

In crew racing shells, the foot stretcher attaches the shoes to the shell and provides a surface for the rower to push off. Significant advancements in rowing foot stretcher technology have not been made in several decades. The background research, collected from patents, rower input, and international safety requirements, identified several aspects of the foot stretcher that could be improved. A working design was developed and analyzed using solid modeling, axiomatic design, and finite element analysis. A prototype was then created and assembled for user testing. Testing was conducted using a modified ergometer and consisted of power workouts to ensure ergonomic and power requirements were met. Based on the results of testing 8 rowers and design analysis, this project’s design was found to make the rower more comfortable, regardless of gender, ability, and rower size. Furthermore, it improves the rower’s ability to adjust to their own physiology, without decreasing the performance of the foot stretcher and power output of the rower.
Executive Summary

Rowing is a sport that runs on precision, commitment, and is won by margins that are fractions of a second. A typical race is conducted on a 2000 meter course, where all competing shells start together and race to the end. In a sport where the smallest improvements can mean the difference between winning and losing, researchers and coaches alike have committed significant resources to finding ways to gain a competitive edge in the technology. Over the past 100 years, several advancements have been made in the oars used for rowing, the size and shape of the racing shells, and the riggers used to extend the pivot point of the oar away from the shell. However, little emphasis has been placed on developing improvements to the foot stretcher, the plate used by the rower as a push-off surface to connect his/her feet to the shell.

Without a significant advancement in foot stretcher technology in the past 100 years, there existed a strong opportunity for developing an advancement that would allow rowers to propel themselves more comfortably and effectively. Our project specifically targeted developing a foot stretcher that would be more ergonomic and comfortable for the rower, without reducing the power output. Making these improvements enables the rower to better reach a position appropriate for their physiology, which could ultimately lead to fractional improvements in performance coveted by coaches, athletes, and the rowing community at large.

Though making modifications to the rowing foot stretcher design may seem like a trivial process, significant background research, development, analysis, and testing was conducted to ensure that a new design met the needs of the rowing community. Initially, background research was conducted in three general areas. First, a patent search was conducted to gain a full reference perspective of current and former intellectual property in foot stretcher development. This research helped us both understand the limitations of our design development based on current intellectual property restrictions, and also learn from past development found in expired intellectual property. Next, we developed a questionnaire, which was given to over 50 rowers of different age, gender, and experience. The input given by these individuals provided us with a framework to understand the current market needs and desires for improving the foot stretcher design. Without this input, customer needs could have been overlooked or not addressed properly. Finally, a literature review was conducted on the biomechanics of rowing. The
purpose of this review was to fully understand the types, magnitudes, and directions of the forces experienced while rowing. This research and data were pivotal to defining the design requirements for the foot stretcher.

Once the background research was completed and a framework was developed, which identified areas of the foot stretcher that could be improved, we were able to create several preliminary designs. All of these designs were developed to address some, or all of the issues identified by our research. However, these designs varied drastically in approach, style, and effectiveness. As a result, we developed a system to evaluate and synthesize the preliminary designs to create an optimal design to carry through into full development. This system used a matrix that was based on weighted values, evaluating each design on safety, rower comfort, adjustability, foot stretcher performance, and rower performance.

Once we completed the design matrix and evaluated our preliminary designs, we were able to move forward into full development. At the beginning of full development, a process called axiomatic design was used to evaluate our functional requirements and design parameters. Using this process enabled an optimized decoupled development process, thus producing a design with very few design induced limitations. With a completed axiomatic design, we then developed a full scale model of our design using a solid modeling package. Our model utilized materials that were selected based on ease of manufacturing, cost, and functionality. This model was then used to analyze and prototype the design.

Analysis of the design was conducted to evaluate the design model against the design requirements and specifications. These analyses included evaluating the strength, geometrical form, and fit of the parts. Based on the results of this analysis, improvements were made to the model to ensure that the prototype of the design would meet all functional requirements. With these improvements made, a working prototype was built using Haas CNC machines. The prototype enabled us to conduct user testing and collect data to ensure that the design met the goals of comfort, adjustability, rower performance, and foot stretcher performance.

The testing was conducted on land, utilizing/expanding on the capabilities of an ergometer. This controlled system provided a device with which to collect data on the power output of rowers using the foot stretcher prototype relative to a current WinTech foot stretcher.
Our study, which was approved by Worcester Polytechnic Institute’s Institutional Review Board, tested 8 subjects, 4 male and 4 female rowers, in a power workout. Each subject performed the same power workout with each foot stretcher. Data from the testing were collected through two methods. First, performance based data were collected from the ergometer. Second, comfort and adjustability data were collected through a questionnaire given to the subjects upon completion of the testing. This questionnaire targeted the rower’s opinion on their experience using the foot stretcher, particularly in comparison to designs currently on the market.

To analyze the performance data, we chose to use a Wilcoxon T-Test. We chose to use this test because we cannot assume that our data are normally distributed. As a result, we needed to use a non-parametric form of statistical modeling. Based on our testing data, we are 95% confident that there is no decrease in power between rowers using our prototype and the WinTech foot stretcher. Furthermore, we received feedback that the ability to freely move the splay of the device was more accommodating to both male and female rowers. Rowers also felt that the added splay movement would help them to achieve a greater angle in swept boats, meaning that the rower could increase the length of the arc that the oar travels in the water. It is hoped that this greater length would increase the power that the rower is able to generate in a boat, however more testing is necessary to prove or disprove this concept.

The prototype we developed provides much more adjustability for the rower than that of a traditional foot stretcher. However, it was absolutely crucial that these adjustments did not sacrifice the power of the rower. The goal is that adding more adjustability will increase the performance/power output of the rower. However, before this prototype can be a fully functional product on the market, additional testing will need to be conducted to determine more specific effects of the design’s adjustments on the rower.
Acknowledgements

The successful completion of this project would not have been possible without the generous support we received from several individuals. First and foremost, we would like to acknowledge our advisors, Professors Ault and Hoffman, for the countless hours they spent advising and reviewing every aspect of our project. We would like to thank Alex Segala, Adam Sears, and James Loiselle for their help in machining the prototype. Next, we would like to thank the WPI Men’s Crew head coach, Larry Noble, for providing access to test subjects, as well as the equipment necessary to complete the testing. Also, the completion of our testing would not have been possible without test subjects volunteering. We would like to thank all 8 subjects for their contribution to this project. Finally, we would like to thank the Mechanical Engineering Department for providing the equipment necessary to prototype the design, as well as administrative support throughout several aspects of our project.
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1. Introduction

Rowing is a sport with longstanding tradition and heritage. The sport began as a means of transport for goods and warfare. Racing competitions can be traced back as early as the 13th century in Venice. The sport evolved to include competitive events at both the amateur and Olympic levels. Some collegiate rowing clubs began in the late 18th century. In the early 19th century, Cambridge and Oxford Universities raced each other. This race has become widely known as The Boat Race and remains one of the most prestigious collegiate sporting events in the world. For centuries, the sport of rowing has provided entertainment to many. The milliseconds that separate winning from losing continue to provide awe and amazement. Changes to equipment that provide fractions of a percent improvement can prove to be vital in winning a race. Much of this equipment is developed around the physiology of the rowers to ensure their power output is optimized.

Several minor variations of the rowing technique exist worldwide. However, the basic concept of rowing remains fairly constant. The goal of rowing is to propel the boat through the water faster than the competition. The way of doing this is to use one’s legs to press their full weight against the oar handle. This, in turn, pulls the oar handle towards the rower and the boat moves forward as the end of the blade is anchored in the water. This is contrary to the belief that the oarsman pulls his oar through the water. In order for this to happen efficiently, several systems are used. These systems are the boat hull, the rower, foot stretcher, oar, and rigger. The power of the rower can be seen in stages by measuring the angular velocity of the rower’s hip, knee, and ankle throughout the stroke. The typical result shows that more power can be applied in the latter half of the stroke, when the boat is moving its fastest. The rowing system is designed primarily to facilitate power transfer. When considering the foot stretcher, it must have the most direct power transfer possible. This means that the deflection of the foot stretcher must be near zero, and any other losses need to be negated. Also, the foot stretcher must allow the rower to position him- or herself in such a way that he/she is in the most powerful position possible, based on their physiology, and must allow the rower to apply the force in such a manner that the maximum percentage of the force applied is being used to propel the boat forward. The direction of these forces would be longitudinally along the keel of the boat towards the stern of the boat.
The current foot stretcher design works well at a very basic level. It provides a surface for the rower to apply power to the stroke, with relatively minimal loss. However, the current foot stretcher has cumbersome adjustments that tend to lose their positioning while rowing. This means that the current device does not enable the rower to realize a comfortable, powerful position that is optimal for their body physiology. The shoes used on current foot stretchers also have limitations in ergonomics and support that lead to the loss of the rower’s stability and power output. Furthermore, the current foot stretcher positions the rower such that a significant portion of the force is directed downward at the beginning of the stroke. This can slow the boat down by increasing the drag force on the hull of the boat.

When 60 rowers of various experience levels were asked about the current foot stretcher design, it was found that 79% have had problems with foot stretcher adjustments. The issues experienced ranged from the inability to make minor adjustments to the foot stretcher to the fit and design of the shoes, and the time it takes to make the required adjustments. Even more staggering was that 91% have experienced a malfunctioning foot stretcher. These rowers have had issues with corrosion, foot stretcher breakage, and holding adjustments. Overall, more than half of the rowers surveyed felt that the current foot stretchers are in immediate need of improvement.

Based on rower feedback and industry research, a need for an improved foot stretcher design was identified. The market research was very successful in identifying several areas of the rower interface in need of innovation. However, for the scope of the project, a few key issues were emphasized. This project addresses improving the foot stretcher by increasing granularity in horizontal and vertical shoe adjustment, as well as enabling movement in the rower’s splay. These changes help to ensure an improvement in overall ergonomics and adjustment, without a decrease in performance.
2. Background

In the initial stage of the project, data and information were collected that would help improve the foot stretcher. Particularly close attention was paid to the biomechanics of the rowing stroke and the physiology of the rower. Research was also conducted on current designs as well as historical patents on foot stretchers. This provided some benchmarks to expand and improve upon. It also showed some designs and ideas that had been tried, with or without success.

2.1. Biomechanics/Physiology of Rowing

Rowing is a sport in which many muscle groups are utilized to produce an efficient, powerful stroke. At the most basic level, the concept of rowing is to put the blade in the water and drive with the legs while suspending the weight across the back. For this to happen, the rowing system must transfer all forces input by the rower through the oar and into the water to effectively move the boat in a forward direction.

First, let’s consider the forces acting on the boat. These forces are represented below in Figure 1. In this diagram, the direction of motion is in the negative x-direction, the drag force is $F_D$, the force of the boat on the water is $F_{G1}$, the force of the blades are $F_{B1}$ and $F_{B2}$, and the buoyant force of the water on the boat is $F_{BU}$. (Baudouin et al, 2002). For a typical racing shell, the force acting against the lateral movement of the boat is a drag force. This drag force can be broken up into two forces, the drag force of the air and the drag force of the water. Since water is much denser than air, about 90% of the drag force on the boat comes from the water. The boat

![Figure 1: Force Diagram of a Racing Shell (Baudouin et al, 2002).](image-url)
is supported upwards by the buoyant force of the water. Since the buoyant force of the water is a function of the density of the fluid displaced, the force of gravity, and the volume of fluid displaced (with the force of gravity and the density of the fluid being constant in this case), the hull of the boat will be pushed lower into the water by an instantaneous increase in the force in the negative Z-direction, increasing the buoyant force. Since the majority of the drag on the boat is caused by the water, an increase in the force in the negative Z-direction will increase the drag force on the boat.

Several groups, organizations, and institutions have done research on rowing and the directional forces that occur during a stroke, including works done by Découfour, Bettinelli, and Baca. In one of these studies, a force plate was attached to the foot plate of an ergometer (land rowing machine) and elite athletes were asked to take a few strokes. The results show that when the stroke begins (the rower is at the “catch”) the Z-direction force has a larger magnitude than the X-direction (Découfour). This can be seen in Figure 2 above. This figure shows the forces at three directions (M/L, A/P, and V) and at two stroke ratings (18 and 40). The M/L force is the Medial Lateral force and is in the y direction, the A/P force is the anterior/posterior force and is in the x direction, and the V force is the vertical force and is in the Z direction. In this study a force in the negative z direction was taken to be positive. It can be seen that, at the beginning of the stroke, V-40 is higher than all of the other force components measured. Then throughout the course of the stroke, the force in the x-direction begins to have a larger magnitude. However, the large vertical force found at the catch will increase the drag on the boat. A new design of the foot plate could consider ways to decrease the downward force felt at the beginning of the stroke.
The graph shows six different trends. The trends are based on a rower rowing at either 18 strokes per minute or 40 strokes per minute. At these two rates, data are recorded for the foot stretcher forces over phase when the rower just started the stroke (Vertical), halfway through the stroke (Anterior/Posterior), and at the end of the stroke.

The next, and most involved, groups of forces to consider are the forces acting on, and caused by, the rowing system. In the rowing system there are four components: the oar, the rigger, the rower, and the foot stretcher. The foot stretcher provides an equal and opposite force to that given by the rower. The foot stretcher is designed to remain stationary when a force is applied to it, thus transferring any and all forces directly to the hull of the boat. The rower generates force (applied to the foot plate) by using the water as a fulcrum. Figure 3 is a top view and represents the forces on the oar. Assuming a perfect stroke, the force of the rower pulling the handle \((F_h)\) is transferred to the force the blade applies to the water \((F_b)\). This force is transferred by the oarlock \((F_o)\) acting as a fulcrum. The oarlock rotates such that it remains perpendicular with the oar itself. Furthermore, in a perfect stroke, the oar does not slip in the water, causing the boat to be pulled past a fixed point in the water. Assuming there is no loss in force transfer across the rower’s back, the force applied by the legs and body is exactly equal to

Figure 2: Foot stretcher forces throughout the stroke. (Découflé et al, 2011)
the force on the oar handle.

Figure 3: Force Diagram of a Sweep Oar (Baudouin, 2002).
Figure 4: The rowing stroke (in reverse order). Pictures 10-7 represent the drive, 6 the finish, 4-2 the recovery, and 1 the catch. (Coachsci, 2011).

The drive in rowing is predominantly powered by the legs. In the movement of the leg, three points are considered: the hip, the knee, and the ankle. Research has been conducted on the
angular velocities of each of the joints. Figure 5 (below) graphs a rower’s angular velocity (top line), as well as power moment (bottom line), at the hip, knee, and ankle. In this figure, the horizontal lines represent a recorded value of 0, or neutral, at that given point in time. Above these lines indicates that the joint is in extension and below the line represents the joint in flexion. (D. Gordon)

The angular velocity of the hip is nearly zero for the first half of the stroke, then in the second half the angular velocity increases until it peaks right before the release, which is the completion of the stroke. This is consistent with typical rowing where the back does not pivot until about halfway through the stroke. The first half of the stroke is typically all leg drive, with the back and hips transferring the power to the handle of the oar. This can be seen with the angular velocity of the knee during the stroke. The angular velocity was found to increase throughout the initial 75% of the drive. As the boat moves faster through the drive, the rower must accelerate the oar to apply the same power throughout the stroke (at a minimum) thus causing an increase in the angular velocity of the knee. When the angular velocity of the knee is increased, the angular velocity of the oar increases, which is due to the force transfer across the rower’s back. The ankle was found to have the least amount of angular velocity. The angular velocity remained constant through the second half of the drive. This models the motion of the rower. In this phase, the rower starts at the catch with the ankle in dorsiflexion and the ball of the foot on the foot stretcher. As the rower takes a stroke, the ankle comes out of dorsiflexion and reaches a neutral position, with the foot flat on the foot stretcher.

The results also found that the majority of the power in the stroke was generated from the hip and knee. Furthermore, the peak of the power correlates to the peak in angular velocity of the two joints. This is not surprising since it becomes easier to generate more power towards the end of the stroke. This is because the boat picks up speed throughout the stroke, which allows the rower to pull harder (increasing force in the X-direction) without breaking the surface of the water. The result is an increase in power throughout the stroke; though the angular velocity curves may be slightly different, the peak power application for both hip and knee joints occurs at about 70% of the drive phase.
Figure 4. Hip angular velocity, moment of force and power) male rower.

Figure 5. Knee angular velocity, moment of force and power) male rower.

Figure 6. Ankle angular velocity, moment of force and power) male rower.
2.2. Current Foot Stretcher Design

The foot stretcher is a vital part of the rowing experience. The rower only has two direct contacts between him or herself and the boat, the sliding seat and the stationary foot stretcher. Because the seat has the ability to slide up and down the deck of the boat, the only fixed point of contact between the boat and the rower is the foot stretcher.

2.2.1. Function and form of foot stretchers

In a racing shell the individual’s feet are placed in shoes which are attached to the shell. The system that attaches the feet to the shell is called the foot stretcher. At the most basic principle, the foot stretcher’s only function is to provide a surface from which the rower can push through the drive of the stroke. In the beginning, the foot stretcher was simply a board to place one’s feet against. Through the years the stretcher has evolved to serve this function better.

Figure 6 shows a patent of a foot stretcher design that resulted from this evolution. The rower can attach shoes (60132) to this foot stretcher so that it is not simply a platform to apply one’s force, but will support and hold the feet in a semi-fixed position through the drive as well as the recovery. The rower can also adjust the position of this foot stretcher longitudinally along the boat’s hull to accommodate rowers of different heights and body proportions. The vertical distance from the heel of the foot to the top of the seat may also be adjusted by the movement of the shoe along the surface of the foot plate (60110) using the supplied holes. This allows rowers with different leg lengths and flexibility to gain the same angle between the torso and the water in the x-z plane at the catch.
Aside from translational movements of the whole foot stretcher or shoes, most modern foot stretchers have the ability to change the angle of the foot stretcher relative to the x-axis in the x-z plane. This allows for the accommodation of different rowers’ preferences of ankle angles while rowing. Recently some companies have started to put in a wedge that goes in under the toes, so as to get the rower to place more emphasis on finishing the drive with the use of the calves to press off on the balls of the feet. This motion allows another inch or two of total drive length on the rower’s end.

Rowing foot stretchers have been made out of many materials through the years. Wood was the first material, followed by metals such as coated steel, and aluminum. Recently, fiberglass and carbon fiber have been utilized in their construction to reduce weight. The current foot stretcher designs weigh approximately 2 to 2.5 pounds, including hardware and shoes. Hardware is mostly stainless steel, though on some cheaper models aluminum fasteners can be seen.

2.2.2. Advantages and Disadvantages to current designs

The current designs do a fairly good job at supporting the rower’s feet and providing a stable surface on which to apply ones force, however there is much room for improvement. The
current designs allow for the adjustment of the foot stretcher longitudinally along the keel of the boat using a track system (60911). This adjustment is cumbersome to perform and difficult to align correctly. A rower will often inadvertently adjust the foot stretchers in a manner such that the cross bar (60121) is not perpendicular to the x-axis. This adjustment is also difficult to make because the track system does not allow the sliding of the foot stretcher along the longitudinal axis of the boat in an easy and smooth manner. The adjustment is jagged and the foot stretcher bumps its way along the tracks. This difficulty of adjustment can sometimes prohibit a rower from squaring up his or her feet correctly, finding their proper adjustment, or even taking the time to change the position of the stretcher in the boat.

The current design does not facilitate the movement of the feet in and out in terms of foot width. In general the foot stretcher positions the shoes at a fixed width using screws. Some rowers may be more comfortable rowing when their feet are further apart, while others may be more comfortable with their feet closer together. Similarly, many of the current designs do not allow for the adjustment of the splay of the feet. Some people may prefer to row with their feet in a duck-footed position, while others may prefer their feet to be parallel.

One of the largest problems with the current design is the inability to quickly change the shoes of the foot stretcher to accommodate different rowers. As a result many rowers use shoes that are too small or large for them, which can have negative effects on rowing. Some foot stretchers do have the ability to change the shoes easily; however the attachment system of the shoes to the foot plate is mediocre at best and does not firmly secure the shoes. The ability to change shoes quickly and effectively would encourage rowers to use the correct sized shoes for themselves, as well as making on-water adjustments much faster and easier when rowers switch seats.

The adjustment of most foot stretchers is not as easy and efficient as it can be. Some adjustments such as changing the position of the stretcher longitudinally along the keel of the boat are fast due to the use of wing nuts, which can be adjusted without tools. However some adjustments require the use of a box wrench or place fasteners in locations that are difficult to reach. This causes the fine adjustment process to take too much time for coaches to allow during the seat racing process, so rowers will often be forced to row with a foot configuration, which is uncomfortable and limiting to them. Some companies have started to use cam style quick
fasteners to tighten their products; however, these systems have the problem of coming loose while rowing.

### 2.2.3. Patents and current designs

Patents on foot stretchers have been in existence since the late 1800s. One of the first patents for the improvement of the foot stretcher is patent number 412080 by E.J. Kerns in 1890. See Figure 7. This patent utilizes a hard soled shoe which has a pivot point (20) positioned on the bottom of the sole of the shoe and between the ball of the foot and the arch of the foot. The axis of rotation of this design is below the sole of the shoe. This may cause problems at the catch when the feet become raised to a higher point than they were at the finish, possible affecting the catch angle that the rower is able to achieve. In his patent the author specifies that the shoes shall be fixed so as to move as one. The author states that a spring (19) shall be utilized to return the feet to the catch position when not in use, or to aid with the shoe returning to that position as the rower travels up the recovery. This design tries to address several problems, but also creates other problems. While allowing the shoes to rotate, thus relieving ankle stress, the author specifies that the shoes be connected so that they rotate as one. This poses problems with the rower stabilizing the boat, as the independent movement of the feet, such as allowed in designs in use today, is vital to the set of the boat. The position of the pivot point will also raise the level of the feet relative to the top of the seat as the rower moves up the catch. This can cause problems with the rower reaching the catch if he or she is not flexible.
In this design point 10 is the pivot point of the foot stretcher. There is no spring in this device to return the feet to a home position; it is up to the rower to bring the feet to the correct angle as he/she rows. This design also has a device (19) to limit the angle through which the feet can rotate.

Point 20 shows a rotating clip while point 19 shows a spring that provides the shoe with tension. In this design, the rower’s feet will not be limited by a fixed angle on the foot stretcher, rather the angle of the foot stretcher will follow the rower’s feet throughout the stroke (Kerns, 1890).
A similar design was proposed in 1927 (Figure 8), which would allow the rotation of the foot about an axis (through the middle of crossbar 6) similar in location to Mr. Kern’s design. This positioning of the rotational axis has the same effect as Mr. Kerns’ design. Also like Mr. Kern’s idea, this design would restrict the movement of the feet such that they were forced to move as one, thereby limiting the ability of the rower to stabilize the boat. A design patented by W.B. Goodwin (Figure 9) utilizes a rotating footplate; however this design is primarily focused on altering the entire construction of the rower-shell interface than with the foot stretcher alone.

![Figure 9: Patent 710147 (Goodwin). In this design the rower’s feet are placed on a rocking foot plate so that they may follow the foot angle through the stroke.](image)

The Shimano Company has applied for a number of patents in the past few years. Patent application number 2009/0241827 (Figure 10) is similar to current foot stretchers except that the feet are attached to the footboard with a permanent magnet (102). This allows for the rower to quickly detach his feet from the foot stretcher and walk around the launching area. The foreseeable problem with this design is that the magnet may not be strong enough for a rower pulling him- or herself up the slide or for the forces seen when a crab is caught, and the feet may come detached while rowing. A crab is the event where ones oar becomes stuck in the water as the boat is moving forward. This causes the handle to be pushed into the chest of the rower, and can result in enough force to eject the rower from the shell of the boat.
Shimano’s next patent application, number 2010/0018450 (Figure 11), utilizes a cycling shoe style binding system to attach the shoe to the foot stretcher. This would allow the rower to wear his or her shoes around the launching area and simply clip them in as s/he was about to row. The shoes clip into part 26 in the patent, which is similar to the Shimano style cycling clipless pedal. This system would also allow the rower to use a hard shoe, which may or may not have positive effects on the rower. Another advantage to this design is that the pivot point of the shoe is placed at the ball of the foot but in a place that is at the top of the foot, as can be seen by the centerline in the patent drawing. This allows the rower’s foot to pivot about the axis and reach a lower position in the boat as s/he rows. As in their earlier patent, the feet are able to rotate independently of each other. Their next patent, 2010/0186658 (Figure 12), is simply a refinement of their previous designs and only adds more adjustability of the feet vertically in the boat.
Figure 11: Shimano Patent Application 2010/0018450

Figure 12: Shimano Patent Application 2010/0186658, further refining the patent seen in Figure 11.
Another system that is available to the rower is the Clicko system from Switzerland. This system utilizes a soft-soled shoe, unlike Shimano’s hard shoe, while still providing a binding attachment system between the shoe and the footplate (see Figure 13). With this system the rower uses a shoe that has a pocket in the bottom. This pocket encompasses a circular shaped disc (1) that fits into a binding system (2 in the top left photo of figure 11). This design is beneficial because it allows the rower to use his or her own fitted shoes for rowing without being forced to row in ill-fitting shoes. It also allows the rower to wear soft soled, rubber shoes around the launching area, hopefully preventing tripping and slipping accidents. One of the two issues visible with this shoe is that a force normal to the footplate but in the direction away from the footplate may cause the release of the shoes if said force is high enough to deform the components. If this were to happen in a race the results could be disastrous. The other issue with this design is if the rower was to walk through mud or other loose media the pocket could become clogged and would not be able to attach properly to the footplate. Or worse, the dirt and residue could prohibit the rower from releasing his or her feet from the footplate in case of an emergency.

![Figure 13: Clicko Shoe Connection System.](image)

In addition to these designs and existing patents, many of the current boat manufacturers have their own foot stretcher designs. These designs vary in complexity, adjustability, and
durability. The first design is shown in Figure 14. This design is the Intrepid X design, made by Resolute. This foot stretcher is one of the best designs on the market. Figure 14 shows that the foot stretcher has over 10 height adjustments for the top plate, as well as 4 height adjustments at the bottom of the plate. The adjustment at the bottom of the plate varies the overall perceived length of the board and, as a result, the angle the board makes relative to the hull deck. Both of these are smaller incremental adjustments than other foot stretchers on the market. As a result their customers pay a premium for their design. The replacement cost for this foot stretcher is $355.

![Figure 14: Resolute Intrepid X Foot Stretcher (Resolute Racing, 2011)](image)

The next foot stretcher design, which can be seen in figure 15, is the standard foot stretcher used by Wintech in their racing shells. The Wintech foot stretcher design is one of the least adjustable designs on the market. The top plate, when attached, provides only 5 different adjustments for the height of the top plate. Additionally, the lower mechanism provides only minimal perceived height adjustment as it is fixed and varies by less than an inch. It is very basic, and offers the rower a baseline fulfillment of the system requirements. This is reflected in their price point, which is $140 for a replacement foot stretcher.
Another popular boat manufacturer is Vespoli. Like the previous companies mentioned, they have their own particular foot stretcher design that they use in their boats (Figure 16). The Vespoli foot stretcher offers a moderate level of adjustment. The top plate, when attached, can adjust two to three increments. The bottom adjustment can adjust three increments to vary the perceived height of the board. The typical replacement cost for the Vespoli foot stretcher is $197.

As can be seen from these three leading designs, current foot stretchers vary in level of complexity and quality. However, based on the success of companies such as Resolute Racing,
rowers and coaches are willing to pay a premium for a product that is more ergonomic and can potentially provide better performance. When considering the goals and specifications of developing a new design it is important to consider the expected market price range. Many times in development standard cost becomes a limiting factor. Based on the data gathered from these three designs, it can be assumed that customers would be willing to pay up to a 10% premium over the current leading design for a superior product. This allows the standard cost for the design to be less than, or equal to, $150.
3. Detailed Description of the Project

Once research for the project had been completed through reviewing the biomechanics of rowing, the information was then used as a foundation to develop the design goals and specifications. These specifications served as a framework for the development of the project. As the project progressed, preliminary designs were created and evaluated using a weighted design matrix, axiomatic decomposition was used, and a 3D model was generated and analyzed.

3.1. Design Goals

The individuals’ rowing experience, using foot stretchers currently in the marketplace, is being hindered by uncomfortable positioning due to a rower-equipment interface that is not compatible to the widest spectrum of rowers. To better understand the problems that rowers face with the rower-equipment the project team conducted a survey in which rowers of various skill levels and ages were polled. The total number of participants was 60, of which 68% were male and 32% female. The majority of the participants were in their early 20s and late teens; however there were several athletes in their 30s or even 50s. The skill level of the athletes ranged from novice rowers to elite rowers who have won national championships, and competed internationally for the United States. In the survey, 79% of all rowers surveyed stated that they could not find the proper foot stretcher adjustment to fit their rowing needs. Furthermore, 57% felt that improvements to the foot stretcher’s adjustability, ergonomics, and performance could be made. Most of the improvements suggested dealt with ergonomic issues such as feet not fitting into the boat, and being unable to find a comfortable position due to limitations placed upon the rowers’ foot position by the foot stretcher.

As a result of both background research and surveying, goals for developing a new foot stretcher design were established. These goals served as a framework for the project, which helped to quantify the overall scope. The goals were increasing comfort of the rower, increasing adjustability of the foot stretcher, improving performance of the foot stretcher system, and maintaining performance of the rower.

The first goal of the project was to make the rower more comfortable as he/she rows. The rowing experience for some is not as pleasant as it is for others. When rowing in an uncomfortable position the workouts seem to take forever. Every stroke puts excess strain on the
muscles and joints. Many try the sport but the extreme discomfort and frustration of the sport will cause them to pursue other forms of physical activity. Even worse, continued rowing in a poor position can cause injuries. For instance, if one is not able to gain the correct body angle at the catch too much strain can be put on the back, which is one of the most commonly injured body parts for the rower.

The second goal was to increase the adjustability of the foot stretcher. This entails more than just the range of the adjustment, but also the manner in which it is adjusted. If the foot stretcher is difficult and time consuming to adjust, rowers will not want to take the time to adjust it to their preferences. If adjustments are able to be made more easily, then individuals will be more willing to make the adjustments, and not row with a set up that is uncomfortable or limiting.

The third goal of the project was to improve the overall system performance of the foot stretcher. Some of the issues with the functionality of the foot stretcher, such as the stretcher not holding its position while rowing, or the parts corroding, the pieces coming apart, the shoe not being fully supported by the stretcher, and the deflection that the stretcher undergoes during rowing will be resolved with this project.

The last goal of the project was to maintain the performance of the rower. The ultimate goal in rowing is to be the fastest crew, regardless of comfort level and adjustability. As a result, it was necessary to ensure that changes to the system performance, comfort, and adjustability did not decrease the performance of the rower.

### 3.2. Design Specifications

The design specifications for the project were as follows:

#### 3.2.1. Safety:

1. A quick release from the hull of the boat must be provided for the feet. If heel ties are used then the heel must not raise 3 inches from the foot plate. This is the safety requirement from USRowing (FISA, 2006).
3.2.2. Ergonomics:

1. Device must be accommodating to different individuals’ foot sizes. Size 5 women to size 16 men should be accommodated in the design. This would accommodate 98 percent of all individuals in the United States (White, 105).

2. Device must be accommodating to different individuals’ foot height preferences. The specific range should be 15 to 21 cm. This distance is the normal distance (vertical) from the bottom of the heel to the top of the seat. This range has been specified based on feedback from the questionnaire.

3. Device must be accommodating to different individuals’ foot width preferences (this range should be a minimum of feet touching to a maximum which will be determined by the width of the foot well in the boat (11in).

4. Device must be accommodating to different individuals’ foot angle preferences (foot plate angle). The range of this angle should be at least 32-48 degrees. This angle is to be measured from the footboard to the horizontal. This range has been determined based on feedback from the questionnaire. The current footboard angle in a Resolute boat is adjustable between 35 and 41 degrees to the horizontal with a 2 degree adjustment interval.

5. Device must be accommodating to different individuals’ foot angle preferences (splay). This angle is to be measured from the vertical between the feet of the rower. This angle should be anywhere from parallel feet (0 degrees) to feet at the 45. This angle shall be measured between the feet of the rower.

6. Device must be easily adjusted by hand or with the use of simple hand tools, such as a box wrench or screwdriver.

7. Adjustment must take no longer than 2 minutes. This time shall not include the time of a rower playing around with the adjustment to find his or her exact fit, but should be the time of a rower who knows exactly where s/he wants to place his/her feet.

8. Feet must be supported correctly for proper stability. This entails that there be no slop in the fit of the shoe to the foot of the rower.

9. Device must fit in the current hull opening in a racing shell. The current opening has a foot well width of 11 in, a depth of 7.25 in, and a footboard length of 11.5 in.
3.2.3. Performance:

1. Device must withstand forces no less than 4500 N (safety factor of three) in a direction normal to the footboard. Bettinelli reports a force of 1500 N applied by the rower to the footboards during a 2k race (Bettinelli, 2010).

2. Device must not corrode in warm salt water environments. This is critical because many teams practice in salt water, and corrosion can be a problem especially in areas such as Florida and the Mediterranean.

3. Device must have a life span of no less than 10 years. Ten years is the average lifespan for a racing shell to be used by the varsity program at WPI.

4. Device must not fail during a race. Failure would include device cracking, breaking in two, loosing adjustment, or other failure of functionality. This would mean that under the required force the device would not fail. It also means that the device should be able to stand up to the loading cycles that it would see over ten years. This would be 4.7 million cycles assuming that it is used to row 15000 meters a day 6 times a week and that each stroke would result in a movement of 10 meters.

5. Device must hold adjustability until adjusted again. This would mean that no force up to and including the 1500N normal force would cause any part of the foot stretcher to move. Fasteners must also not come loose over time which may cause the movement of a component as one is rowing.

6. Deflection of not more than 4mm when 1500N force is applied normal to the foot stretcher. This force should be applied as a distributed force over the surface area of the feet on the foot plate. The deflection shall be measured at the midpoint of the crossbar between the deck, and the midpoint of the foot plate. A 1500N force is used because it was shown through research that a professional rower implies about a 1200N force through a 500 meter race, so a 1500N force should be sufficient for such instances as a start (Bettinelli, 2010).

7. Device must not decrease the rowers’ overall power output. Though not all rowers may see a power increase through the use of this device, it is expected that no individual suffer from its use.
3.2.4. Other:

1. Device must not have an increase in weight of more than 0.25 lbs over current foot stretcher; use Resolute (2.5 lbs) as standard. Though the weight is not so much of an issue for a new boat construction as the weight of the foot stretcher is taken into account when designing the boat to meet minimum FISA weights, for a retrofit we would like the foot stretcher to be as close to the current weight as possible.

2. Must have a standard cost less than $150

3.3. Methodology

After significant research was conducted and the design goals and specifications were established, the completion of the project followed a specific procedure. The general methodology used was to design based on the goals and specifications, analyze and validate the design, build the design using CAM and CNC programming, test with human subjects, and draw results and conclusions.

With the design goals and specifications clearly defined, several design ideas were generated that incorporate the project specifications. Then, a decision matrix was created in order to determine which designs best fulfill the design specifications to meet the design goals. The design was then selected, and final refinements needed to be made to the hand sketches to ensure that any items that were left as generalities or assumptions were cleared up. To achieve this, appropriate measurements were made and incorporated into the designs. The next step took the sketched design and developed a 3-dimensional model using parametric solid modeling software. Once the model was finalized, the analysis was conducted on the design to ensure that it can be manufactured and that it met all specifications that did not require user feedback. Once the design was validated to meet the specifications and the limitations of the manufacturing tools, materials were ordered and CNC programming was completed. Finally, once all of this was completed, the design was machined and assembled.

Once the design was built, it was time to conduct testing. However, in order to ensure there was no lag in time, there were some tasks that needed to be completed concurrently with the design aspect. First, there needed to be an established means for successfully completing the design specifications. Then a standard needed to be set for each design specification that quantified the completion of the design specifications. Once this was completed, a test
procedure was written to ensure the test can be reproduced and accurately followed. The completed procedure and documentation were then submitted to the Institutional Review Board (IRB) and approved. Finally, a fixture was built to enable the subjects to test the prototype. Once all of these tasks were completed, the test was completed as per the protocol.

Since the design feedback is based on both opinion and technical requirements, both testing and analysis needed to be conducted. First, a pool of volunteer rowers (4 men and 4 women) was selected to test the design. To test performance, a power-based workout was used. The workout was designed to have the rower row at a low stroke rating and push their maximum power output on an ergometer. Any fluctuation in this output between a current foot stretcher design and the new design gave insight into how the design affected performance. Furthermore, after the completion of the test, rowers were given a survey that asked for feedback on aspects of the design such as ergonomics and adjustment. The analysis portion was conducted using the CAD model. This checked the validity of the design to the specifications outlined to ensure that all aspects were met. FEM was used, in addition to hand calculations, to ensure that the design would meet the loading requirements.

After the testing was completed, the results were then analyzed to determine whether the users found improvements in the areas identified by the goals of the project.

3.4. Preliminary Designs and Analysis

After the design goals and specifications were outlined, it was necessary to begin developing ideas for how to best solve the problems outlined. Moreover, it was necessary to also evaluate those designs on their ability to meet the specifications outlined. After the designs were developed, the following questions were applied to the design to determine its viability.

1) Safety
   a) Does the design meet the safety standard?

2) Rower Comfort
   a) Does the design provide all of the desired adjustments (x, y, z, splay, foot plate angle)?
   b) Does the design accommodate different foot sizes?
   a) Are the feet supported sufficiently?
2) **Adjustability**  
   a) Is the device adjustable to the standards set by the design specifications?

3) **Foot Stretcher Performance**  
   a) Will the device interface with the current shell?  
   b) Is the device durable?  
   c) Is device reliable?

4) **Rower Performance**  
   a) Will the design inhibit the rower at all?  
   b) Can any determination be made about potential performance improvements to the rower?

Below are the preliminary designs created for this application and the evaluation of each device relative to the specifications outlined above. These evaluations are broken down based on the categories outlined above. This qualitative analysis for each design provided key insight into the viability of the design. However, merely doing a qualitative analysis of the designs did not provide much insight into comparing the designs. This is why, in addition to the qualitative analysis, quantitative analysis was done. These numbers, which are initially given in the analysis of each design, were compiled into a design/decision matrix to quantitatively evaluate which design and/or aspects of each design are best.

To construct the design matrix, the design goals were utilized and weighted based on importance. When ranking the design goals, multipliers were used that ranged from 0-100, where 71-100 is critical, 31-70 is important, and 0-30 is optional. Rower comfort was given a weight of 100 because it is the driving force behind the project. Adjustability was given a weight of 75 because many people who responded to the questionnaire cited that the adjustment range was not sufficient for them to find a comfortable position, or that it took too long to get to the comfortable position. Foot stretcher performance was only given a 50 because, while it is an important issue, the current performance of the foot stretcher system is not one of the main reasons for a redesign of the system, as supported by questionnaire answers. Rower performance was given the lowest rating of 40. Though it may seem that the most important aspect was weighted lowest, questionnaire feedback supports that as long as the foot stretcher does not limit
the performance of the rower, and makes the rower more comfortable, that the rower will become more efficient and powerful.

When completing the design matrix all of the variables were given values from 0-10. When assigning the values we stated that anything less than 5 would be worse than the current design, 5 would be equal to the current design, and greater than 5 would be better than the current design. When assigning values for rower comfort we looked at factors including the ability to use correct fitting shoes, the ability of the rower to move the stretcher into a comfortable position, and the strain that the foot stretcher might put on the body. In general, designs with higher values in this category had the ability to change the shoes easily, a large range of adjustment, and the adjustment had a small increment of change, so that one was not limited to simply three or four adjustments over the entire range.

When assigning values to the adjustability category the range of adjustment was considered, as well as the speed with which adjustments could be done and the required skills and tools needed to adjust the device. In general, designs with the ability for one to easily change their shoes were given high values. Also designs with a large range, as well as multiple directions of adjustability were given high values. Devices, which do not require the use of simple tools, or take little time to adjust, were given high values.

In foot stretcher performance, factors such as the ability of the foot stretcher to hold its position during rowing as well as the strength, weight, durability, and resistance to corrosion. Many of these designs were given lower values because we felt that they were not as sturdy as they could be and may deform too much during rowing. Other designs were given lower ratings if they consisted of components that may become clogged when used and inhibit the adjustment that they were supposed to improve.

If the rower has the ability to quickly click his/her own shoe into the foot stretcher, it is safe to assume that it would improve the overall rower experience. Several WPI rowers wear their own neoprene boots into the boat to increase their own performance. The neoprene booties give the rower a better fit to the shoes of the boat. So if the rower was able to obtain a better connection to the boat through his or her own shoes, without the wasted energy of compressing the neoprene as s/he rowed, an increase in performance should be seen. The caveat to this is that
the foot stretcher must not limit the performance of the rower at the expense of allowing him or her to attach his or her own personal shoes.

Based on feedback from the design matrix, there were 3 designs with an overall score above 0.7. Features from those 3 designs were incorporated to create a strong design to develop.

Below is the detailed analysis of all the preliminary designs that were developed. Additionally, there are intermediate figures showing detailed aspects that were included in some designs. The detailed analysis was conducted based on the parameters outlined above.
Figure 17: Foot Stretcher Design for Soft Shoe (DP1)

Annotations:

1) Pole, which connects to the boat via an upper track.
2) Plate, which attaches to the rowing shoe.
3) Independent footboard.
4) Drilled holes for the adjustment of the plate (2) in the x and z direction.
5) Bolts attaching independent footboard to the pole for the upper deck.
6) Bolts attaching independent footboard to the pole for the lower track.
7) Pole to support and connect independent footboard to the lower track.
8) Holes for shoe ties.
Safety

The design has heel ties to meet national and international safety requirements. Thus the ranking is considered for evaluation.

Ergonomics

This design allows for the adjustment of the heel to seat height of the rower through adjustment of the position of the shoes along the footboard. It also allows for the width of the feet to be adjusted through the same system, thus providing a coupled system where the same design parameter affects both adjustments. This design provides for adjustment of the footboard angle through the adjustment of the total footboard length. This design does not however provide for a splay adjustment. Therefore one of the adjustment directions is not met. This design provides for the changing of shoe sizes through the attachment mechanism of the shoe plate to the footboard.

This design gets a 6.5 for Rower Comfort because it is missing the splay adjustment, which could be a large part of rower comfort.

Adjustability

This design is not as adjustable as it could be. It uses two wing bolts on each footplate, which have to be adjusted separately. The wing bolts could take some time to adjust and get into the holes of the footplate. Lining up the holes of the shoe plate and the holes in the footplate could be difficult. The range of the adjustability is adequate to fulfill all of the design requirements. Also the mechanism for adjusting the height of the feet is coupled with the mechanism for adjusting the width of the feet.

This design gets a 7 on the adjustability because of the time it could take to adjust it

Foot Stretcher Performance

This is a very sturdy design without many parts that are likely to break. There are also no moving parts to get clogged or corroded. The adjustment mechanisms are simple bolts, which should not fail or come undone easily while rowing. This being said, the bolts and nuts in our current foot stretchers come undone some of the time.

This design gets a 6 for foot stretcher performance

Rower Performance

This design gets a 5 because it neither increases nor decreases rower performance.
Figure 18: Foot Stretcher Design for Hard Shoes (DP2)

Annotations:

1) Pole that connects to the boat via the upper track.
2) Holes in the vertical pole for adjustment in the Z-direction.
3) Foot pad allows the shoe plate to be adjusted in the X-direction.
4) Shoe plate connector. Where cycling shoes will lock in.
5) Ball bearing that allows the shoes to rotate about the X-axis.
Safety:

Since the design does not have heel ties, it may not meet all of the safety requirements in the United States, even though it meets the international quick release requirement. This design will be evaluated, but strong consideration will be placed on the viability of the design in the United States.

Ergonomics

This design has adjustment from heel to seat top from the movement of the shoes up the center pole. It also has adjustment in the width through the movement of the cleats on the footplates. The shoes in this design are removable through the use of a bicycle clipless system. This will allow the individual to wear a shoe that fits him or her well, and change it out as s/he gets in and out of the boat. This device can be adjusted along the keel of the boat through the existing tracks of the boat. This device will allow rotation of the feet about the rods to which the cleats are attached.

This device gets an 8.5 for rower comfort. The rower can wear his or her shoes at all times preventing any cuts that may occur from the ground, and speed up the preparation process. It also allows for a lot of adjustability, allowing the rower to find a comfortable position. None of the adjustment directions are coupled with another direction, so they can all be adjusted independently without any iteration.

Adjustability

This device is easily adjustable up and down the center rod through the use of a locating pin. All one needs to do is pull the pin up, slide the apparatus up or down, and replace the pin. The cleats can be adjusted with bolts into the shoe plate. And the device will have the existing adjusting mechanism. This device gets an 8 because of the ease of adjustment.

Foot Stretcher Performance

This device only has one center-supporting rod. If the rower’s force is not applied evenly between the feet there will be a large moment placed on the center rod. This may cause large deflections if not deformations. Because of this the device is only given a 5.

Rower Performance

This device uses stiff bike shoes, which will help transmit more energy from the rower to the boat. This design gets a 5.5.
Figure 19: Rotating Foot Attachment Design

Annotations:

1) Ridges for Indexing.
2) Adjustment slots for splay of the rower’s feet.
3) Holes to attach to the footboard.
4) Holes to attach shoes to the system.
5) Holes to attach plate 1 to plate 2.
Figure 20: Horizontal Adjustment Design and Tracks

Annotations:

1) Bolts that secure the foot holder to the adjustment.
2) Adjustment tracks.
3) Indexing on footplate for even adjustment.
4) Plates to secure feet
1) Track mate that locks the foot stretcher into place.
2) Sawtooth track designed to be inside of the track system, instead of on top.
Figure 21: Rack and Pinion Adjustment Design

Annotations:

1) Pinion.
2) Rack
3) Shoe holding plate.
4) Holes for attaching holding plate to footboard.
Annotations:

1) Clipping plate Z-direction adjustment tracks.
2) Boat tracks with teeth on the inside.
3) U shaped rod to connect footboard to bottom track.
4) Adjustment holes for the U shaped rod.
5) Rack & Pinion X-direction adjustment.
6) Rotating feet 1 design (from above).
7) Footboard.
Safety:

The design has heel ties to meet national and international safety requirements. Thus this design will be considered for evaluation.

Ergonomics

This device allows for adjustment of the angle of the footboard, the height of the feet, the width of the feet, the splay of the feet, and the position of the footboard along the keel of the boat. The device is fitted with a set of tracks on the footboard that are used to adjust the height of the shoe plate. The shoe plate is then equipped with a set of tracks, which are used to adjust the width of the feet. Because they use two separate track systems, the functional requirements are decoupled. The shoes are mounted on a device such that the splay angle of the feet can be adjusted. The angle of the footboard is adjusted by changing the overall length of the footboard. A longer footboard will yield a shallower angle.

This device gets a 7 for rower comfort. All of the directions of motion were met in the design. The splay angle will add a lot for comfort adjustment for the rower.

Adjustability

This design has a feature similar to that of a leaved table, allowing the feet to stay the same distance from the center of the footboard as they are moved further apart or closer together. The feet are also to be adjusted within a track, allowing the user so simply slide the feet to the desired location and tighten them down to lock their position. This track system would also offer a smaller resolution of adjustment than bolt-holes would. However, the tracks could become clogged easily or bind. This design was given an eight because of the range, directions, and resolution of adjustment.

Foot Stretcher Performance

This is another very sturdy design. The feet have a solid platform to rest against and the attachment mechanism is sufficiently strong for the forces applied. The footboard is supported in such a way that no large deflections should be noticed when the person is using the device. The device also uses an attachment mechanism between the foot stretcher and the boat, which should not come undone during the course of the race causing an accident. One concern we had is with the geared device that keeps the feet equidistant from the center of the footboard. This could clog easily or may experience more wear than other parts.
This device was given a 6 for foot stretcher performance because it provides a stable platform, which should have minimal deflection. But there are some small parts that could break more easily than other designs.

**Rower Performance**

This design is almost similar to the existing design, with the addition of more adjustment. Because of this we gave the device a 5 signifying that it should have no improvement or negative effects.
Figure 23: Hard Shoe Assembly (JM2)

Annotations:

1) Heel supports for rowing.
2) Track design with teeth on the inside.
3) Tracks to adjust the shoes in the X-direction.
4) Adjustment holes for the heel supports.
5) Holes for adjusting the clipping plate in the Z-direction.
6) Rotating feet 1 (seen above).
Safety
Since the design does not have heel ties, it may not meet all of the safety requirements in the United States, even though it meets the international quick release requirement. This design will be evaluated, but strong consideration will be placed on the viability of the design in the United States.

Ergonomics
This design allows for the adjustment of the foot height, the longitudinal position of the foot stretcher relative to the keel, and the adjustment of the width of the feet. This device does not allow for one to adjust the splay of the feet, or the angle of the foot stretcher. The shoes themselves are held in place by a clipping mechanism so that the rower could simply enter the boat and clip his or her feet in. To accommodate the different size feet, the heel pads would have to be moved up or down accordingly relative to the toe piece. Because the middle of the foot would be left unsupported by the foot plate, the shoes of the rower would have to have a hard midsole. Since not all of the adjustment directions were met this design only received a 5 for rower comfort.

Adjustability
The width of the feet in this design would be easy to adjust because of the use of tracks to hold down the shoe plates. The adjustment along the keel of the boat would also be done through the use of tracks. The problem with this design occurs when a rower wants to use a different shoe or adjust the height of the feet. To do this s/he must adjust both the height of the toe piece along with the height of the heel piece. This inconvenience causes this device to only be given a 6.

Foot Stretcher Performance
This device uses a singular center post to support the toe pieces and heel rests. If a rower were to exert different forces between his or her feet, then a torque would be induced upon this center post. This could cause deflections and deformations. Because of its tenuous nature this design was only given a 4 for foot stretcher performance.

Rower Performance
Even though a hard mid soled shoe would be used for this design, we feel that there would still be some flexion of the foot in the arch area due to the area not being supported by a footplate. This could cause pain in the feet while rowing. We also feel that a hard mid-soled shoe
may have negative consequences while rowing. This leads this device to a 4 for rower performance.
Figure 24: Rotating Foot Hinge for Hard Shoes

Annotations:

1) Rod holes to act as a hinge.
2) Connecting plate for cycling shoe clip.
3) Screw holes to adjust splay.
4) Splay tracks.
Figure 25: Hard Shoe Assembly with Shoe Hinge (JM3)

Annotations:

1) Heel supports for rowing.
2) Track design with teeth on the inside.
3) Tracks to adjust the shoes in the X-direction.
4) Adjustment holes for the heel supports.
5) Holes for adjusting the clipping plate in the Z-direction.
6) Rotating foot hinge (seen above).
**Safety**

Since the design does not have heel ties, it may not meet all of the safety requirements in the United States, even though it meets the international quick release requirement. This design will be evaluated, but strong consideration will be placed on the viability of the design in the United States.

**Ergonomics**

This design allows for the adjustment of the foot height, the position along the keel of the boat, the width of the feet, and the splay of the feet. This device also uses hard soled shoes that can be worn by the rower and clipped in when s/he enters the boat. To accommodate the hard soled shoes the attachment points are placed on platforms that rotate about an axis at the top of the shoe. This axis will allow the feet to lower in the boat as the rower approaches the catch. This may help a rower get to full compression more easily without putting strain on his or her back.

Since this design meets all of the adjustment directions, allows the rower to place in his or her own fitted shoes, and may even make it easier to get into a comfortable position, we gave this design an 8.5.

**Adjustability**

The range of adjustability of this foot stretcher is good. It also features tracks, which will help the rower adjust easily by sliding the components along the tracks until s/he finds a comfortable position. One disadvantage of this design is that when a rower changes the shoe size that the stretcher is set for s/he is going to have to change the height of the heel plates so that the heels make contact with the part. Thus the adjustment of this design gets a rating of 7.

**Foot Stretcher Performance**

This design also only uses one center rod for support, which as stated before may not provide the most stable support for the feet. There are also a lot of parts that can corrode, wear, and become seized. Thus, this has been given a 5 for foot stretcher performance.

**Rower Performance**

The use of a hard sole shoe design has not been fully tested in a rowing application. However, this setup could potentially provide the rower an increase in overall performance, but would need to be tested to fully substantiate. This has been given a 7 for rower performance.
Figure 26: Clip-less System Assembly (JM4)

Annotations:

1) Z-direction adjustment holes.
2) Clipless turning disc.
3) Holes to adjust the position of the feet on the plate in the X&Z-direction.
4) Footboard
Safety

Since the design does not have heel ties, it may not meet all of the safety requirements in the United States, even though it meets the international quick release requirement.

Ergonomics

This design allows the rower to adjust the vertical height of their foot position, while also utilizing a clip-less connection system that allows the rower to have splay, while also enabling entry and exit of the boat with shoes on. This clipless system is designed such that the rower would have the ability to adjust his splay continually while rowing. We feel that this may help the rower to remain in a comfortable position throughout the stroke, rather than being in a comfortable position for only select parts of the stroke. Since this design meets all of the adjustment directions, and allows the rower to place in his own fitted shoes, we gave this design an 8.5.

Adjustability

The adjustability on this design is excellent. It allows the rower to meet almost all of our adjustment requirements with great ease of use. The one area that the design could be improved is that it does not provide the rower with a way to adjust the angle of the footboard, but this is an easy add-on to the design. Thus, this design has been given a 9 for adjustability.

Foot Stretcher Performance

This design would provide a stable platform for the rower. It is similar to the existing design, which provides a sufficient platform, keeping deflections to a minimum. This design has been given a 6.5 for foot stretcher performance.

Rower Performance

This device would provide for continuous splay adjustment. It would also allow the rower to insert his or her own fitted shoe into the boat. It is believed that this will improve the rower’s overall performance, if only slightly. This design has been given a 6 for rower performance.

Chart Summary

Figure 30 (shown below) is a summary chart of each of the designs, mentioned above, with the assigned variable scores (1-10) and subsequent weights (0-100). The weights have been assigned based on each criterion’s effect on the success of the design. Rower comfort was given a weight of 100 because it would have the most impact on the success of the design. Adjustability was given a 75 because it is still necessary for the success of our design, but not as
important as Rowing Comfort. The foot stretcher performance was weighted at a 50 because while it is necessary for the design to be a success, it is not the driving force behind the project. Rower Performance was given the lowest weight because, while we fully expect to not decrease rower performance, the improvement of rower performance is both not pivotal to the success of the design, and would be on such a small scale that it would be nearly impossible to show a statistically significant improvement over the current design. The result is an overall ranked score for each design below.
Based on the results of this analysis, the highest scoring overall design was JM4, and the highest scoring hard sole design was DP2. It is important to recognize that several items scored close to these, and may have key design features that could make the highest scoring designs even better. JM4 was improved by adding a mechanism to adjust the angle of the footboard.

One key aspect that could not be evaluated in the design matrix was the effect of a hard sole shoe design vs. a soft sole shoe design. Currently, no substantiated data exist on the use of a hard sole shoe in a boat. However, with little market traction the feasibility of a hard sole design was relatively low. As a result a soft shoe design was selected for this project.

### 3.5. Development

After going through some initial designs and analysis, an axiomatic design process was used to come up with the final design. The final design was to be a combination of highly ranked parts of the initial designs to fulfill all of the design requirements in the best way possible. In
axiomatic design, one uses the two axioms devised by Massachusetts Institute of Technology’s Nam Suh to develop the best design solution for any specific problem (Brown, 2011).

Axiom 1 of axiomatic design is that one must maximize the value added to the product. To use Axiom 1, one breaks up the first functional requirement into subsequent smaller functional requirements. To fulfill the first axiom, these functional requirements must be collectively exhaustive, mutually exclusive, and use the minimum number required. When decomposing the functional requirements it is important to ensure that the sum of the children will yield the parent. If one can show that the sum of the children will equal the parent, while being collectively exhaustive, and having no redundancies, then the value added to the product is at its maximum, while not taking any away from coupled functional requirements.

Some of our functional requirements (FR) can be seen below in Figure 28: Axiomatic Decomposition Functional Requirements and Design Parameters, along with the design parameters (DP) that we chose to fulfill them.

![Figure 28: Axiomatic Decomposition Functional Requirements and Design Parameters](image)

A method for checking that the FRs and DPs are mutually exclusive is to place all of them into a matrix and mark off what functional requirements each design parameter will affect.
Ideally each design parameter will only affect one functional requirement, resulting in a diagonal matrix. This may not always be possible, and the next best thing is to have either a lower or upper triangular matrix. In this case one can adjust the more coupled DPs first, then adjust the less coupled DPs to achieve the desired result. One should try to limit the amount of coupling that occurs on each side of the diagonal because this will result in a design with parts that are not adjustable without affecting something else.

One can see our matrix below in Figure 29: Axiomatic Decomposition Results Matrix. The matrix for this project’s design is mostly diagonal with a small amount of coupling. This coupling means that some of the FR-DP pairs will not be as adjustable as fully desired, but the small amount should not have a substantial effect on the design.

![Figure 29: Axiomatic Decomposition Results Matrix](image)

NOTE: Please Reference Figure 28 for full functional requirement and design parameter titles.

Axiom 2 of axiomatic design states that one must maximize the chance of success in a design. This can be done through minimizing the information in the design. If one has two designs, both of which will achieve the same result but one has lower information content than
the other, the one with the lower information content should be chosen as the better design. In this design Axiom 2 was utilized to eliminate a translational shoe release and replace it with a rotational one. The rotational one would have a lower chance of failure, and thus less information. For more information on Axiom 2 as well as axiomatic design, please see Appendix B: Axiomatic Design.

Throughout the development process several modifications were made to the initial design to help ensure that, after a prototype was made, the build would best meet the design specifications of the system. Though many smaller changes were made, the most notable changes occurred with the plate used to connect the shoes to the foot stretcher. In the preliminary design phase, it was decided that a clipless system, similar to cycling pedals, would be used for the release of the shoe. This system would be pressure sensitive such that it would not release unless it experienced a force in a specific direction. This force would not be one that was commonly experienced while rowing, limiting the chance of an inadvertent release. The intent was that this would provide more support, better usability, and better safety. However, upon closer examination it was determined that, in order to meet United States Safety requirements, the shoes would also need to have heel ties. In the event of a capsized boat, if the shoes released, but were still attached at the heels, there would be a serious safety issue.

As a result, it was decided that the clipless system would use a lever mechanism that allows the rower to release their shoes only when it is necessary. This system design would provide the added support and usability, while also meeting national and international safety requirements. Though making this modification is seemingly simplistic, the size requirements of the plate itself made it such that strength was a significant constraint in the positioning of the mechanism, and the materials used.

**3.6. Modeling**

After conducting the axiomatic decomposition enough information was gathered to develop a solid (CAD) model of the initial design, seen in Error! Reference source not found.. The solid model served as a valuable resource to visualize the design in three dimensions, ensuring that it is designed for manufacturability, all strength constraints were met for the loads anticipated, and the positioning of the design fit the geometric shape provided by the existing
The group utilized the solid modeling package SolidWorks developed by Dassault Systèmes.

In our final design the rower would wear his/her own shoes that could be fitted to the individual rower to achieve an optimal fit. These shoes would have a peg on the bottom that would interface with the rowing foot stretcher. The pegs can be seen in Figure 31; the flat piece would attach to the shoe with screws, not seen in this figure, and the peg would extend down from the sole of the shoe. For our prototype this piece is made of steel because the coefficient of friction between steel and aluminum is much lower than aluminum and aluminum. In a finished marketable product this piece would likely be molded into the sole of the shoe, not an additional piece.

One key feature of this peg is that it is round in shape. The round shape allows it to be inserted into the foot stretcher at any angle, as long as the flat faces remain parallel with the flat faces of the foot stretcher. It also allows the rower to alter the splay of his or her feet without the use of any tools, as the current designs require the use of a screwdriver to alter this angle if it is adjustable at all. Not only that, but the rower can change the splay angle of his or her feet “actively”, meaning that as the rower rows s/he is free to change the splay of his or her feet within the interval of one stroke.
The pegs will interface with slots cut into the shoe clipping plate of the boat. A view of the slot can be seen in Figure 32. View A in the figure demonstrates a frontal view of the feature. One can see the shape of the slot is that of an inverted “T”. This shape will accommodate the “T” shaped peg fitted to the bottom of the shoe. View B in the figure shows a top view of the slot with hidden lines showing the undercut of the slot. Both the slot and peg are tolerated to have a running fit so that the peg can rotate within the slot while still being held securely enough that the rower will not notice any play between the two.
Figure 32: View of slot for shoe pegs
The peg is held in the slot by a locking piece that will hold the peg from behind after it has been inserted into the slot. Figure 33 shows several views of the locking piece. This piece is tolerated with a running fit to the peg so that it allows for rotation of the peg but will limit translational movements. This piece has a ramp cut into it to allow for the entrance of the peg. As the peg is slid into the slot the locking piece will depress. After the peg has cleared the locking piece it will return to its raised position with the aid of mechanical springs. The locking piece is shown in two positions, in the bottom left image it is shown in the locked position. In this position the peg will be held tightly into the slot by the locking piece. The bottom right image shows the locking piece in the open position. In this position the peg is free to enter or leave the slot.

Figure 33: Image of locking piece that secures the peg

This slot is a feature of the foot clipping plate. This foot clipping plate serves two purposes; it interfaces with the shoes to hold them at a fixed position, removing 5 degrees of freedom while leaving one rotational degree of freedom to allow for active splay adjustment, as
well as attaches the feet to the foot plate, and thus to the boat. The foot clipping plate has several key features, the first of which are mounting holes that allow the rower to adjust the position of the foot clipping plate vertically along the foot plate. These holes are identified by letter A in Figure 34. Thumb screws are inserted through these holes and screwed into the foot plate. Thumb screws are utilized so that the rower can adjust this height without the use of any tools. This component also contains the locking assembly which locks the feet into the system. Figure 34 identifies the locking pieces mentioned earlier as letter B. To release the feet from the system the rower would pull up on a lever, indicated by letter C in Figure 34.

Figure 34: Foot Clipping Plate.

Letter A represents the holes, which allow for vertical adjustment on the foot plate. Letter B identifies the locking pieces in the position to lock the feet into the foot stretcher. Letter C identifies the lever one would pull to release the feet from the system.

The locking system of the foot clipping plate is composed of 5 main unique components. The base component is the plate to which all of the other components are attached. This is represented by letter A in Figure 35. One feature of the plate is that it is cut at an angle so that when it is attached to the foot plate the top of the component will be raised higher than the bottom of the component. This is to provide a separate face for the rower to push off of as s/he travels up the slide. The concept of this is similar to that of starting blocks for track and field, which provide an angled face relative to the ground for the runner to push off of. The plate is also equipped with a bearing surface in which the locking piece rod rotates. This bearing surface is toleranced with a close running fit so that the rod may rotate inside of the bearing, while
limiting the translational motion of the rod. This is critical to maintain the tolerance of the locking pieces relative to the peg.

The second component of the foot clipping plate is the rod, which carries all of the locking pieces. The rod is to be made of brass because it has a low coefficient of friction with aluminum, the material of the plate in the prototype. The rod is identified by letter B in Figure 35. The rod is also tolerance as a close running fit to the bearing surface of the plate as discussed above.

The bearing surface of the plate is designed as a two piece system, where the first piece is provided by the plate and the second surfaces are provided by components identified as letter C in Figure 35. These components hold the rod tight to the plate while maintaining the tolerance discussed earlier.

The release lever, identified as letter D in Figure 35, and the locking arms, identified as letter E in Figure 35, are attached to the rod. The lever rotates the rod and lowers the locking pieces from the peg as discussed previously. The locking arms attach the locking pieces to the rod, as well as hold the locking pieces in the correct position to maintain their tolerance with the peg. Not shown in Figure 35 are the torque springs which keep the locking pieces engaged with the peg unless the user lowers them either from the use of the lever or by inserting his/her feet into the plate. These springs will fit over the rod and apply a torque in direction F as seen in Figure 35. The motion of the locking mechanism is shown in Figure 36.

![Figure 35: Exploded view of Foot Clipping Plate highlighting the locking mechanism](image)
The foot stretcher itself is comprised of 6 parts, the foot plate, clipping plate, lower adjustment rod, 2 tube end pieces, and foot plate support. One can see how the pieces of the foot stretcher fit together in Figure 37 in the exploded and collapsed views. All of the pieces are held
together using machine screws except for the tube end pieces. These pieces are simply inserted into two holes in the ends of the foot plate support. This is because these are the pieces which attach the foot stretcher to the boat, and thus must remain in a certain orientation relative to the boat. The ability of these devices to rotate about their axis allows the foot stretcher to change angles while still allowing it to be connected to the boat.

![Figure 37: Exploded view of foot stretcher (left) and assembled view of foot stretcher (right)](image)

Figure 37 shows how the foot stretcher interfaces with the hull of the boat. The clipping plate is attached to the foot plate of the foot stretcher. The foot plate is identified by letter A in Figure 38. The foot plate provides the surface on which the rower pushes. It is supported by the foot plate support, identified as letter B in Figure 38, and the lower adjustment rod, identified as letter C in Figure 38. The lower adjustment rod serves two purposes, to support the bottom of the foot plate, and to set the angle of the foot plate. The angle can be adjusted by moving the component up and down relative to the foot plate. Adjustment is provided by a series of mounting holes in the foot plate.

The foot stretcher, which is made up of all the above components is attached to the boat through a series of tracks and guides. These tracks, identified as letter D in Figure 38, are
attached to the hull of the shell. The foot stretcher interfaces with these tracks through the lower adjustment rod and tube end pieces identified as letter E in Figure 38.

![Figure 38: Image of the foot stretcher attached to the hull of the shell](image)

While many of the current designs on the market use carbon fiber in their designs to meet a weight requirement, this design used aluminum and steel in the design. While this did not meet the specified weight requirement, it was a much cheaper alternative for preliminary testing. However, the materials selected for this build needed to satisfy the same strength requirements as those desired with the final materials. As a result, a series of stress analyses and calculations were performed on the clipping plate as well as the foot plate support.

Two methodologies were used to conduct these calculations. First, finite element modeling within SolidWorks was used to model these forces. Second, hand calculations were completed to verify the accuracy of the models. To analyze the parts, the group decided to be
conservative in how the parts were loaded. Instead of distributed loads the group used line loads at the centers of the parts. Figure 39 shows how the foot plate support was loaded with a line load in the center of the part, even though the actual loading of this part would be a distributed load over the entire top surface. These conservative models were used to simplify any hand calculations that were done on the parts. When performing hand calculation, simplified geometries were assumed. This allowed for the use of established equations for loaded beams. For example, the foot plate support was assumed to be a rectangular solid of constant cross section. While this is not the actual geometry of the part, it should provide a reasonable and conservative representation from which to verify the results of the finite element analysis.

The results of the finite element modeling found that the materials selected would perform either similar to, or better than, the design specifications. When the clipping plate is loaded with a 1500N force, the deflection of the plate is 0.359mm, with a stress of 94.3x10^6 Pa, resulting in a safety factor of 3. When the foot plate support is loaded with the same force, a deflection of .075 mm, and a stress of 22.7x10^6 Pa was found. This results in a safety factor of 12. These deflections are well below the 4 mm set as a maximum allowable deflection, and the stress analysis revealed that the factor of safety will be at least three for the parts tested. These deflections and stresses will decrease when the foot stretcher is assembled because the parts combined will be stronger than any one piece alone. For more information on the specific calculations, as well as a detailed description of all the FEA trials, please see Appendix D: Stress and Deflection Analysis.

![Figure 39: Representation of FEA on foot plate support](image-url)
3.7. Prototyping

To manufacture the prototype, both hand and power machine tools were utilized. Worcester Polytechnic Institute’s shops provided access to CNC machine tools provided by Haas. This prototype utilized the Haas Mini Mill and the TL1 lathe. The ranges of these machines combined with some creative fixturing allowed us to machine all of our parts using these two CNC machines.

The prototype was largely built of 6061 T6 Aluminum because of its strength as well as easy machinability. Because aluminum is a relatively soft metal the complex shapes of the design could be cut into the metal with much less effort than if it were to be made of steel. Aluminum also machines much faster than steel does. The clipping plate had one operation that was almost 2 hours long, this would have taken 4 or more hours if steel was used instead of aluminum. Machining out of aluminum is also much cheaper than sending the part out for plastic injection molding, which would have been an economically poor choice for a single prototype. The group decided not to use rapid prototype technology because although these machines can produce complex geometries out of lightweight materials, the machine available to the students at WPI creates parts out of strands of ABS plastic, and is thus not as strong as desired.

Some of the parts were designed to rotate inside of other parts. For these parts at least one of them was to be made of something other than aluminum. This is because the coefficient of friction between aluminum and aluminum is 1.4. The group elected to use UNS 10200 steel for the shoe pegs because the material was cheap and the coefficient of friction between aluminum and mild steel is 0.47. The group created the rod which supports the locking mechanism out of brass because the material was easily found in the shop. Brass also has a low coefficient of friction with aluminum, so the rotation of the rod in the bearing should not be an issue.

The group used as many parts that are available pre manufactured as possible. This included the tube ends, lower adjustment rod, Lower adjustment rod to track mounting mechanism, tracks, T-bolts for tracks, rowing shoes, and all fasteners. This greatly reduced the number of parts that the group would have to create for the prototype, saving time and money. The full bill of materials for this build can be found in Appendix A: Budget.
Once the CAD model of the prototype was completed the tool paths for the CNC machines were created in ESPRIT, developed by DP Technologies. ESPRIT allowed the group to easily create the tool paths with an intuitive CAM software which allowed for faster development of the tool paths than manual coding. ESPRIT also allowed the group to experiment with new cutting edge machining techniques such as molding commands to create complex three-dimensional geometries, and trochoidal pocketing which allows for faster, more efficient machining of pockets.

These tool paths were then transferred to HAAS machine tools for the realization of our design. The HAAS machine tools gave the group the ability to machine the complex geometries that the design required. Spindle speeds of up to 1200 RPM were utilized to transform the metal into chips as fast as possible. The group was able to use standard end mills, ball end mills, drill mills, face mills, and drills for most of the parts; however, a special undercutting tool with through spindle coolant was needed to cut the slots in the clipping plate for the pegs.

Most of the parts that the group made could be held with vices and parallels, or with set up blocks and machine straps, but a few parts required special fixturing methods. A special V block had to be created to hold the brass rod while flats were machined onto it and holes were drilled onto the flats. This eliminated the need to use a 4 axis program, or a lathe with live tooling, eliminating possible places for error in the machining process. Because of its size the foot plate had to be manufactured while bolted to a sacrificial plate. And a special fixturing method utilizing the side of a vice, a C clamp, a pipe clamp, a right angle, and machine straps was used to machine the holes in the ends of the foot plate support. For more information on the machining as well as pictures please see Appendix C: Manufacturing.

3.8. Evaluation of the Prototype

After the successful completion of the design/build phase of our project, it was then crucial to both test the build to identify which design specifications it meets, and which areas need to be improved upon, and analyze the design to ensure it met the specifications. Analyzing the design occurred through several methods.
The first group of design specifications focused on the selection of the parts and materials used in the foot stretcher. The methodology used for analyzing the specification is listed below the specification itself. They are the following:

**Design Specification 1:** Device must be easily adjusted by hand or with the use of simple hand tools, such as a box wrench or screwdriver.

a. This was checked and accomplished by selecting the bolts, screws, etc. that use the same size Phillips head screwdriver. This allowed for easy adjustment, while also enabling a firmer fit for the design.

**Design Specification 2:** Adjustment must take no longer than 2 minutes. This time shall not include the time for a rower to find his or her exact fit, but should be the time of a rower who knows exactly where s/he wants to place his or her feet.

b. Similar to the part selection above, the fasteners used in this design were either thumb screws or screws/bolts that use the same size Phillips head screwdriver. The result was the ability to adjust the prototype foot stretcher in 1:45 minutes, compared to nearly 5 minutes required to adjust the current design.

**Design Specification 3:** Feet must be supported correctly for proper stability. This entails that there be no slop in the fit of the shoe to the foot of the rower.

c. Both analysis and testing was conducted for this specification. First, the design model was analyzed to ensure that all tolerances are set to their reasonably smallest values. Second, once the prototype was built, direct testing of the design provided further information. Each of the testing subjects completed a survey after their experience to provide consistent feedback. A sample survey can be found in Appendix F: Questionnaire Responses.

**Design Specification 4:** Device must not corrode in warm salt-water environments. This is critical because many teams practice in salt water, and corrosion can be a problem especially in areas such as Florida and the Mediterranean.

d. Since the materials selected for this prototype are not the materials that would be used in a final build of a product, this design specification was not tested.

**Design Specification 5:** Device must have a life span of no less than 10 years. Ten years is the average lifespan for a racing shell to be used by the varsity program at WPI.
Since the materials selected for this prototype are not the materials that would be used in a final build of a product, this design specification is not applicable.

The next form of analysis was done through calculation and simulation. The following specifications fall under this form of analysis. Below each specification (taken from the design specifications section) listed is a specific description of how each item was tested.

**Design Specification 10:** Device must accommodate different individuals’ foot sizes. Size 5 women to size 16 men should be accommodated in the design. This would accommodate 98 percent of all individuals in the United States (White, 105).

a. The primary limitation for this specification was the physical size of the hull. The foot stretcher was designed such that it would support shoes within the specified ranges, given the hull dimensions.

**Design Specification 11:** Device must be accommodating to different individuals’ foot height preferences. The specific range should be 15 to 21 cm. This distance is the normal distance (vertical) from the bottom of the heel to the top of the seat. This range has been specified based on feedback from the questionnaire.

a. This was checked by measuring the distances from the plane created by the bottom of the heel to the plane for the top of the seat. To find the 15 cm distance, the bottom of a men’s size 16 shoe was measured to the seat. To find the 21 cm distance, the bottom of a women’s size 5 shoe was measured to the seat. Based on the needs of the test subjects, shoes were used ranging from men’s size 13 to women’s size 8, well within the range for the design.

**Design Specification 12:** Device must be accommodating to different individuals’ foot angle preferences (foot plate angle). The range of this angle should be at least 32-48 degrees. This angle is to be measured from the footboard to the horizontal. This range has been determined based on feedback from the questionnaire. The current footboard angle in a Resolute boat is adjustable between 35 and 41 degrees to the horizontal with a 2-degree adjustment interval.

a. Since the footboard acts as a hypotenuse of a right triangle, and the height is fixed, this specification was checked by trigonometry, calculating the angle provided by each hole used for angular adjustment. The angle of the foot plate in
the finished design was between 34 and 43 degrees, with an incremental angle of adjustment of around 2.2 degrees. These holes are located on the bottom of the footboard.

**Design Specification 13:** Device must be accommodating to different individuals’ foot angle preferences (splay). This angle is to be measured from the vertical between the feet of the rower. This angle should be anywhere from parallel feet (0 degrees) to feet at 22.5 degrees from the centerline.

a. The splay was checked by measuring the minimum and maximum angle the rower’s feet could make. First, a vertical center plane must be made that is parallel to the side of the foot stretcher. This is the 0 degree plane. Then the angle between the 0 degree plane and the maximum splay (between the two shoes) will be measured. Though the design specifications specified that the angle to the center plane should be 22.5 degrees, the constraints placed on the team by the size of the foot well did not permit this. The group was able to achieve an angle of 15 degrees for the men’s size 16 shoe, and an angle of 21 degrees for the women’s size 5 shoe.

**Design Specification 14:** Device must fit in the current hull opening in a racing shell. The current opening has a foot well width of 11 in, a depth of 7.25 in, and a footboard length of 11.5 in.

a. The check for this was done by taking measurements of the depth, length, and height of the footboard and ensure it is less than or equal to the values of the hull opening. Additionally, the design will be attached to the tracks in a boat to ensure that the design is compatible with the current boat structure.

### 3.9. Testing

The last group of design specifications was tested in the rowing system. The most accurate way to do this would be in a boat. However, this does not guarantee consistent results, nor does it provide an easy way to collect data. Thus a test fixture was built that allowed for the utilization of an ergometer. This enabled the collection of data on parameters, such as power, in a controlled setting. The specifications are the following:
**Design Specification 8:** Device must not fail during a race. Failure would include device cracking, breaking in two or other failure of functionality. This would mean that under the required force the device would not fail. It also means that the device should be able to stand up to the loading cycles that it would see over ten years. This would be 4.7 million cycles assuming that it is used to row 15000 meters a day 6 times a week and that each stroke would result in a movement of 10 meters.

a. The main way this specification was tested was to have rowers do a workout designed to optimize and maximize power using the prototype. After the workout, the participants were surveyed to see if any failure occurred other than that which could be seen or found through observation.

**Design Specification 2:** Device must hold adjustability until adjusted again. This would mean that no force up to and including the 1500N normal force would cause the any part of the foot stretcher to move. Fasteners must also not come loose over time, which may cause the movement of a component as one is rowing.

a. This specification was tested using the same procedure outlined above.

**Design Specification 3:** Device must not decrease the rowers’ overall power output. Though not all rowers may see a power increase through the use of this device, it is expected that no individual suffer from its use.

a. The testing for this specification was completed by having the subjects complete a power workout. This particular workout focused on the rower optimizing their highest power output. Each participant did this work out three times, on three different days, once with the new design, once with the old design, and once with a standard ergometer. The power outputs of the rower during the workout were used to determine if there was a statistically significant difference between the prototype and current designs on the market. The hypothesis was that there would be no negative significance.

**Design Specification 4:** Device must not have an increase in weight of more than 0.25 lbs over current foot stretcher; use Resolute (2.5 lbs) as standard. Though the weight is not so much of an issue for a new boat construction as the weight of the foot stretcher is taken into account when designing the boat to meet minimum FISA weights, for a retrofit we would like the foot stretcher to be as close to the current weight as possible.
a. This specification is not applicable for this build. Final materials were not used. The new prototype build was made out of aluminum, stainless steel, and brass, and weight close to 5lbs.

The best way to test the design would be under the conditions it will experience on the water. However, it is difficult to collect data in a boat, not to mention the testing cycle for this project was in the middle of the winter. The next best option then would be to use an ergometer. An ergometer is an indoor rowing machine that collects power/speed data as the rower uses the machine. However, ergometers use a different, more simplistic style for attaching the rower’s feet to the machine. In order to accurately measure and collect data, modifications were made to an ergometer.

After some evaluation, it was concluded that the best way to accomplish this was to replace the seated part of the ergometer with a new wooden test fixture. As part of the design and analysis of this fixture, consideration needed to be placed on the stresses and loads experienced, location of the moments, and safety of the rower.

![Figure 40: Ergometer with Test Fixture Attached](image)
Figure 41 shows an ergometer with the new fixture attached to it. With a connector that is on the back end of a typical erg, the fixture easily connected to the front end of the erg. The dimensions for the opening were based upon those found in a typical boat hull. This allowed the subject to use the same tracks, seat, and adjustments used in the boat. As a result, it yielded very similar results to those seen in a boat. Wood was used instead of aluminum to reduce the cost of the fixture. Since wood does not provide the same rigid stability as metal, a more complex structural system than the traditional ergometer was used to ensure that the loads of a rower would be supported while rowing with minimal deflection. Figure 42 shows a side view of the testing fixture while Figure 43 shows a side view of a traditional ergometer. The fixture has (2) 2x10 pressure treated boards bolted to the top and bottom of a pressure treated 4x4 tongue, and the 2x4 side panels. In addition, (2) ½” sheets of plywood were used on the top of the fixture. Finally, weights were placed underneath the traditional ergometer foot holders to provide more support against a downward force.

![Ergometer with Test Fixture](image)

Figure 41: Ergometer with Test Fixture
This device was crucial in the testing of the newly built prototype. It allowed for testing to be conducted on a traditional ergometer, enabling a comparison of the prototype to a design currently on the market. Each subject was asked to do three tests, following the process below.

3.10 Test Procedure/ Data Collection

After a 20-minute warm up on the design used, the subjects did a power-based workout at a slow stroke rating (number of strokes per minute) with a goal of getting the highest power output possible. To get the most accurate data, each subject came in for three separate testing blocks. We conducted these three testing blocks over a four-week period, allowing for rest in between each block and accounting for scheduling conflicts. The time period was of reasonable size, allowing for training improvements in the rower to be minimized, but large enough to provide adequate rest for muscle recovery and testing coordination. The first block used a current ergometer. This served as a baseline for the testing. The second block and third block order were randomized, testing of the current design and the prototype. The ergometer was utilized to collect data on the subject’s average watt output for each of the blocks. The stroke rating for the workout was set at 16 strokes per minute. The workout had 7 sets with 1 minute of rest between each set. Each set has a varied number of repetitions (strokes); they are as follows: set 1=10 strokes; set 2=20 strokes; set 3=30 strokes; set 4=40 strokes; set 5=30 strokes; set 6=20 strokes; set 7=10 strokes.

In addition to the data collected from the ergometer, a questionnaire was issued to each subject after the completion of testing. This questionnaire, and testing procedure, were reviewed and approved by WPI’s Institutional Review Board.
We selected 8 subjects to use for this study; 4 males and 4 females from the WPI Crew program. The 8 subjects selected were rowers on the team with prior rowing experience. The subjects participated on a voluntary basis, with all guidelines and procedures explained prior to them signing up. All data collected were kept confidential. Each participant was given a corresponding number. The number correlated to a chart for the sole use of the project’s team members and its advisors. Personal information will not be disclosed.
4. Results

After the completion of testing the prototype with 8 subjects following the protocol, the data were then analyzed. As discussed above, the primary form of data was the power output of the subjects during each of the three power workouts. The results of each individual set were averaged together to determine the average power output for each workout. A Wilcoxon T-Test was then used to compare the power outputs found in the new prototype to the power output found with the current WinTech foot stretcher. For this test, the null hypothesis was that there would be no statistically significant difference in the power output of the rower between the two devices. The alternate hypothesis was that there would be a statistically significant difference in the power output of the rower between the two devices. After performing the Wilcoxon T-Test, a value of $W=16$ was found, which is less than $W_{\text{critical}} = 4$ for a sample size of 8. This means that our null hypothesis was proven. The results show that we are 95% confident that there is no statistically significant difference in the power output of the rower between the two devices. For more information on the Wilcoxon T-Test, please see Appendix E: Wilcoxon T-Test.
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Table 1: Average Watt Testing Results

As mentioned above, in addition to collecting power output data, each of the subjects was given a questionnaire upon completion of the testing protocol. The questionnaire asked the subjects several questions, in which responses were either qualitative or quantitative. The key focus of the analysis of the questionnaires was the comparison of the current foot stretcher design to the new prototype. The first qualitative question asked the subjects what comfort level they found with the new prototype compared to the current foot stretcher. Six of the subjects cited that the comfort of the new prototype was the same, or better, than the current foot stretcher. The two subjects who found the prototype less comfortable than the current foot stretcher cited the seat comfort of the test fixture as an issue with the overall system.

The next qualitative question asked whether subjects found the new prototype to be easily adjustable. Six of the subjects found that it was easy to adjust. The two that said it was not easy to adjust either did not need to adjust the prototype, or noted that they did not adjust to the range appropriately for their physiology, but found it easy to make the physical adjustments. Though the test fixture was a good way to mimic the inside of a hull, some angular adjustment limitations existed with the fixture that would not be found in a racing shell.

The following related question addressed the range of motion provided by the new prototype in comparison to the current foot stretcher. All subjects tested felt that the range of motion was the same, or better, with the prototype. Those who thought it was the same felt that having free splay would provide much better range of motion in a boat using sweep oars, but could not determine it based on using a modified ergometer.
The final qualitative question presented to the subjects compared their performance on the prototype vs. the current foot stretcher. All but one of the subjects felt that they performed the same, or better with the new prototype. The subject who felt that he did not perform as well cited the same issue with limitations to the fixture as the cause for the perceived lower performance. It is additionally important to note that female subjects found the free splay to allow for a better angle of the feet. It was mentioned that the difference in hip structure between males and females requires a different splay angle, which is easier to find with free moving splay. Also, one subject experienced a breakage with the current foot stretcher design while testing that took nearly 6 minutes to fix. No issues such as this were experienced with the new prototype.

Next, the subjects were given the opportunity to qualitatively rank the new prototype in comparison to the current design. The rankings were conducted on a scale of 1-5, where 1 was the least and 5 was the greatest. On average, the new prototype scored 1 point lower than the current design.
5. Discussion

The project began with identifying four key design goals that needed to be met in order to ensure the success of the project. The first goal was to increase the adjustability of the foot stretcher, both in range and increment. The second design goal was to increase the comfort of the foot stretcher to the rower. The third design goal was to increase the overall performance of the foot stretcher. The final design goal was to ensure that the rower performance did not decrease. After completing the modeling, analysis, prototyping, and testing phases of the project, data has been fully collected to determine whether the design goals were met.

5.1 Adjustability

The purpose of working to increase the adjustability of the foot stretcher was to account for differences in rower physiology. Every individual has subtle differences in their physiology that need to be optimized to ensure the best, most comfortable power output. Increasing the range of adjustability, as well as increasing the increment of adjustment would enable this to be possible. The prototype built has three forms of adjustment. The first is an adjustment for the height of the clipping plate. The increment of adjustment for this is ½”, compared to the 11/16” of the current design used in testing. The prototype also has angular adjustment, which is done through adjusting the length of the hypotenuse. The range for the angular adjustment of the prototype is 9°, nearly double that of the current design with 5° (34-43° compared to 40-45°). Finally, the current design uses a fixed position for the shoes. This has negative effects on a rower, particularly in female rowers, and can lead to knee and hip injuries. The new prototype utilizes free splay to allow the rower to freely move his/her feet from 0° to 22.5° from the center.

5.2 Rower Comfort

The intensity of elite rowing causes serious muscle fatigue, regardless of the system design. However, while rowing, if a rower has the ability to reach a more comfortable position, then he/she will be able to have a longer stroke and, hopefully, a higher power output that can lead to winning races. Though rower comfort is beneficial, it is also hard to measure. Changes to the adjustability of the foot stretcher were made to help provide rowers with the ability to reach a more comfortable position. This, however, could not have been fully determined without testing rowers through using the system. As mentioned in the results section, many of the rowers tested felt as though they were able to reach a more comfortable position using the new
Some rowers had comments that provided additional feedback into areas of the foot stretcher that could be refined. For further information, please see section 5.5 Additional Feedback.

**5.3 Foot Stretcher Performance**

When the project began, part of the background research conducted was a survey of current rowers to learn their opinions on the current foot stretcher. The survey revealed that several rowers had experienced breakages while rowing that required time and effort to fix. This is an unacceptable issue to have, especially when these breakages occur during a race. The new prototype was built using stainless steel fasteners, and the positioning of the fasteners were placed to reduce the possibility of breakages. During the testing, a rower experienced a breakage similar to what was found in the survey, which took over 5 minutes to fix. There were no breakages, or loosening of parts, during the course of testing the new prototype.

**5.4 Rower Performance**

The final goal was to ensure that there was no reduction in power output of the rowers while rowing on the new foot stretcher. Comfort, adjustability, and foot stretcher performance are only important if the power output does not decrease. When testing was conducted and average power data was collected, it was found that the new prototype did not statistically decrease the power output of the rower. This allows the new prototype to increase all of the other design goals, without affecting the overall output of the rower. The ultimate goal is that making these changes will enable rowers to achieve the fractions of a percent improvement necessary to win a race.

**5.5 Additional Feedback**

Based on the feedback received from the subjects when ranking the designs, the new prototype scored an average of 1 point lower than the current design. However, it is important to note that the questionnaire enabled the subjects to provide feedback on their experience, which helped to further explain this discrepancy. After reviewing the questionnaires, four common points were identified as areas that needed to be improved. First was the tolerance between the shoe peg and the clipping plate. In the new prototype, the peg had play within the clipping plate, which detracted from the overall rowing experience. The play the peg had with the clipping
plate was caused by manufacturing errors, which could not be fully rectified prior to testing due to time constraints. In a future design, this issue would be resolved, and would not inhibit the rowing experience.

The second point was the spacing of the feet. Many of the subjects felt that the spacing of their feet felt too narrow, especially in comparison to the traditional ergometer, however, some subjects noted that the new prototype was wider than the current design. Unfortunately, this issue is one that is caused by a design constraint in the width of the foot well opening in the hull deck. While the size of the hull deck opening can be changed, it would also require a change in the width of the hull. Adding width to the hull would result in a loss of speed due to added drag in the system, which would be more significant than the gain in power output by widening the feet of the rower.

The third was that most subjects felt as though the testing system did not appropriately demonstrate the advantage to having free splay in the foot stretcher. Many of the subjects referenced the difference between sweep rowing (rowing with 1 oar) and sculling (rowing with 2 oars) as a key point. When sweep rowing, the free splay would enable the rower to reach a more powerful rowing position, which is different than that experienced while sculling (or erging). This point is fully supported. In order to perform preliminary testing and collect data on power outputs, a land based system needed to be utilized. In future testing iterations, water based testing would need to be conducted to fully understand the impact of free splay on the rowers’ ability to row effectively.

Finally, many of the subjects commented that, while they felt that the new prototype would provide them with much more adjustability, they did not need to make many adjustments when setting up the system for the ergometer. This point is not surprising. Making adjustments to the ergometer system does not have as much of an impact on performance in comparison to making similar adjustments while in a racing shell. In future tests, the full capability of the foot stretcher’s adjustment range would be realized when testing in a racing shell, instead of on an ergometer.

The power output results proved the null hypothesis, showing that there is no statistically significant difference in the power output of the rower between the new prototype and the
current design. This test was particularly important to support the design specification, which was set to ensure that the prototype did not decrease the power output of the rower. The prototype was able to allow for more adjustability, which was easier to use, without decreasing the power output of the rower. In subsequent tests a much larger sample would be used to quantify any incremental improvement in power output made by the new prototype.

Furthermore, while the subjects were testing, all settings/preferred foot positions remained fixed and nothing loosened up. This was particularly important because several rowers surveyed during the project’s background research stated that breakage, or loss of adjustments, was a significant issue with current foot stretcher designs. This was exemplified during the testing of this project when the current foot stretcher lost its adjustment during one of the tests, which caused the rower to have to make adjustments to the system during the rest section of the pieces.

5.6 Materials Selection and Potential Improvements

The materials for this prototype were selected for their ease of machining for prototyping purposes. Aluminum was selected for the bulk of the prototype because it is easily machined and relatively inexpensive, as well as lightweight. Parts that were to have a sliding interface with the aluminum were produced as either steel or brass for a lower coefficient of friction. These materials resulted in a prototype that was much too heavy to be used in a racing shell. However, since the testing to prove the concept was conducted on land, meeting the weight requirements was not a concern for this build.

To lower the weight of the system, lightweight polymer materials will be used. The foot plate itself can be made of carbon fiber reinforced polymer. This material would provide adequate stiffness with a much reduced weight over the current aluminum foot plate. The foot plate support could be made of the same carbon fiber reinforced polymer as the foot plate, and could also be redesigned to be less bulky while still providing the same function.

The shoe clipping plate could be produced out of an injection molded polymer. This would allow the complex geometries of the part to be created, while using a lightweight material. Proper polymer selection should lead to a design which is both lighter, and adequately strong for the design.

The locking mechanism could be produced out of a single piece of stainless steel, or an assembly of stainless steel pieces. Since the rest of the product will be produced out of polymers, there is little chance of galvanic corrosion between this piece and the surrounding material,
which is a concern in the prototype where the clipping plate is aluminum and the rod in the locking mechanism is composed of brass.

5.7 Design Modifications

This prototype was intended to be a proof of concept, therefore there are several major design changes which would need to take place to bring this into production. The pegs on the shoes would have to be recessed into the shoe so that the rower could walk around without the peg touching the ground. To compliment this change the clipping plate would have to be slightly redesigned to accommodate the new peg design. Also, to facilitate the change in material from aluminum to carbon fiber and other polymers, threaded inserts would have to be inserted wherever there is a tapped hole in the design. This will prevent pull-out of the threaded fasteners. Finally, each boat manufacturer has slight differences in the shape of the hull. As a result, the design will need to be slightly modified to fit properly for each boat manufacturer.
6. Conclusion

This project represents the successful completion of the design process. The idea for a new foot stretcher design was carried through from research to prototyping and testing. During testing, all adjustments made by the rowers were held, fully supported, and no parts loosened. Finally, adjustability, comfort, and foot stretcher performance were increased while maintaining the performance of the rower. Statistical analysis of the testing found that there was no statistically significant change in the power output between rowers using the new prototype compared to the current design.
7. Recommendations

This project demonstrated the ability to make beneficial improvements to the design of foot stretchers for crew racing shells. However, several improvements must be made to the design prior to realizing a commercialized design.

- In a subsequent generation of the design, carbon fiber and other polymers/polymer composites will need to be used to meet weight requirements and stainless steel will be used for any and all metal components.
- In a future design the shoe peg should be molded into the shoe so that the rower can walk around in the shoe, then clip into the racing shell. This will allow the rower to easily attach himself/herself to the boat without any additional steps.
- The preliminary test used for this project suggests that the design concept is viable, but significantly more testing would need to be conducted on the design with a much larger subject pool. In particular, testing would need to be done using both sculling and sweep rowing configurations to gain feedback and make further refinements.
8. References


Arnold Baca, Phillipp Kornfeind. “A Feedback System for Coordinating Training in Double Rowing” The Engineering of Sport Vol. 7. 659-668


Marques, Pedro Alexandre et al. *Integration of the Contact and Channel model with Axiomatic Design*, The Fifth International Conference on Axiomatic Design, March 25-27, 2009


White, Robert M. “Comparative Anthropometry of the Foot” Army Natick Research and Development Labs MA Individual Protection Lab, December 1982.

Appendix A: Budget

The full budget for this project was approved and submitted to the Mechanical Engineering Department Office. There are three main subsections to the budget, which can be seen below. First, there is a section for the phase 1 build. This budget is completed as a detailed bill of materials needed. The second is for the test fixture. This budget is for the supplies needed to build the fixture, which attaches to an ergometer during the testing phase of the project. The final section is for a phase 2 build. After the testing part of the project is completed, there were monetary funds budgeted so that if refinements could be made to the design, it could be rebuilt in full up to the cost for the design specified in the design specifications section.
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*Figure 43: Project Budget*
Appendix B: Axiomatic Design

Axiomatic design is a design theory developed by Professor Nam Suh at the Massachusetts Institute of Technology. In axiomatic design the designer takes customer needs and transforms them into functional requirements (FR). These functional requirements define what the design wants to achieve, and are always started with a verb such as “provide”, “allow”, “generate”, etcetera. The designer then generates design parameters (DP) to meet these functional requirements. After, or in the process of generating these FRs and DPs the two axioms of axiomatic design are applied. The design, which fulfills both axioms will be the best possible design for the problem.

When defining FRs it is important to ensure that all of them are collectively exhaustive and mutually exclusive. FRs are mutually exclusive if every FR stands alone in what it defines. If one were to have a FR that stated “Provide ability to maintain Stationary” as well as “Provide motion control”, the motion of the device would be defined by two separate FRs. To eliminate this either one of the FRs can be deleted, or the FRs can be worded in such a manner that they are no longer defining the same thing. It is also important to ensure that the FRs are mutually exclusive. If one were to sum up the FRs, the sum should equal the parent. This parent can either be the initial FR that defines the problem, or a lower level FR that was broken down from the parent.

If one were to solve the problem of traveling from point A to point B, where points A and B lie in a straight line, are unobstructed, and all motion must cease at point B, FR0 (the initial FR) may be “Provide travel from Point A to Point B”. FR1 could then be stated as “Provide velocity from point A in direction of Point B”, and FR2 could state “Provide Stopping when Point B has been reached”. Are these two FRs collectively exhaustive and mutually exclusive? Well, let’s examine the mutually exclusive portion. FR1 is defining the forward motion with no mention of stopping upon reaching point B, and FR2 is defining stopping upon reaching point B with no mention of forward velocity towards point B or any other point. We can say that these two FRs are mutually exclusive. The next question is, are they collectively exhaustive; if we sum FR1 and FR2 do we arrive at FR0? In this case it is clear that we do, FR1 defines the forward progress from point A to point B and FR2 states that the path shall end on point B. We can say that these FRs fully define the parent and no further decomposition is necessary.
These FRs and DPs can be related by the equation $\text{FR} = A \times \text{DP}$, where FR is a vector of all FRs, DP is a vector of all DPs, and $A$ is the design matrix (Park, 19). For a system of three FRs the equation should take the form seen in Figure 44. If $\text{FR}_x$ can be effect by $\text{DP}_x$ then a value or characteristic is placed in $A_{x,x}$, if not a 0 is placed in the position.

$$
\begin{bmatrix}
\text{FR}_1 \\
\text{FR}_2 \\
\text{FR}_3
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
\text{DP}_1 \\
\text{DP}_2 \\
\text{DP}_3
\end{bmatrix}
$$

*Figure 44: FR-DP Matrix Equation (Park, 19)*

What makes axiomatic design different are the axioms. Axiom 1, the independence axiom, states that the best possible design should be one that maintains independence of FRs, and that each FR shall only be affected by one DP (Park, 18). If all of the FRs are collectively exhaustive and mutually exclusive the first portion of axiom 1 will be fulfilled. The second part of axiom 1 is a little trickier. All of the DPs that the designer creates must only affect one FR for axiom 1 to be fulfilled completely. This will result in an uncoupled design, which can be seen in Figure 45. If an uncoupled design cannot be achieved, then the designer should make an effort to create a decoupled design. In a decoupled design DPs may affect more than one FR, however the order of adjustment of the DPs can be set so that the desired outcome can be reached if adjusted in the correct order. This can be seen in Figure 45 where a lower triangular matrix has been formed. Typically a decoupled matrix will either take the form of a lower triangular matrix, where adjustment takes place from the bottom up, or an upper triangular matrix, where adjustment takes place from the top down. An uncoupled matrix will always provide a superior design to a decoupled matrix.

A poor design would be one that has a coupled matrix. In these designs, no matter what the order of adjustment, the FRs cannot be satisfied without considerable iteration. The classic example of this is the faucet with the hot and cold knob. In this design both the temperature of the water and the flow of the water are controlled by opening and closing both valves to a certain degree. Using this design it takes several iterations before both the flow and temperature can be adjusted to the desired amount. A better design would be to have separate controls for the
temperature as well as the flow of water. An example of a fully coupled matrix can be seen in Figure 45.

<table>
<thead>
<tr>
<th>Design equation</th>
<th>Design process</th>
</tr>
</thead>
</table>
| \[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix}
= \begin{bmatrix}
A_{11} & 0 & 0 \\
0 & A_{22} & 0 \\
0 & 0 & A_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\] | \[
FR_1 = A_{11} \times DP_1 \\
FR_2 = A_{22} \times DP_2 \\
FR_3 = A_{33} \times DP_3
\] |
| Uncoupled design |              |

<table>
<thead>
<tr>
<th>Design equation</th>
<th>Design process</th>
</tr>
</thead>
</table>
| \[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix}
= \begin{bmatrix}
A_{11} & 0 & 0 \\
A_{21} & A_{22} & 0 \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\] | \[
FR_1 = A_{11} \times DP_1 \\
FR_2 = A_{21} \times DP_1 + A_{22} \times DP_2 \\
FR_3 = A_{31} \times DP_1 + A_{32} \times DP_2 + A_{33} \times DP_3
\] |
| Decoupled design |              |

<table>
<thead>
<tr>
<th>Design equation</th>
<th>Design process</th>
</tr>
</thead>
</table>
| \[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix}
= \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\] | \[
FR_1 = A_{11} \times DP_1 + A_{12} \times DP_2 + A_{13} \times DP_3 \\
FR_2 = A_{21} \times DP_1 + A_{22} \times DP_2 + A_{23} \times DP_3 \\
FR_3 = A_{31} \times DP_1 + A_{32} \times DP_2 + A_{33} \times DP_3
\] |
| Coupled design   |              |

Figure 45: FR-DP Relationships According to the Design Matrix (Park, 20)

The second axiom in axiomatic design is Axiom 2, or the information axiom, which states that the best design will be a functionally uncoupled design with the minimum information content (Park, 18). Since there may be more than one design that satisfies axiom 1, axiom 2 is used to settle upon the best design of them all.

The information content of a design can be defined as seen in Equation 1, where \(I\) is the information content, and \(p\) is the probability of success or the probability of satisfying FR\(i\) with DP\(i\). Ideally there should be some sort of experiment or test to determine \(p\) so that the information content can be calculated. All of the information contents are then summed to find the total information content of the design.
\[ I_i = \log \frac{1}{p} \]

Equation 1: Definition of Information Content (Park, 33)

Since there is not always an experiment or test to determine the probability of success, the designer will often time guess at the probability, or make a comparison between the designs to see which ones have DPs that have a smaller chance of satisfying their FRs. If this is still difficult to determine, the design with the fewest number of FR-DP pairs is often times the best choice.

Axiomatic design can be applied to any number of problems from design of machinery, manufacturing, or even daily life problems. If applied correctly, it should lead to the best possible design for the given problem and the given knowledge of the design team.
Appendix C: Manufacturing

To manufacture the design created, the Haas Technical Education Center in the Washburn Shops of WPI was utilized. There the group found the necessary tools to create their prototype. For the prototype the group relied heavily on Haas vertical CNC milling centers. In a vertical milling center the spindle is located above the able of the machine and moves in a vertical manner as the table moves horizontally below it. An image of a Haas vertical milling center similar to the one utilized in this project can be seen in Figure 46.

![Haas Vertical Milling Center](image)

Figure 46: Haas Vertical Milling Center

In addition to the vertical milling center, a horizontal CNC lathe was used. This machine was used to create the brass rod which the locking pieces of the device were to be attached. The particular machine that the group used was a Haas tool room lathe with an intuitive control, which does not require that a CNC code be developed before operating the lathe. The user can instead specify the features that he wants to create on the controller of the machine. An image of a machine similar to the one that the group utilized can be seen in Figure 47.
To fixture the parts machined for this project, machine vices as well as parallels were used heavily. An image of a machining setup utilizing a vice and parallels can be seen in Figure 48, where 1 is the vice, 2 is the work piece, and 3 are the parallels.

Figure 47: Haas Tool Room Lathe

Figure 48: Image of Vice, Parallels, and Work Piece (Frank, 2012).
Although vices were used heavily during the machining process, there were times when creative fixturing methods needed to be utilized to effectively machine the parts. Figure 49 shows an example of creative fixturing, which was necessary to machine the long foot plate support. To do this the group utilized the edge of a vice, a right angle machining support, a pipe clamp, a C-clamp, and machine straps. The group also made use of soft jaws made of aluminum, custom made v-blocks, and sacrificial plates (to which the work piece was bolted) to manufacture some of the parts of the prototype.

To develop the tool paths for the machines, the group utilized the software Esprit. Esprit allowed the group to machine some of the complex angles and curves in the design of the prototype. The three dimensional machining capabilities of the program were used extensively to create these features. The group also utilized some of the high speed machining capabilities of Esprit especially trochoidal pocketing. Trochoidal pocketing is a method where the largest
possible curve is selected as the path of the tool to keep the tool engaged in the material for longer periods of time. Trochoidal pocketing allows the machinist to select higher feed rates, machine faster, as well as maintain a constant load on the tool during the machining operation.
Appendix D: Stress and Deflection Analysis

In the beginning of the project design research was conducted to define a series of specifications for the design. Some of these specifications addressed the loading requirements for the system. Once the prototype was modeled, it became necessary to ensure that the design met the loading requirements set forth. Those requirements were being able to withstand a 1500N normal load to the foot stretcher and have less than 4mm in deflection.

To determine if the device we designed would withstand the loadings that the group anticipates, while deflecting as little as possible, an FEA analysis was conducted using SolidWorks. The first piece analyzed was the clipping plate, which would receive the pegs from the shoes that the rower would wear. Since this device is to be attached to the foot plate using two bolts, both of the faces in contact with the foot plate outside of the bolts were fixed. This would simulate the constraints that will be seen on the part. This fixturing can better be seen in Figure 50 where the yellow areas are fixed.

Figure 50: Fixturing of the Clipping Plate for Stress Analysis
Since the bottom of the clipping plate will be supported by the foot plate, only forces acting away from the foot plate would cause noticeable deflections in the clipping plate. To simulate the loadings that may occur under normal use of the clipping plate, a 1500N force was applied normal to the top face of the clipping plate in the direction away from the foot plate. This is illustrated in Figure 51 below by the purple arrows. The single force at the center will provide a conservative estimate of the deflections and stresses seen in the part, though in reality the force applied to the clipping plate would be in two places, occurring at each peg hole.

![Figure 51: Loading of the Clipping Plate for Stress Analysis](image)

When the analysis was run, the maximum deflection seen in the plate was 0.359 mm, as demonstrated in Figure 52.
Next, the group looked at the stresses that the part could experience as it is given the 1500N load specified in the design specifications. When the computer calculated the Von Mises stress throughout the part, the maximum stress seen was 94.3 \times 10^6 \text{ Pa}, resulting in a safety factor of 3. The maximum stresses were seen at sharp corners and cuts in the part resulting from the geometry. A representation of the stress distribution can be seen in Figure 53.
To confirm the results seen in the FEA, hand calculations were performed on simplified versions of the parts. For the clipping plate the group assumed a beam or constant cross section with a length of 9.45 inches, width of 2.5 inches and a height of 0.375 inches. The end conditions of the beam were set at fixed-fixed with the force applied in the center to mimic the FEA. To calculate the deflections in the beam the group utilized Equation 2 where $Max\ y$ is the displacement, $W$ is the force, $l$ is the length, $E$ is the elastic modulus, and $I$ is the moment of inertia. The maximum displacement in the case will occur at a position half way between the two supported faces. The work behind this calculation can be seen in Figure 54.

$$Max\ y = \frac{-WL^3}{192EI}$$

Equation 2: Deflection formula for a fixed-fixed, centrally loaded beam (Young and Budynas, 190)

$$M = \frac{WL}{8}$$

Equation 3: Maximum moment seen in a fixed-fixed, centrally loaded beam (Young and Budynas, 190)
\[
\sigma = \frac{M \cdot \frac{h}{2}}{I}
\]

**Equation 4: Maximum stress seen in a fixed-fixed, centrally leaded beam (Young and Budynas, 190)**

The group then performed an analysis using Roark’s formulas to verify the stress that was seen in the part. Equation 3 was used to calculate for the stress seen in the center of the part. In this equation \(M\) is the moment, \(l\) is the length, and \(W\) is the load. The maximum moment was calculated to be 45 Nm. The group then used Equation 4, where \(\sigma\) is the stress, \(M\) is the moment, \(h\) is the height of the part, and \(I\) is the moment of inertia. The same simplified conditions were used in the stress calculation as were used in the deflection calculation. The maximum stress in the part was calculated to be 46,700,000 Pa, which would be the stress located at the center of the part along the top or bottom face. A stress of similar magnitude can be seen in Figure 53 along the top face of the part. This verifies that the values seen in the FEA are what are expected. And because of this, the group can say the under the loads that it anticipates, the part will not fail. The hand calculations behind this conclusion can be seen in Figure 54.
The next piece that the group looked at was the support for the foot plate. This piece is held to the hull of the boat in such a manner that it can be considered a fixed-fixed beam. In the model each end was fixed by the holes for the tube ends, which is what will be fixed in the actual part. This fixturing can be seen in the Figure 55 and is indicated by the yellow feature. The force was applied in the center of the part in a direction normal to the top face. The force is represented in the Figure 55 by the purple arrows. Though in the actual part the force will be distributed along the entire top surface of the foot plate support, the centrally loaded case will provide a conservative estimate of the deflections seen in the part.
When the analysis was run the maximum deflection seen was 0.075 mm, as demonstrated in Figure 56.

To confirm this deflection the group utilized the work on deflections done by Roark to verify the deflection by calculation. The group used a simplified version of the part to simplify the calculations. The simplified version was a fixed-fixed centrally loaded beam with a constant cross section of 1.75 inches wide by 0.65 inches tall, and 8.75 inches long. Using the Equation 2, the group found the maximum displacement to be 0.095 mm. Though this is different from the
FEA value, it is close enough that we can confirm the results of the FEA. The results of this hand calculation can be seen in Figure 58.

Next the group looked at the stresses that the part may experience as it is loaded. When the computer calculated the Von Mises stress throughout the part, the maximum stress seen was 22.7 X 10^6 Pa, resulting in a safety factor of 12. The distribution of the stresses throughout the part can be seen in Figure 57.

To verify this, an analysis using Roark’s formulas was performed. The group used the same simplified version of the part that was used in the deflection analysis. Using Equation 3 and Equation 4 the group found the maximum moment to be 42 Nm and the maximum stress to be 24.3 X 10^6 Pa. This stress is similar in magnitude to the stress that appears at the center of the part on the top and bottom face. This verifies that the values seen in the FEA are what are expected. And because of this the group can say the under the loads that it anticipates, the part will not fail. The hand calculations behind this conclusion can be seen in Figure 58.
Figure 58: Hand Calculation of the Stress and Deflection of the Foot Plate Support
Appendix E: Wilcoxon T-Test

The testing of our MQP was conducted using the protocol previously defined in the report. The power results of the testing were then recorded in a spreadsheet, where the average value for the power output was calculated. The results for these tests can be found in the table below. The traditional ergometer data was collected as a baseline test to ensure the fixture was working properly for the other two data sets, and to ensure that all subjects understood the procedure. Once these results were calculated, a Wilcoxon T-Test was used, since it is not safe to assume that the data is normally distributed. The two data sets that were used were for the WinTech Foot Stretcher and our prototype design. To calculate the data using the Wilcoxon T-Test, several steps were involved. They were the following:

1. The difference must be calculated between the two data sets used.
2. The sign of the difference calculated in step 1 must be recorded.
3. The absolute value of the difference must be recorded.
4. The differences must be assigned a rank number, from lowest to highest (lowest difference =1).
5. The rank must then be given the sign of the difference.
6. All negative values must be summed to calculate W_.
7. All the positive values must be summed to calculate W+.
8. The lesser of these two values must be compared to the Wcritical value (see Table 2: Wilcoxon T-Test Critical Values)
   a. If the W value is less than Wcritical, then the null hypothesis is disproven.

Based on the calculations that were conducted, the null hypothesis was proven, showing that our prototype did not significantly change the power output of the rower. This is particularly important to ensure that there is no decrease in power output.
Table of critical values for the Wilcoxon test:

To use this table: compare your obtained value of Wilcoxon's test statistic to the critical value in the table (taking into account N, the number of subjects).

Your obtained value is statistically significant if it is equal to or SMALLER than the value in the table.

e.g.: suppose my obtained value is 22, and I had 15 participants.

<table>
<thead>
<tr>
<th>N</th>
<th>0.05</th>
<th>0.02</th>
<th>0.01</th>
</tr>
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<td>-</td>
<td>-</td>
</tr>
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<td>0</td>
<td>-</td>
</tr>
<tr>
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<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
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</tr>
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<td>21</td>
<td>59</td>
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</tr>
<tr>
<td>25</td>
<td>89</td>
<td>77</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 2: Wilcoxon T-Test Critical Values
Here is the table for Wilcoxon T-Test Calculations:

<table>
<thead>
<tr>
<th>Subject</th>
<th>Ours</th>
<th>WinTech</th>
<th>Sign</th>
<th>Value</th>
<th>%</th>
<th>Absolute</th>
<th>Rank</th>
<th>Signed Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>204.3</td>
<td>207.3</td>
<td>-</td>
<td>-1.7</td>
<td>-0.007</td>
<td>-0.007</td>
<td>1</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>117.7</td>
<td>141</td>
<td>+</td>
<td>6.7</td>
<td>0.0175</td>
<td>0.0175</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>189.0</td>
<td>174.1</td>
<td>+</td>
<td>14.6</td>
<td>0.084</td>
<td>0.084</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
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<td>153.8</td>
<td>+</td>
<td>4.9</td>
<td>0.0283</td>
<td>0.0283</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>269.7</td>
<td>280.4</td>
<td>-</td>
<td>-11.7</td>
<td>-0.047</td>
<td>-0.047</td>
<td>5</td>
<td>-1</td>
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<tr>
<td>6</td>
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<td>164.4</td>
<td>+</td>
<td>3.3</td>
<td>0.020</td>
<td>0.020</td>
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<td>-0.1052</td>
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<td>-1</td>
</tr>
<tr>
<td>8</td>
<td>274.3</td>
<td>296.3</td>
<td>-</td>
<td>-2</td>
<td>-0.0067</td>
<td>-0.0067</td>
<td>2</td>
<td>-7</td>
</tr>
</tbody>
</table>

\[ W_+ = 16 \]
\[ W_- = 20 \]
\[ W_+ = 16 \]
\[ W_- = 16 \]

\( H_0: \) There is no significant difference between our power output and WinTech's.

\( H_1: \) There is a significant difference between our power output and WinTech's.

Since \( W_- = 16 > 4 \), we do not accept the null hypothesis. Our design does not cause a significant change (decrease) in the power output of the rower, when compared to the current WinTech foot stretchers used in racing shells.

We are 95% confident.
Appendix F: Questionnaire Responses

Rowing Foot Stretcher Design

Testing Questionnaire

Subject 1

1) What is your testing number? __________

2) Which workout did you do?
   A. Cardio Workout   B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

4) Please briefly explain your reasoning for the previous selection.
   It is the same comfort level because the shoes were adjustable in height and a limited angle. This allowed me to adjust the feet to a maximum power output position and it felt slightly easier to obtain the same power with a new position. I would have said that it was more comfortable if there were no slip in the shoes at the finish position. Specifically in the aluminum design, the pins that attached the shoes to the stretcher would give out at the finish and most likely cause a slight loss in power as well.

5) How would you rank the comfort level of the new prototype vs. the current foot stretcher?
   a. More comfortable than the current foot stretcher
   b. Less comfortable than the current foot stretcher
   c. About the same level of comfort as the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.
   Again, due to slipping it was about the same. The structure itself feels fairly solid and makes use of some hardware that is new to the user. This may be an area of concern because there are more parts that would require replacement and a higher probability of something going wrong.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
c. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection.
The foot stretcher is a much more comfortable and intuitive device to row in. Because it has shoes that one puts on, it feels more personalized. The straps on an erg easily loosen during raster paced rows and distract the rower from the workout. This does not happen with the foot stretcher.

9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
   b. No*

10) If you experienced an equipment failure, please describe what happened.
   *While there were no failures, the device did have some slip due to loose tolerance between the shoe attachment piece and the foot stretcher.

11) Were you able to easily adjust the new prototype to a comfortable setting?
   a. Yes
   b. No

12) If you answered no, please describe the issues you experienced.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted motion).

<table>
<thead>
<tr>
<th>Device</th>
<th>1</th>
<th>2</th>
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<th>4</th>
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</thead>
<tbody>
<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>New Prototype</td>
<td></td>
<td></td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Current Foot Stretcher</td>
<td></td>
<td></td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

14) How would you rank the adjustability of the new prototype to the current foot stretcher?
   a. The new prototype is much more adjustable than the current foot stretcher
   b. The new prototype is more adjustable than the current foot stretcher
   c. The new prototype has about the same adjustability as the current foot stretcher
   d. The new prototype is less adjustable than the current foot stretcher
   e. The new prototype is much less adjustable than the current foot stretcher.

15) Please briefly explain your reasoning for the previous selection.
   There are some very small differences in adjustment that is achievable with the new prototype such as foot angle, though it is only a slight angle it is noticeable.
16) How would you rank the range of motion provided by the new prototype to the current foot stretcher?
   a. The new prototype provides more range of motion than the current foot stretcher
   b. The new prototype provides less range of motion than the current foot stretcher
   c. The new prototype provides about the same range of motion as the current foot stretcher.

17) Please briefly explain your reasoning for the previous selection.
    There was no real difference in range of motion between the two devices, each allowed on to achieve a similar position.

18) How would you rank your performance while using the new prototype vs. the current foot stretcher?
   a. Performed better than when using the current foot stretcher
   b. Performed worse than when using the current foot stretcher
   c. Performed about the same as when using the current foot stretcher

19) Please briefly explain your reasoning for the previous selection.
    I seemed to get about the same power rating in each trial.

20) How would you rank your performance while using the new prototype vs. the ergometer?
    a. Performed better than when using the ergometer
    b. Performed worse than when using the ergometer
    c. Performed about the same as when using the ergometer

21) Please briefly explain your reasoning for the previous selection.
    There was no large noticeable difference in the trials.

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
    a. Performed better than when using the ergometer
    b. Performed worse than when using the ergometer
    c. Performed about the same as when using the ergometer

23) Please briefly explain your reasoning for the previous selection.
    The device seemed more comfortable and familiar to row in and my shoes did not get loose.

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
    Once the tolerance issue is resolved, the device will surely allow for more improvement over traditional devices.
1) What is your testing number? ________
2) Which workout did you do?
   A. Cardio Workout  B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer
4) Please briefly explain your reasoning for the previous selection.
   Other than the wooden vs. plastic seat I didn’t notice any difference in how the rowing
   motion felt.

5) How would you rank the comfort level of the new prototype vs. the current foot
   stretcher?
   a. More comfortable than the current foot stretcher
   b. Less comfortable than the current foot stretcher
   c. About the same level of comfort as the current foot stretcher
6) Please briefly explain your reasoning for the previous selection.
   Having an increased range of motion didn’t feel different to having my feet set in one
   spot. I noticed my heels naturally came together but didn’t notice a difference in how the
   rowing felt.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer
8) Please briefly explain your reasoning for the previous selection.
   I feel as though my feet are in the same position in both of them.
9) Did you experience any equipment failures during your testing of the new prototype?  
a. Yes  
b. No  

10) If you experienced an equipment failure, please describe what happened.

11) Were you able to easily adjust the new prototype to a comfortable setting?  
a. Yes  
b. No  

12) If you answered no, please describe the issues you experienced.  
I didn’t adjust it, my tester did for me. The slides needed adjusting when I hit the front of them during the warm up. We couldn’t adjust the foot stretcher itself because the chain wouldn’t reach that far back.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted motion).

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14) How would you rank the adjustability of the new prototype to the current foot stretcher?  
a. The new prototype is much more adjustable than the current foot stretcher  
b. The new prototype is more adjustable than the current foot stretcher  
c. The new prototype has about the same adjustability as the current foot stretcher  
d. The new prototype is less adjustable than the current foot stretcher  
e. The new prototype is much less adjustable than the current foot stretcher.

15) Please briefly explain your reasoning for the previous selection.  
It had the same setup and would have adjusted fine, just limited by the erg chain.

16) How would you rank the range of motion provided by the new prototype to the current foot stretcher?  
a. The new prototype provides more range of motion than the current foot stretcher  
b. The new prototype provides less range of motion than the current foot stretcher  
c. The new prototype provides about the same range of motion as the current foot stretcher.

17) Please briefly explain you reasoning for the previous selection.  
In terms of side to side movement, the new prototype allowed you to move your heels left to right a lot more. In terms of up and down movement it was the same.
18) How would you rank your performance while using the new prototype vs. the current foot stretcher?
   a. Performed better than when using the current foot stretcher
   b. Performed worse than when using the current foot stretcher
   c. Performed about the same as when using the current foot stretcher

19) Please briefly explain your reasoning for the previous selection.
   It felt as though it neither hindered nor aided my performance.

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

21) Please briefly explain your reasoning for the previous selection.
   It felt as though it neither hindered nor aided my performance.

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

23) Please briefly explain your reasoning for the previous selection.
   It felt as though it neither hindered nor aided my performance.

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
1) What is your testing number? ________
2) Which workout did you do?
   A. Cardio Workout   B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

4) Please briefly explain your reasoning for the previous selection.
   I am more used to the erg, but the new prototype did feel more like a boat.

5) How would you rank the comfort level of the new prototype vs. the current foot stretcher?
   a. More comfortable than the current foot stretcher
   b. Less comfortable than the current foot stretcher
   c. About the same level of comfort as the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.
   I liked how the feet could turn to adjust for hip width.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection.
   The feet just made me feel like I couldn’t move properly.

9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
   b. No

10) If you experienced an equipment failure, please describe what happened.
11) Were you able to easily adjust the new prototype to a comfortable setting?
   a. Yes
   b. No
12) If you answered no, please describe the issues you experienced.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted motion).
  经纪器 | 1 | 2 | 3 | 4 | 5
   新型原型 | 1 | 2 | 3 | 4 | 5
   当前脚绷紧器 | 1 | 2 | 3 | 4 | 5

14) How would you rank the adjustability of the new prototype to the current foot stretcher?
   a. The new prototype is much more adjustable than the current foot stretcher
   b. The new prototype is more adjustable than the current foot stretcher
   c. The new prototype has about the same adjustability as the current foot stretcher
   d. The new prototype is less adjustable than the current foot stretcher
   e. The new prototype is much less adjustable than the current foot stretcher.
15) Please briefly explain your reasoning for the previous selection.
   我的脚能够移动以适应

16) How would you rank the range of motion provided by the new prototype to the current foot stretcher?
   a. The new prototype provides more range of motion than the current foot stretcher
   b. The new prototype provides less range of motion than the current foot stretcher
   c. The new prototype provides about the same range of motion as the current foot stretcher.
17) Please briefly explain you reasoning for the previous selection.
   我感觉自己可以移动得更远

18) How would you rank your performance while using the new prototype vs. the current foot stretcher?
   a. Performed better than when using the current foot stretcher
   b. Performed worse than when using the current foot stretcher
   c. Performed about the same as when using the current foot stretcher
19) Please briefly explain your reasoning for the previous selection.
It felt pretty bad with the current foot stretcher

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer
21) Please briefly explain your reasoning for the previous selection. Already pretty used to the erg

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer
23) Please briefly explain your reasoning for the previous selection. More used to the erg and it was more comfortable

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
   I definitely preferred the new prototype, was more comfortable and I felt I was able to use more power
Rowing Foot Stretcher Design

Testing Questionnaire

Subject 4

1) What is your testing number? _________
2) Which workout did you do?
   A. Cardio Workout   B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

4) Please briefly explain your reasoning for the previous selection.
   I am more used to the erg, but the new prototype did feel more like a boat

5) How would you rank the comfort level of the new prototype vs. the current foot stretcher?
   a. More comfortable than the current foot stretcher
   b. Less comfortable than the current foot stretcher
   c. About the same level of comfort as the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.
   I liked how the feet could turn to adjust for hip width

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection.
   The feet just made me feel like I couldn’t move properly

9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
   b. No

10) If you experienced an equipment failure, please describe what happened.
11) Were you able to easily adjust the new prototype to a comfortable setting?
   a. Yes
   b. No

12) If you answered no, please describe the issues you experienced.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted motion).

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14) How would you rank the adjustability of the new prototype to the current foot stretcher?
   a. The new prototype is much more adjustable than the current foot stretcher
   b. The new prototype is more adjustable than the current foot stretcher
   c. The new prototype has about the same adjustability as the current foot stretcher
   d. The new prototype is less adjustable than the current foot stretcher
   e. The new prototype is much less adjustable than the current foot stretcher.

15) Please briefly explain your reasoning for the previous selection.
   My feet were able to move to accommodate

16) How would you rank the range of motion provided by the new prototype to the current foot stretcher?
   a. The new prototype provides more range of motion than the current foot stretcher
   b. The new prototype provides less range of motion than the current foot stretcher
   c. The new prototype provides about the same range of motion as the current foot stretcher.

17) Please briefly explain your reasoning for the previous selection.
   I felt like I could move farther up the slide.

18) How would you rank your performance while using the new prototype vs. the current foot stretcher?
   a. Performed better than when using the current foot stretcher
   b. Performed worse than when using the current foot stretcher
   c. Performed about the same as when using the current foot stretcher

19) Please briefly explain your reasoning for the previous selection.
It felt pretty bad with the current foot stretcher

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

21) Please briefly explain your reasoning for the previous selection.
   Already pretty used to the erg

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

23) Please briefly explain your reasoning for the previous selection.
   More used to the erg and it was more comfortable

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
   I definitely preferred the new prototype, was more comfortable and I felt I was able to use more power
Rowing Foot Stretcher Design

Testing Questionnaire

Subject 5

1) What is your testing number? ________

2) Which workout did you do?

   B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. Less comfortable than the ergometer

4) Please briefly explain your reasoning for the previous selection.
   The plate that the foot stretcher was put on was at an odd angle and would leave me
   pointing my toes too much at the finish. There was also an unwanted up and down
   movement of the feet.

5) How would you rank the comfort level of the new prototype vs. the current foot
   stretcher?
   a. Less comfortable than the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.
   The above answers for number 4. Although the free ankles had a different feel to it I
   would be interested to see how it would feel while rowing on the water.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection.
   Slightly in favor of the current foot stretcher just because it has a shoe to hold your foot
   not just a little strap.

9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
10) If you experienced an equipment failure, please describe what happened.
   Only a problem with the rig itself and I pushed the footplate past the back of the tracks
   that it is held on and had to pull it back into a place where I could push off it and not push
   it off the rig.

11) Were you able to easily adjust the new prototype to a comfortable setting?
   a. Yes
12) If you answered no, please describe the issues you experienced.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least
   (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted
   motion).
   
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<tr>
<td>Current Foot Stretcher</td>
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14) How would you rank the adjustability of the new prototype to the current foot stretcher?
   a. The new prototype has about the same adjustability as the current foot stretcher
15) Please briefly explain your reasoning for the previous selection
   I didn’t need to adjust feet height or anything so im not quite sure if there is the
   adjustability.

16) How would you rank the range of motion provided by the new prototype to the current
    foot stretcher?
   a. The new prototype provides more range of motion than the current foot stretcher
17) Please briefly explain you reasoning for the previous selection.
   Leaving the ankles free gave a little more freedom for your feet when you got up to the
   catch so you could have a slightly wider stance closer to one you would have if you were
   doing a dead lift or other weight lifting.

18) How would you rank your performance while using the new prototype vs. the current
    foot stretcher?
   a. Performed better than when using the current foot stretcher
19) Please briefly explain your reasoning for the previous selection.
Although not used to the process of getting your feet into the foot stretcher, wearing the shoes into the boat could make things easier as instead of having to put on socks or take off the shoes you are wearing you can simply just slide and lock your feet into place.

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed worse than when using the ergometer
21) Please briefly explain your reasoning for the previous selection.
   Only slightly worse just because the angle of the feet was just too awkward to really get the power.

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed worse than when using the ergometer
23) Please briefly explain your reasoning for the previous selection.
   The breakage during the 3rd and 4th piece was one problem and the feet are closer than they are on the erg so you don’t have that same lifting stance.

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.

   - Adjust the angle of the feet themselves so it is closer to that of a boat.
   - Tighten up the feet so that there is no forward/backward motion
   - I felt like the toes of the feet were still a little closer than they should have been
Rowing Foot Stretcher Design

Testing Questionnaire

Subject 6

1) What is your testing number? ___?_____

2) Which workout did you do?

   A. Cardio Workout   B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. **Less comfortable than the ergometer**
   c. About the same level of comfort as the ergometer

4) Please briefly explain your reasoning for the previous selection.
   I prefer to have my feet farther apart which the erg allowed for but the new prototype did not.

5) How would you rank the comfort level of the new prototype vs. the current foot stretcher?
   a. More comfortable than the current foot stretcher
   b. **Less comfortable than the current foot stretcher**
   c. About the same level of comfort as the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.
   It was uncomfortable to have to apply an extra force inwards on my heel to keep my feet straight. After trying having my heels spread father apart, it was less comfortable to apply pressure on the drive. This could slightly be because I’m used to rowing the other way.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
   b. **Less comfortable than the ergometer**
c. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection. They’re slightly less comfortable because my feet felt very close together, as I mentioned in question 4.

9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
   b. No

10) If you experienced an equipment failure, please describe what happened.

11) Were you able to easily adjust the new prototype to a comfortable setting?
   a. Yes
   b. No

12) If you answered no, please describe the issues you experienced.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted motion).

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14) How would you rank the adjustability of the new prototype to the current foot stretcher?
   a. The new prototype is much more adjustable than the current foot stretcher
   b. The new prototype is more adjustable than the current foot stretcher
   c. The new prototype has about the same adjustability as the current foot stretcher
   d. The new prototype is less adjustable than the current foot stretcher
   e. The new prototype is much less adjustable than the current foot stretcher.

15) Please briefly explain your reasoning for the previous selection
    I did not notice any difference in the adjustability of the foot stretchers compared to the new prototype.

16) How would you rank the range of motion provided by the new prototype to the current foot stretcher?
   a. The new prototype provides more range of motion than the current foot stretcher
   b. The new prototype provides less range of motion than the current foot stretcher
c. The new prototype provides about the same range of motion as the current foot stretcher.

17) Please briefly explain your reasoning for the previous selection.
You were able to adjust the angle of your foot continuously as you wished, whereas in the current foot stretcher this was not an option.

18) How would you rank your performance while using the new prototype vs. the current foot stretcher?
   a. Performed better than when using the current foot stretcher
   b. Performed worse than when using the current foot stretcher
   c. Performed about the same as when using the current foot stretcher

19) Please briefly explain your reasoning for the previous selection.
I did not look at my results after using each foot stretcher, although I did not move my heels while erging so they did not seem to affect how I erged.

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

21) Please briefly explain your reasoning for the previous selection.
I prefer my feet to be slightly farther apart while testing and that was provided for me on the erg while my feet were closer together on the new prototype.

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

23) Please briefly explain your reasoning for the previous selection.
I prefer my feet to be slightly farther apart while testing and that was provided for me on the erg while my feet were closer together on the foot stretchers.

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
I think the idea to give a greater range of motion in the foot stretchers is a good one, although moving the heels does little to help especially when tested on the erg. It may be of greater benefit when rowing sweep when a rower is trying to increase their lean out of the boat or while trying to set the boat, although these things were not tested.
Rowing Foot Stretcher Design

Testing Questionnaire

Subject 7

1) What is your testing number? ________

2) Which workout did you do?

   A. Cardio Workout  B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
      c. About the same level of comfort as the ergometer

4) Please briefly explain your reasoning for the previous selection.

5) How would you rank the comfort level of the new prototype vs. the current foot stretcher?
   a. More comfortable than the current foot stretcher
      b. Less comfortable than the current foot stretcher
         c. About the same level of comfort as the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
      b. Less comfortable than the ergometer
         c. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection.
   
   the current foot stretcher felt as if it provided for more connection on the drive. It also 
   was a solid point in which to push off of, which I did not feel with the shoes that pivoted 
   in their housing. However, with the shoes that pivoted I do feel as if they would provide 
   greater reach in swept-oar boats.
9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
   b. No

10) If you experienced an equipment failure, please describe what happened.

11) Were you able to easily adjust the new prototype to a comfortable setting?
   a. Yes
   b. No

12) If you answered no, please describe the issues you experienced.
   *The shallow pitch of the new prototype felt uncomfortable. This pitch was limited by equipment, so in a boat it would be less shallow I’m assuming.*

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted motion).

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14) How would you rank the adjustability of the new prototype to the current foot stretcher?
   a. The new prototype is much more adjustable than the current foot stretcher
   b. The new prototype is more adjustable than the current foot stretcher
   c. The new prototype has about the same adjustability as the current foot stretcher
   d. The new prototype is less adjustable than the current foot stretcher
   e. The new prototype is much less adjustable than the current foot stretcher.

15) Please briefly explain your reasoning for the previous selection.

16) How would you rank the range of motion provided by the new prototype to the current foot stretcher?
   a. The new prototype provides more range of motion than the current foot stretcher
   b. The new prototype provides less range of motion than the current foot stretcher
   c. The new prototype provides about the same range of motion as the current foot stretcher.

17) Please briefly explain you reasoning for the previous selection.
   *On the ergometer (and subsequently a sculling boat) the prototype provided for less range of motion. However, when I attempted to lean out just to see how a swept-oar boat would feel, I felt as if there was greater range of motion.*
18) How would you rank your performance while using the new prototype vs. the current foot stretcher?
   a. Performed better than when using the current foot stretcher
   b. Performed worse than when using the current foot stretcher
   c. Performed about the same as when using the current foot stretcher

19) Please briefly explain your reasoning for the previous selection.
   *Power ratings were much slower*

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

21) Please briefly explain your reasoning for the previous selection.
   *Power ratings were slower*

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

23) Please briefly explain your reasoning for the previous selection.
   *Had a much better connection and stability at the catch.*

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
Rowing Foot Stretcher Design

Testing Questionnaire

Subject 8

1) What is your testing number? ________

2) Which workout did you do?

   B. Power Workout

3) How would you rank the comfort level of the new prototype vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

4) Please briefly explain your reasoning for the previous selection.
   It’s more comfortable because the shoes are attached to the foot stretcher and can’t loosen up at all.

5) How would you rank the comfort level of the new prototype vs. the current foot stretcher?
   a. More comfortable than the current foot stretcher
   b. Less comfortable than the current foot stretcher
   c. About the same level of comfort as the current foot stretcher

6) Please briefly explain your reasoning for the previous selection.
   They were the same comfort level, your shoes were a good size and they were easily adjusted.

7) How would you rank the comfort level of the current foot stretcher vs. the ergometer?
   a. More comfortable than the ergometer
   b. Less comfortable than the ergometer
   c. About the same level of comfort as the ergometer

8) Please briefly explain your reasoning for the previous selection.
   It’s more comfortable because the shoes are attached to the foot stretcher and can’t loosen up at all.
9) Did you experience any equipment failures during your testing of the new prototype?
   a. Yes
   b. No

10) If you experienced an equipment failure, please describe what happened.

11) Were you able to easily adjust the new prototype to a comfortable setting?
    a. Yes
    b. No

12) If you answered no, please describe the issues you experienced.

13) Please rank how each device held your shoe/foot on a scale of 1-5, where 1 is the least
    (did not hold the shoe at all) and 5 is the greatest (held the shoe without any unwanted
    motion).
    
    | Device                | 1 | 2 | 3 | 4 | 5 |
    |-----------------------|---|---|---|---|---|
    | Ergometer             |   |   |   |   |   |
    | New Prototype         |   |   |   |   |   |
    | Current Foot Stretcher|   |   |   |   |   |

14) How would you rank the adjustability of the new prototype to the current foot stretcher?
    a. The new prototype is much more adjustable than the current foot stretcher
    b. The new prototype is more adjustable than the current foot stretcher
    c. The new prototype has about the same adjustability as the current foot stretcher
    d. The new prototype is less adjustable than the current foot stretcher
    e. The new prototype is much less adjustable than the current foot stretcher.

15) Please briefly explain your reasoning for the previous selection.
    I didn’t have to adjust much, so there might be more adjustment I didn’t use or
    something it didn’t have.

16) How would you rank the range of motion provided by the new prototype to the current
    foot stretcher?
    a. The new prototype provides more range of motion than the current foot stretcher
    b. The new prototype provides less range of motion than the current foot stretcher
    c. The new prototype provides about the same range of motion as the current foot
       stretcher.

17) Please briefly explain your reasoning for the previous selection.
    Rowing is all about the feel of the equipment and it just felt like it did.

18) How would you rank your performance while using the new prototype vs. the current
    foot stretcher?
    a. Performed better than when using the current foot stretcher
    b. Performed worse than when using the current foot stretcher
c. Performed about the same as when using the current foot stretcher

19) Please briefly explain your reasoning for the previous selection.
After doing all the test there was a minimal change between the different tests thus the performance is similar.

20) How would you rank your performance while using the new prototype vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

21) Please briefly explain your reasoning for the previous selection.
After doing all the test there was a minimal change between the different tests thus the performance is similar.

22) How would you rank your performance while using the current foot stretcher vs. the ergometer?
   a. Performed better than when using the ergometer
   b. Performed worse than when using the ergometer
   c. Performed about the same as when using the ergometer

23) Please briefly explain your reasoning for the previous selection.
After doing all the test there was a minimal change between the different tests thus the performance is similar.

24) Please provide any additional feedback you may have for the new prototype based on your experience testing the design.
This is a great first prototype but there is definitely room to improve.
Appendix G: Institutional Review Board Application

WORCESTER POLYTECHNIC INSTITUTE
Institutional Review Board
Application for Approval to Use Human Subjects in Research

This application is for: (Please check one)  □ Expected Review  □ Full Review

Principal Investigator (PI) or Project Faculty Advisor: (NOT a student or fellow; must be a WPI employee)
Name: Professor Allen Hoffman  Tel No: 608.831.6217  E-Mail: ahoffman@wpi.edu
Department: Mechanical Engineering

Co-Investigator(s): (Co-PI(s)/non students)
Name: Professor Holly Ault  Tel No:  E-Mail: hault@wpi.edu
Name:  Tel No:  Address: 

Student Investigator(s):
Name: Dan Plerson  Tel No: 603.488.7744  E-Mail: dplerson10@gmail.com
Name: John Madura  Tel No:  E-Mail: jhnmadura@wpi.edu

Check if □ Undergraduate project (MQP, IQP, Suff., other)  □ Graduate project (M.S. Ph.D., other)

WPI IRB use only
IRB # Date:

Has an IRB ever suspended or terminated a study of any investigator listed above?
No □ Yes □ (Attach a summary of the event and resolution.)

Vulnerable Populations: The proposed research will involve the following (Check all that apply):
pregnant women □  human fetuses □  neonates □  minors/children □  prisoners □
students □  individuals with mental disabilities □  individuals with physical disabilities □

Collaborating Institutions: (Please list all collaborating institutions.)
N/A

Locations of Research: (If at WPI, please indicate where on campus. If off campus, please give details of locations.)
WPI, Alumni Gymnasium - Lake Quinsigamond, Worcester/Shrewsbury, MA (Practice Location)

Project Title: Rowing Foot Stretcher Design

Funding: (If the research is funded, please enclose one copy of the research proposal or most recent draft with your application.)
Funding Agency: N/A  WPI Fund: N/A

Human Subjects Research: (All study personnel having direct contact with subjects must take and pass a training course on human subjects research. There are links to web-based training courses that can be accessed under the Training link on the IRB web site http://www.wpi.edu/offices/irb/training.html. The IRB requires a copy of the completion certificate from the course or proof of an equivalent program.)

Anticipated Dates of Research:
Start Date: 1/1/2012  Completion Date: 5/1/2012

WPI/IRB revised 10/5/2010  1 of 6
WORCESTER POLYTECHNIC INSTITUTE
Institutional Review Board
Application for Approval to Use Human Subjects in Research

Instructions: Answer all questions. If you are asked to provide an explanation, please do so with adequate details. If needed, attach itemized replies. Any incomplete application will be returned.

1.) Purpose of Study: (Please provide a concise statement of the background, nature and reasons for the proposed study. Insert below using non-technical language that can be understood by non-scientist members of the IRB.)

Our MQP is working on developing a new foot stretcher for crew racing shells (the board used to push off while rowing). As part of testing our design specifications we want to get feedback from rowers as to the strengths, weaknesses, and general ergonomics of the design. By gathering this data we will be able to incorporate their feedback into our design and make the appropriate improvements.

2.) Study Protocol: (Please attach sufficient information for effective review by non-scientist members of the IRB. Define all abbreviations and use simple words. Unless justification is provided this part of the application must not exceed 5 pages. Attaching sections of a grant application is not an acceptable substitute.)

A.) For biomedical, engineering and related research, please provide an outline of the actual experiments to be performed. Where applicable, provide a detailed description of the experimental devices or procedures to be used, detailed information on the exact dosages of drugs or chemicals to be used, total quantity of blood samples to be used, and descriptions of special diets.

B.) For applications in the social sciences, management and other non-biomedical disciplines please provide a detailed description of your proposed study. Where applicable, include copies of any questionnaires or standardized tests you plan to incorporate into your study. If your study involves interviews please submit an outline indicating the types of questions you will include.

C.) If the study involves investigational drugs or investigational medical devices, and the PI is obtaining an Investigational New Drug (IND) number or Investigational Device Exemption (IDE) number from the FDA, please provide details.

D.) Please note if any hazardous materials are being used in this study.

E.) Please note if any special diets are being used in this study.

3.) Subject Information:

A.) Please provide the exact number of subjects you plan to enroll in this study and describe your subject population. (eg. WPI students, WPI staff, UMASS Medical patient, other)

Males: 5  Females: 5  Description: WPI Students, WPI Staff

B.) Will subjects who do not understand English be enrolled?

No ☒ Yes ☐ (Please insert below the language(s) that will be translated on the consent form.)

C.) Are there any circumstances under which your study population may feel coerced into participating in this study?

No ☒ Yes ☐ (Please insert below a description of how you will assure your subjects do not feel coerced.)

D.) Are the subjects at risk of harm if their participation in the study becomes known?

No ☒ Yes ☐ (Please insert below a description of possible effects on your subjects.)

E.) Are there reasons for excluding possible subjects from this research?

WPI IRB revised 10/5/2010
WORCESTER POLYTECHNIC INSTITUTE
Institutional Review Board
Application for Approval to Use Human Subjects in Research

No ☐ Yes ☒ (If yes, please explain.)
Our testing needs to be conducted relative to current foot stretchers on the market. As such, the participants in the testing need to be experienced rowers.

F.) How will subjects be recruited for participation? (Check all that apply.)
☐ Direct subject advertising, including: (Please provide a copy of the proposed ad. All direct subject advertising must be approved by the WPI IRB prior to use.)
☐ Referral: (By whom) ___
☐ Other: (Identify) ___
☐ Database: (Describe how database populated) ___
☐ Newspaper ___ ☐ Bulletin board
☐ Radio ___ ☐ Flyers
☐ Television ___ ☐ Letters
☐ Internet ___ ☐ E-mail

G.) Are the subjects being paid for participating? (Consider all types of reimbursement, ex: stipend, parking, travel.)
No ☐ Yes ☒ (Check all that apply.) ☐ Cash ☐ Check ☐ Gift certificate ☐ Other: ___________

Amount of compensation

4.) Informed Consent:

A.) Who will discuss the study with and obtain consent of prospective subjects? (Check all that apply.)
☐ Principal Investigator ☐ Co-Investigator(s) ☒ Student Investigator(s)

B.) Are you aware that subjects must read and sign and informed Consent Form prior to conducting any study-related procedures and agree that all subjects will be consented prior to initiating study related procedures?
No ☐ Yes ☒

C.) Are you aware that you must consent subjects using only the IRB-approved Informed Consent Form?
No ☐ Yes ☒

D.) Will subjects be consented in a private room, not in a public space?
No ☐ Yes ☒

E.) Do you agree to spend as much time as needed to thoroughly explain and respond to any subject’s questions about the study, and allow them as much time as needed to consider their decision prior to enrolling them as subjects?
No ☐ Yes ☒

F.) Do you agree that the person obtaining consent will explain the risks of the study, the subject’s right to decide not to participate, and the subject’s right to withdraw from the study at any time?
No ☐ Yes ☒

G.) Do you agree to either 1) retain signed copies of all informed consent agreements in a secure location for at least three years or 2) supply copies of all signed informed consent agreements in .pdf format for retention by the IRB in electronic form?
No ☐ Yes ☒

(If you answer No to any of the questions above, please provide an explanation.) Since we are not selecting subjects who are unfamiliar with the system or the project, we do not feel it is necessary to meet in a private place. Rather, having a one on one conversation with the potential participants at alumni gym will prove satisfactory for a test of this type.

5.) Potential Risks: (A risk is a potential harm that a reasonable person would consider important in deciding whether to participate in research. Risks can be categorized as physical, psychological, sociological, economic and legal, and include pain, stress, invasion of privacy, embarrassment or exposure of sensitive or confidential data. All potential risks and discomforts must be minimized to the greatest extent possible by using e.g. appropriate monitoring, safety devices

WPI IRB revised 10/9/2010
3 of 6
and withdrawal of a subject if there is evidence of a specific adverse event.)

A.) What are the risks / discomforts associated with each intervention or procedure in the study?
None beyond those associated with using a conventional rowing ergometer.

B.) What procedures will be in place to prevent / minimize potential risks or discomfort?
Subjects will be encouraged to discontinue the test if the conditions deviate from the normal rowing exercise experience.

6.) Potential Benefits:
A.) What potential benefits other than payment may subjects receive from participating in the study?
They will potentially be part of the development of a future product that will improve the rowing experience.

B.) What potential benefits can society expect from the study?
A new foot stretcher design that has incorporated feedback from collegiate rowers.

7.) Data Collection, Storage, and Confidentiality:
A.) How will data be collected?
Data will be collected via using an ergometer (rowing machine) and questionnaires given to the participants after testing the design.

B.) Will a subject’s voice, face or identifiable body features (e.g. tattoo, scar) be recorded by audio or videotaping?
No ☐ Yes ☐ (Explain the recording procedures you plan to follow.)

C.) Will personal identifying information be recorded? No ☐ Yes ☒ (If yes, explain how the identifying information will be protected. How will personal identifying information be coded and how will the code key be kept confidential?)
We will need to differentiate between the participants. To maintain confidentiality we will assign a number to each participant and keep the name-number key in a password protected word document, which only the investigators will have access to.

D.) Where will the data be stored and how will it be secured?
The data will be stored in an excel spreadsheet and will be secured using the same methodology outlined in 7c.

E.) What will happen to the data when the study is completed?
The data will be analyzed and generic results will be used in the MQP Report to provide proof that the design meets the specifications outlined in our design process.

F.) Can data acquired in the study adversely affect a subject's relationship with other individuals? (i.e. employee-supervisor, student-teacher, family relationships)
No, the data will have no adverse effects to the subjects.

G.) Do you plan to use or disclose identifiable information outside of the investigation personnel?
No ☐ Yes ☐ (Please explain.)

N/A
H.) Do you plan to use or disclose identifiable information outside of WPI including non-WPI investigators?

No ☒ Yes ☐ (Please explain.)

8.) Incidental findings: In the conduct of information gathering, is it possible that the investigator will encounter any incidental findings? If so, how will these be handled? (An incidental finding is information discovered about a subject which should be of concern to the subject but is not the focus of the research. For example, a researcher monitoring heart rates during exercise could discover that a subject has an irregular heartbeat.)

While no incidental findings are expected, any incidental findings will be brought to the attention of the subject who will be advised to gain further knowledge from an appropriate professional, if necessary.

9.) Deception: (Investigators must not exclude information from a subject that a reasonable person would want to know in deciding whether to participate in a study.)

Will the information about the research purpose and design be withheld from the subjects?

No ☒ Yes ☐ (Please explain.)

10.) Adverse effects: (Serious or unexpected adverse reactions or injuries must be reported to the WPI IRB within 48 hours using the IRB Adverse Event Form found out at [URL]. Other adverse events should be reported within 10 working days.)

What follow-up efforts will be made to detect any harm to subjects and how will the WPI IRB be kept informed? While our testing process is designed such that there are no adverse effects beyond those normally experienced in a sport, any and all situations related to adverse effects will be reported directly and promptly to the WPI IRB.

11.) Informed consent: (Documented informed consent must be obtained from all participants in studies that involve human subjects. You must use the templates available at [URL] to prepare these forms. [Footnote: Informed consent forms must be included with this application. Under certain circumstances the WPI IRB may waive the requirement for informed consent.])

Investigator's Assurance:

I certify the information provided in this application is complete and correct.

I understand that I have ultimate responsibility for the conduct of the study, the ethical performance of the project, the protection of the rights and welfare of human subjects, and strict adherence to any stipulations imposed by the WPI IRB.

I agree to comply with all WPI policies, as well all federal, state and local laws on the protection of human subjects in research, including:

- ensuring the satisfactory completion of human subjects training.
- performing the study in accordance with the WPI IRB approved protocol.
- implementing study changes only after WPI IRB approval.
- obtaining informed consent from subjects using only the WPI IRB approved consent form.
- promptly reporting significant adverse effects to the WPI IRB.

Signature of Principal Investigator [Signature] Date Feb 6, 2012
Informed Consent Agreement for Participation in a Research Study

Investigator: Professor Allen Hoffman

Contact Information: email-ahoffman@wpi.edu; tel-508.831.5217

Title of Research Study: Rowing Foot Stretcher Design Testing

Sponsor: N/A

Introduction:
You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study:
Our MQP is working on developing a new foot stretcher for crew racing shells (the board used to push off while rowing). As part of testing our design specifications we want to get feedback from rowers as to the strengths, weaknesses, and general ergonomics of the design. By gathering this data we will be able to incorporate their feedback into our design and make the appropriate improvements.

Procedures to be followed:
The testing will involve utilizing different scheduled workouts to test the system. Results from the test will be collected using two methods. First, data will be collected from the workout data, which is stored on the ergometer. Second, a questionnaire will be given after each workout to gather additional information from the participant about their rowing experience using the foot stretcher being tested.

Risks to study participants:
There are no risks to the participant beyond those normally experienced on an ergometer.

Benefits to research participants and others:
There are no additional benefits to the participant beyond those normally gained while using an ergometer.

Record keeping and confidentiality:
All information will be kept confidential. Each participant will be assigned a number such that no public data is linked personally to the participant. In addition, records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.
Compensation or treatment in the event of injury:
While there is no risk of injury during the study, you do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:
Dan Pierson, Tel. 603.498.7744, Email: dpierson@wpi.edu
John Madura, Email: johnmadura@wpi.edu
IRB Chair (Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu)
University Compliance Officer (Michael J. Curley, Tel. 508-831-6919, Email: mjcurley@wpi.edu).

Your participation in this research is voluntary.
Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

__________________________________________ Date: ________________
Study Participant Signature

__________________________________________ Date: ________________
Study Participant Name (Please print)

__________________________________________ Date: ________________
Signature of Person who explained this study
Rowing Foot Stretcher Design

Testing Procedure

Test Outline:

We will be conducting subject testing through the use of an ergometer (stationary indoor rowing machine) and a fixture attached to an ergometer. This will enable us to test our design against a current design on the market, and against the traditional ergometer. Using these three systems will allow us to identify any variability that may occur throughout the testing process. Each subject will do two tests, following the process below.

Test Procedure/Data Collection:

60 Minutes of Cardio:

When testing the design with the cardio workout the rower will row three consecutive 20-minute pieces. The order of design use will be randomized. During this workout, the heart rate of the rower will be monitored. The target heart rate will be between 150 and 160 beats per minute. At this pace the rower will be able to sustain a constant pace throughout the workout with minimal deterioration in performance. This will give the subjects the opportunity to focus on the ergonomics of the design and provide feedback on the general "feel" of the prototype compared to the current design used (Resolute’s Intrepid model, which is most common for the WPI Crew program).

Power Based Workout:

The power-based workout will be at a slow stroke rating (number of strokes per minute) with a goal of getting the highest power output possible. To get the most effective data, we will have the subject come in for three separate testing blocks. We will conduct these three testing blocks over a two-week period, allowing for equal rest in between each block. The time period is small enough that the training improvements of the rower will be negligible, but large enough to provide adequate rest for muscle recovery. The first block will use a current ergometer. This will serve as a baseline for the testing. The second block will use the new prototype and the third block will use the current design. The ergometer provides rowers with a lot of useful feedback. We will utilize this to collect data on the subject’s average watt output for each of the repetitions. The stroke rating for the workout is set at 16 strokes per minute. The workout has 8 sets with 1 minute of rest between each set. Each set has a varied amount of repetitions (strokes); they are as follows: set 1=10 strokes; set 2=20 strokes; set 3=30 strokes; set 4=40 strokes; set 5=40 strokes; set 6=30 strokes; set 7=20 strokes; set 8=10 strokes.

In addition to the data collected from the ergometer, a questionnaire will be issued to each subject after each workout. This questionnaire has been attached to the IRB application.
Appendix H: Preliminary Questionnaire:

Gender

<table>
<thead>
<tr>
<th>Gender</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>41</td>
<td>68%</td>
</tr>
<tr>
<td>Female</td>
<td>19</td>
<td>32%</td>
</tr>
</tbody>
</table>

How many years have you rowed

<table>
<thead>
<tr>
<th>Years</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 1</td>
<td>6</td>
<td>10%</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>17%</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>7%</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>8%</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>13%</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>8%</td>
</tr>
<tr>
<td>6+</td>
<td>22</td>
<td>37%</td>
</tr>
</tbody>
</table>

At what level(s) have you rowed?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Club</td>
<td>28</td>
<td>47%</td>
</tr>
<tr>
<td>High School</td>
<td>17</td>
<td>28%</td>
</tr>
<tr>
<td>College</td>
<td>52</td>
<td>87%</td>
</tr>
<tr>
<td>National Team</td>
<td>6</td>
<td>10%</td>
</tr>
</tbody>
</table>

People may select more than one checkbox, so percentages may add up to more than 100%.
Are you familiar with the foot stretcher in the boat?

<table>
<thead>
<tr>
<th>Yes</th>
<th>57</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>3</td>
<td>5%</td>
</tr>
</tbody>
</table>

Have you personally adjusted the foot stretchers in a boat?

<table>
<thead>
<tr>
<th>Yes</th>
<th>56</th>
<th>93%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>4</td>
<td>7%</td>
</tr>
</tbody>
</table>

Please identify the type of foot stretcher you have worked with the most

- Downward power output at the catch
- Shoes seem to come undone relatively easy and can are not always very sturdy.
- Adjusting the angle of the foot stretcher is not an option.
- Difficulty adjusting pitch or height while in the boat. It's a little difficult to adjust the foot stretcher while on the water.
- Many foot stretchers lie at an awkward angle for sitting at the finish, and are generally less comfortable at full slide catch position.
- When adjusting, gravity forces the teeth to lock (even when unscrewed) this becomes difficult when having to deal with 3 points of contact (especially the bottom one)...

How do you see the problem being resolved if the foot stretcher was redesigned or altered?

- Better lateral force output
- More adjustable shoes to better fit the individual
- By adjusting the angle of the foot stretcher, one may be able to apply a greater horizontal force that will minimize the amount of force lost in the vertical direction with every stroke. A problem with this is determining the maximum angle that can be used without affecting the rower's position at the catch. The fastener for the center rail could have a telescopic fixture to adjust pitch while in the boat. When extended, it would make for a shallower pitch, while shortening the telescopic fixture would make the pitch...

Have you had problems with the foot stretcher adjustment?

<table>
<thead>
<tr>
<th>Yes</th>
<th>47</th>
<th>78%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>13</td>
<td>22%</td>
</tr>
</tbody>
</table>
Please describe the problems if you had any.

- Locking the foot stretcher down properly while in the boat
- Difficulty in changing the position of the stretcher, usually caused by problems with the nuts that hold them in place. In the Wintech boats, I’ve had instances where while adjusting slides forward or back, the pins fastening the stretcher to the tracks slid out of the tracks, making it very difficult to reset while on the water.
- It takes a while to adjust it on the water and you need to take the feet out to do it correctly
- The screw system, while lightweight tend to loosen up as they get older, and require constant retightening.

How long does it take to adjust the foot stretcher to your liking on average?

51/2/2011 2/201132-3 minutes too much scatter 3/2/2011 too long 531325 minutes too long

Are you able to find an adjustment that suits your rowing preferences?

<table>
<thead>
<tr>
<th>Yes</th>
<th>52</th>
<th>87%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>8</td>
<td>13%</td>
</tr>
</tbody>
</table>

If not, in which manner (directions/axes) do you feel it could be improved?

- Rotational Generally so, but sometimes pitch/shoe height are difficult to change while rowing, rotating the angle of the shoes. However in some boats the angle is really weird. Only because it is what is available. As stated above would prefer if my foot stretchers were slightly more vertical
- The feet need to be able to move higher or lower, or maybe more to perpendicular to the boat feet up/down, angle BUT requires adjustment off the water with a screw driver.
- All Easier adjusted angle for footplate angle I think a wider stance might lead to a stronger stroke.

Do you feel that the current foot stretcher design allows you to assume a powerful position throughout the stroke?

<table>
<thead>
<tr>
<th>Yes</th>
<th>46</th>
<th>77%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>14</td>
<td>23%</td>
</tr>
</tbody>
</table>

Do you feel that the current design allows enough lateral freedom (within foot position) to allow you to row correctly and efficiently?
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>44</td>
<td>73%</td>
</tr>
<tr>
<td>No</td>
<td>16</td>
<td>27%</td>
</tr>
</tbody>
</table>

**Do you feel that the current design allows enough rotational freedom (within the foot position) to allow you to row correctly and efficiently?**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>39</td>
<td>65%</td>
</tr>
<tr>
<td>No</td>
<td>21</td>
<td>35%</td>
</tr>
</tbody>
</table>

**Have you ever had problems with a malfunctioning foot stretcher?**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>53</td>
<td>88%</td>
</tr>
<tr>
<td>No</td>
<td>7</td>
<td>12%</td>
</tr>
</tbody>
</table>

**In what way was the foot stretcher malfunctioning?**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>14</td>
<td>23%</td>
</tr>
<tr>
<td>Cracked/ broken</td>
<td>34</td>
<td>57%</td>
</tr>
<tr>
<td>Doesn't hold adjustment</td>
<td>37</td>
<td>62%</td>
</tr>
<tr>
<td>Problems with shoe attachment</td>
<td>30</td>
<td>50%</td>
</tr>
<tr>
<td>Other</td>
<td>12</td>
<td>20%</td>
</tr>
</tbody>
</table>

People may select more than one checkbox, so percentages may add up to more than 100%.

**If/When you have had the foot stretcher malfunction, has it been easy to repair?**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>25</td>
<td>42%</td>
</tr>
<tr>
<td>No</td>
<td>35</td>
<td>58%</td>
</tr>
</tbody>
</table>
Do you believe that the shoes you row in are a good fit for you?

Yes 27 45%

No 33 55%

Do you feel that the rowing shoes hinder you in any way?

Yes 34 57%

No 26 43%

If you rowing shoes hinder you, please describe how.

- Effectively positioning on the ball of the foot. They are too big! Small people row as well! Rowing with a shoe that is too large allows for movement of the feet during and after the stroke. This translates to lost power and a slower boat. It is critical that the shoe size is correct because it will increase performance by a considerable amount.

- They are too big, so I float in them, but if I wear my booties, it's not quite as bad.

- Shoes are often the wrong size and allow too much or too little motion. If it's too big, then it's annoying, not really hindering.

Do you feel that the rowing shoes need improvement?

Yes 32 53%

No 28 47%

If so, please suggest a solution or specific problem that needs to be addressed.

- Effectively positioning on the ball of the foot.

- Come up with an adjustable shoe, one that can be made bigger or smaller without having to replace the entire shoe every time a new rover takes the seat. Vespoli has the adjustable ones, mabe just those with out the wide front, shimano has shoes; haven't seen them but see what they do.

- Better sizing for everyone. Maybe a shoe like elastic that would stretch the necessary amount for anyone's feet.

- Some way to make them even more adjustable to foot size, possibly staying away from heel straps and focusing more on straps that could tighten around mid foot.