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Biomechanics: kayak exercise machine

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Capstone Design
Biomechanics: Kayak Exercise Machine

Final Report

Design Advisor: Prof. Kowalski

Design Team

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Abstract

A kayak exercise machine that accurately reproduces the forces and motions of a real kayak was designed and built. Kayaking is an increasingly popular sport and both enthusiasts and amateurs need a way to train during the off season. There are very few kayak exercise machines that are commercially available and those that exist are oversized, expensive, complicated and do not work all of the correct muscle groups required for kayaking. They are not designed for high volume use, such as in a gym setting, or compact enough for the home environment. The approach for the design was to simulate the basic paddling motion, as well as the motions and forces the kayak encounters from water resistance. Rotation of the torso and water resistance is simulated through the use of a two part frame design, a lower stationary frame and an upper rotating frame. The energy absorption mechanism is from a Concept II™ rowing machine and is an accepted form of energy absorption in watercraft exercise machines.

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Problem Statement

Kayaking is an increasingly popular sport. Professional kayakers and enthusiasts need a way to accurately train and condition in the off season. There are currently no kayak exercise machines that accurately reproduce all of the forces experienced in a real kayak. Without reproducing the forces of a real kayak, the current machines cannot exercise all of the appropriate muscle groups. Most current generation machines focus on the arm motion of kayaking, and some include the core muscles but none truly simulate the feel of a kayak. The current kayak exercise machines are complicated, oversized, and too expensive for most gym or home environments. The machine needs to be fatigue resistant, and must be able to handle high traffic use such as in a gym environment.

Introduction

It is important to condition and train for any sport to avoid soreness and injury. Many regions do not allow for kayak training during the winter and a serious kayaker will lose valuable training time. The current generation of kayak exercise machines does not accurately reproduce all of the motions and forces experienced in a real kayak. Also, most of the machines are too large, expensive and complicated to be appropriate for enthusiasts or gyms.

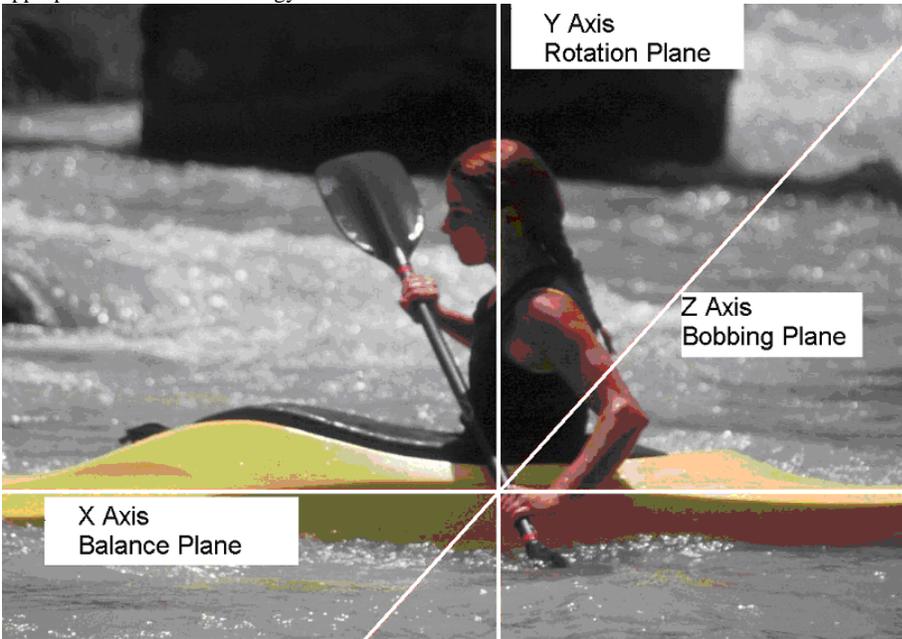


Figure 1 – Kayak Planes of Motion

The motions and forces involved in kayaking are complex and must be recreated accurately. There are degrees of freedom on all 3 axis, x, y, and z, as shown in figure 1. There is rotation about the vertical axis Y, which results in the kayak turning left and right relative to forward motion. Small rotations also occur about the Z axis due to waves in the water, resulting in the kayak bobbing up and down. These bobbing motions are directly related to the height and frequency of the waves, and can vary greatly between river, lake and sea kayaking. Rotations in the X plane result in the kayak and user tipping to the right and left, these motions are dependant on the waves encountered and the leaning of the user. If the tipping motion is too large it can cause the kayak to overturn. The project will focus on the rotation in the Y axis which provides the majority of the core muscle exercise, but is neglected by most of the current machines.

The plan for this project was to divide it into several stages. Stage 1 consisted of researching current generation kayak ergometers as well as market research. The strengths and weaknesses of each machine were noted, and by examining them we were able to add design criteria in order to produce a more realistic workout. Market research will be performed to determine the target consumers and influence the final design. Stage 2 was the researching of the biomechanics involved in kayaking, which was needed in order to recreate proper technique and realistic forces. Stage 3 was the brainstorming of designs, including energy absorption methods. The final stage was the selection of a final design, creating a 3D CAD model, building a prototype and testing it.

Stage 1: Existing Patents, Products and Market Research

Existing Patents

Although there are several patents for kayak exercise devices, they do not accurately reproduce the motion and forces experienced by a real kayaker. The patents only take into account the arm motion during the exercise and neglect the rotational movement and resistance generated by the water. Additional forces and motions need to be taken into consideration to simulate the motion of a kayak in water. Kayaking is a complex series of motions and these machines can only perform one of the basic components. Training or practicing on one of these current patent machines could lead to poor habits from improper simulation because they only focus on one aspect of the kayak exercise.

Simulated - Kayak Upper Body Machine Patent no. 6328677

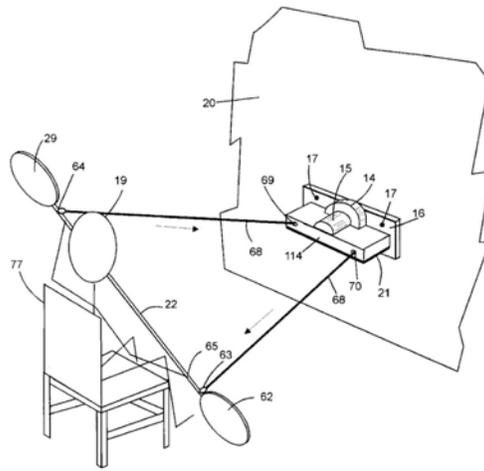


Figure 2 – Simulated-Kayak Upper Body Machine

Figure 2 shows a device which uses a flywheel to provide resistance. Various adjustments to the flywheel can change the resisting force, to simulate the resistance encountered by different types of kayaks. The handles are interchangeable, either having separate paddles, or one shaft like a kayak. This machine also has one continuous length of rope instead of an independent design. This means that when one arm is pulling the paddle, the other arm is being forced back towards the resistance device with another pulling force. This does not accurately represent the arm motion of a kayak.

This device fails to work some of the key muscle groups that are involved in kayaking. Since the design for this machine has a stationary seat, all of the motion associated with the core muscle group is lost. The user does not need to balance and rotate their midsection such as in a real kayak. This machine may result in a semi-realistic paddling force, but the machine will not provide the realistic feel that professional kayakers and enthusiasts would require to train in the off season. [1]

Exercise Device to Simulate Kayaking Patent

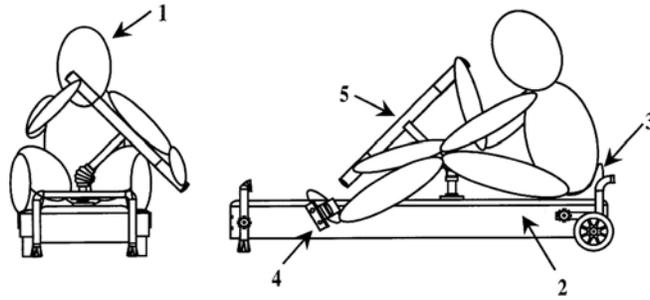


Figure 3 - Exercise Device to Simulate Kayaking

This device seen in figure 3 uses a T bar connected to a frame, using an articulating joint. The T bar is used from a seated position to simulate the arm motions of paddling a kayak. The device operates in a similar manner to the previous device, except that a T bar is used for the resistance. However, like the other devices, it fails to simulate the motion of the kayak being in water, and it may not hit all the core muscles necessary for kayaking. [2]

Kayak Exercise Simulator Patent

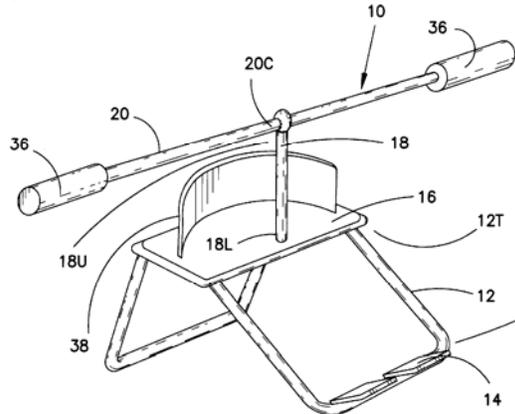


Figure 4 - Kayak Exercise Simulator

The simulator is a simple device, figure 4, offering the same concepts as the earlier devices. However, this design uses a shaft, with a single center joint to anchor the device, and all the resistance is created by weights on the end of the shaft. This design is an inaccurate simulation because due to gravity, the upper weight assists the paddle stroke in an unrealistic way. In addition, there is a safety concern, as it has the potential for weights moving around rapidly, potentially hitting the user or others. [3]

Existing Products

Current commercially available machines have similar shortcomings to the patent devices described in the previous section. The problem of accurately reproducing the torsional forces and motions of a real kayak are ignored by these current machines. They simply implement a stationary seat and focus their design on the arm motion. All of these current generation designs will result in an unrealistic feel for kayaking. They require no balancing while exercising, and they ignore the torsional resistance caused by water.

Dansprint Machine

The Dansprint machine is similar to the current project, but there are some key differences. Figure 5 shows that the motion provided by this machine is similar to actual kayaking arm motions and stroke form. The Dansprint machine uses a flywheel along with a bungee-pulley assembly to vary the resistance. However, the Dansprint does not address the stability aspect of kayaking. Kayaking requires balance and forces the kayaker to use their core muscles to remain right side up. This machine is mounted on a rigid frame and seat, which is a poor simulation of a kayak. The Dansprint will give a decent kayak related workout, but it will not accurately simulate kayaking due to the lack of any motions from the “boat.”

A main selling point of the Dansprint machine is that it uses electronic sensors and a display to give time, distance, power, speed, stroke rate and heart rate in real time. The Dansprint also has the ability to hook up to a personal computer for monitoring and graphing stroke and heart rate data. The Dansprint machine retails for \$5,000 U.S. dollars, which is rather expensive. The Dansprint machine also has a huge footprint of 75 ft². It uses a 3 meter shaft along with a 6 meter frame. [4]



Figure 5 – Dansprint Machine

KayakPro Device

The Kayak Pro shown in figure 6 is a currently available device. This machine is similar to the Dansprint in the fact that it focuses solely on the upper body workout. The athlete sits on the small platform, and the feet are held in by a bar positioned over the athlete's toes. The resistance is provided via a shaft with cables attached to the ends.

The main difference between this design and the proposed design is that the KayakPro device remains stationary throughout the paddle stroke. The KayakPro device retails for \$2,000 and has a footprint of 55ft². This is slightly smaller and cheaper than the Dansprint machine, but the need for a more realistic, cheaper, smaller design still exists. [5]



Figure 6 - Kayak Pro Device

Calgym Device



Figure 7 – Calgym Machine

The Calgym device, shown in figure 7 is essentially a shortened version of both the Dansprint, and KayakPro devices. The motion is the same, using a shaft with cables attached to the end. The benefit over the other models is that the Calgym is more compact. This machine, like the previous two examples, cannot rotate to model the motion of a kayak. The rotation around the Y plane is not taken into design consideration, nor is the balancing motion in the X plane. The Calgym machine also uses a flywheel to generate the resistance due to paddling. This machine is currently not being mass produced so there is no finite price that could be found for this machine. Calgym manufactures gym and weight equipment, but the Calgym kayak machine is not being sold on their website. [6]

Market Research

Meeting with Sue Ekezian

A meeting was held with Sue Ekezian who purchases exercise equipment for the Northeastern gym. Sue was kind enough to share some of the important factors in both purchasing and designing gym equipment. Size constraints are a major issue when a gym goes to purchase new equipment. There are some safety rules that most gyms will abide by. One example is a required 3ft safety zone around any given machine. The safety zone is important in the design because the users arm's will be rotating and moving through the air. It is important to keep a safe distance between machines in order to prevent any injuries due to moving parts. Another safety concern is that the machine does not protrude too far into the safety aisle. In case of emergencies, gyms need to space out the machines in order to maintain a safe fire lane.

There are functional constraints that have to be considered for the design. The machine must be able to fit on an elevator or be carried up stairs if necessary. Size is important because most gyms will order their machines already assembled. Gyms do not want to have to buy unassembled machines and then build them in house. This means that the kayak exercise machine cannot be excessively heavy or bulky.

Another concern about gym equipment is power. The location of the power cord can be the difference between a neat and tidy row and a tangled mess of wires. Also, power usage is an issue because if a powerful motor is used then an independent electrical circuit is needed to provide power. These problems can be avoided by designing a purely mechanical machine.

The inclusion of an electrical monitoring system would be a positive asset for the machine, but it is out of the scope of this project. Similar machines use sensors and even computers to compute stroke

speed, exercise time and calories burned. Electronic sensors and an electronic display should be included in future revisions of the project. However, this project will focus solely on the mechanical aspects of the design.

Initial Cost Analysis

Professional gym equipment is fairly expensive, and the purchaser of a machine would like to have solid reliability over the machine's lifespan. One example of a current exercise machine, in the Northeastern gym, is a treadmill. Treadmills cost \$8,000 each and only have an expected lifespan of about 3 years.

Weight machines cost significantly less, but last about twice as long, usually 6 to 7 years. Rowing machines have a huge range in price, anywhere from a few hundred dollars, up to \$2,500 for a single machine. The quality of the machine depends on the price and most gym quality rowing machines will cost around \$2,000.

The kayak exercise machine will have a target lifespan similar to the weight machine, 6 years, and at a reasonable cost. Cost will be dependent on the materials used and the complexity of the mechanical devices. Complex parts such as cams, custom fan wheels, and other machined parts will keep costs high. The kayak exercise machine could cost significantly less than existing gym equipment by trying to use currently available parts and keeping complex machined parts to a minimum.

Maintenance/Availability

Gyms prefer simple maintenance. Most exercise machines will be cleaned and maintained at least once a day. The kayak exercise machine must be durable enough that it can last for thousands of cycles before any major parts need to be changed. Simple maintenance such as oil being added to bearings, or springs being replaced over time, would be expected and not considered major maintenance. The machine should be simple enough to be maintained by students.

Availability of parts is a key to building a successful exercise machine. The major reason that exercise machines stop being used is that their manufacturers move on to new designs and older parts get phased out. This means the parts cannot be replaced and the machine is basically useless. The complexity of the parts, and their availability, will help determine the success of a given design. If a design can be made with few custom machined parts, the overall lifespan of the machine can be greatly increased. It is in the group's best interest to design a machine that uses existing parts which can be purchased, instead of designing new parts that need to be manufactured.

Stage 2: Biomechanics

Efficient and powerful paddle strokes are a key part of kayaking, maximizing each stroke of the paddle through the water. Our machine needed to accurately reproduce the motions and forces encountered when kayaking, especially the forces current machines neglect, such as the rotation of the kayak. Professional kayakers, for example, need their off season conditioning to be as accurate as possible in order to maintain proper technique. Improper conditioning, such as the use of a standard rowing machine, does not work the proper muscles and can result in injury or fatigue when the season starts.

Biomechanical studies such as the one shown in Figure 8 use current pools and multiple cameras to analyze the motions encountered when kayaking. This type of testing was needed so that accurate biomechanical data could be factored into the machine design. Existing kayak exercise machine manufacturers have published biomechanical data which will also be used in this project. The Dansprint machine is the most well known current generation machine, and has independently published test results showing stroke length vs. depth comparisons, as well as resistance vs. speed results. These numerical guidelines helped shape the target goals of this project. [7]

Comment [d1]: Ref the tables.



Figure 8 – Kayak Motion Test in Current Pool

Basic Paddle Forces

The image below illustrates the basic forces acting on a kayak. Figure 9 is a top view of a kayak. Three forces are observed, they are F_r , the resistance force of the water on the kayak, F_{return} , the return force acting on the sides of the kayak, and F_p , the force of the paddle in the water. The figure also demonstrates the moment about the kayak that is created from the rotation of the user.

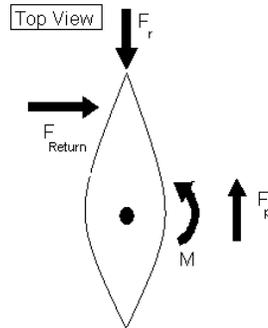


Figure 9 – Kayak Paddle FBD

Basic Technique

Proper paddling form is essential to kayaking efficiency. Poor stroke form will lead to less power generated per stroke, and therefore result in lower speeds. Figure 10 shows that kayakers use their upper body, arms, shoulders, chest, and torso to provide an efficient and powerful stroke. The image shows the pushing and pulling of the arms, the rotation of the torso, and the plunging of the paddle into the water. This is the kayaking form desired to be reproduced in the kayak exercise machine.

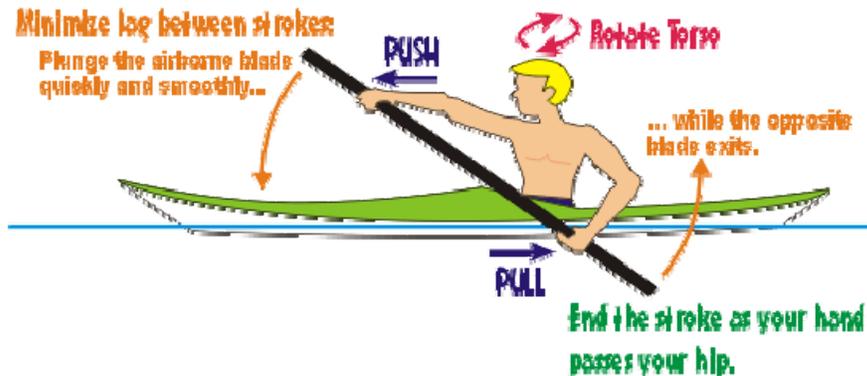


Figure 10 – Proper Kayak Motion

Padding Form, Amateur vs. Professional

The difference between good and bad technique is hard to see for an inexperienced kayaker, but any enthusiast can tell you the importance of a proper kayaking stroke. The images below show these subtle differences between a professional and amateur stroke. The amateur stroke has several key features that reduce its overall efficiency as seen in Figure 11. An amateur stroke will have a high center of rotation as compared to the professional stroke illustrated in Figure 12. An amateur will have improper torso movement, so a pro will gain more power from their torso than an amateur will. Another key element of a proper kayak stroke is consistency and repeatability. From the images below, it is clear that the amateur stroke is more random than the proper stroke of the professional. Good form and consistency are important in getting the most power from each stroke. [7]

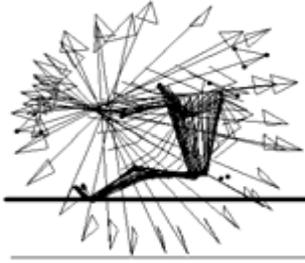


Figure 11 - Amateur Kayaker Stroke

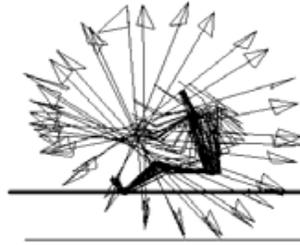


Figure 12 – Professional Kayaker Stroke

Padding Form Visual Analysis

Figure 13 shows a visual plot, captured from behind the user, of the motion of a paddle during kayaking. The ends of the paddle are being tracked and plotted while different athletes paddle in a kayak. A is better than B which is better than C, same for D, E and F. A horizontal 8 is the ideal shape for this 2D plot. The closer a plot is to this ideal shape, the better the stroke: a more regular stroke, A, is better than an erratic stroke, C. [7]

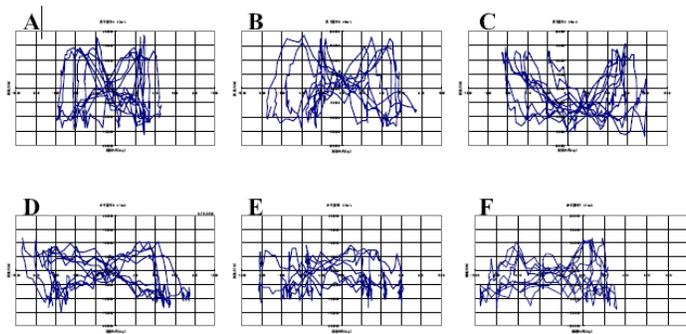


Figure 13 – Kayak Stroke Visual Plot

Figure 14 is another plot of a kayak stroke from the same study as Figure 6, except this time stroke direction relative to the center of the kayak is being tracked. The two athletes left and right paddle offset is about 50cm on either side of the stroke. The front to back motion of each athlete's stroke is 150cm.

These dimensions can be factored in to the design and used to determine the most realistic direction of the forces.

Athlete A has a steady straight stroke right up until the end of the stroke, while athlete H tends to track his paddle farther from the kayak through his stroke. This point just illustrates the minor differences in technique and form of each individual. [7]

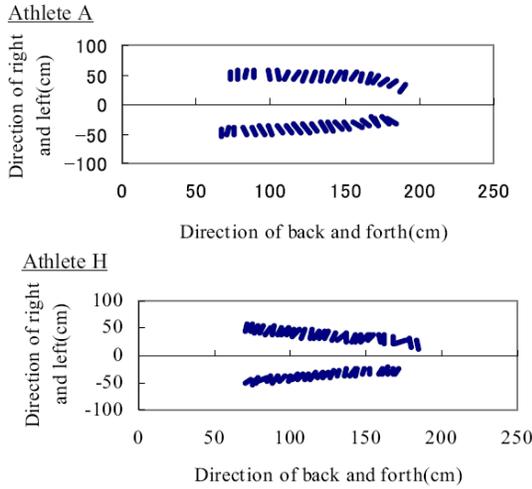


Figure 14 – Kayak Stroke: left and right vs. back and forth

Real-life Factors and Current Machine Simulation

The forces encountered during kayaking depend on a long list of factors: twisting, blade shape, blade size, blade pitch, shaft length and shaft shape can all influence the resistance encountered by the kayaker. Research and literature shows the most realistic kayak speed is between 4.5 and 5 meters per second. Assuming a speed of 5 m/s, resistance was determined through the use of a competitor’s machine. The graph, Figure 15, shows a range of 40 to 120 Newtons, or 10 to 25 lb-force for a stroke at 5 m/s. With this data, a realistic feel of 20 lb-force will be the goal of the project. [4]

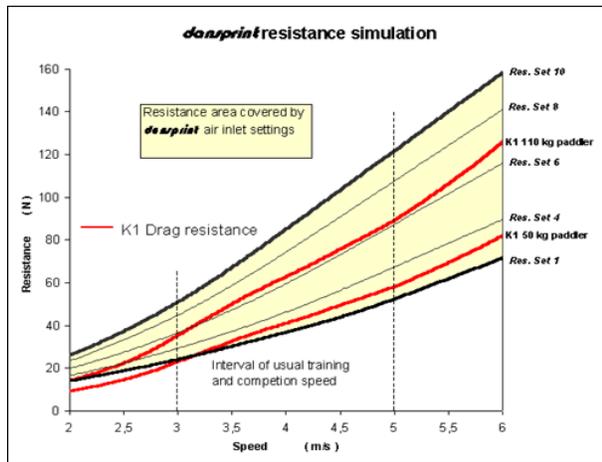


Figure 15 – Dansprint Resistance Simulation Graph

Practical Biomechanical Test

A practical biomechanical test was performed to study and analyze the kinematics involved in a kayak stroke. The test was used to determine hand position on the paddle, minimum height requirements, and the stroke distance that the end of the paddle traveled.

To determine the minimum paddle length that could be used, group members held a mock paddle as they would a kayak paddle. The paddle should be held with the users elbows cocked at a 90 degree angle. The distance between the kayaker’s hands was recorded. It was determined that a paddle length of four feet will be sufficient to accommodate most users. A 4 inch hand clearance was factored into the requirement to allow for attachment of a rope. The length of the paddle will be a major factor in the footprint of the machine, by minimizing paddle length a more compact design can be produced for a gym and home environment.

Hand Position on Paddle			
Height	Hand Distance from Center (inch)	Hand Clearance	Minimum Required Paddle Length (inches)
59"	10	4	24
5'11"	12	4	28
60"	12.5	4	29
59"	11.5	4	27
57"	12	4	28
			AVG 27.2

Table 1 – Hand Position on a Paddle

To ensure that the paddle does not scrape the floor when being used, there must be a minimum height to the machine. Group members were seated on two stools and asked to take a stroke. Distance measurements from the seat to the paddle end were taken when the paddle was stopped at the deepest part of the stroke. This test resulted in a minimum height requirement of 6.9 inches from the floor to the kayaker.

Minimum height clearance of 4' Paddle	
Height	Minimum Required Distance (inch)
59"	6.5
5'11"	7
60"	7
59"	7.5
57"	6.5
Average	6.9 inches

Table 2 – Height Clearance of a 4' Paddle

The next part of the practical test involved tying a piece of string onto the end of the paddle. The user paddled as in the previous test, but this time the paddle was stopped at the closest point to the user’s feet. The rope was marked, and then the rest of the stroke completed. The distance measurement was repeated several times to determine a reasonable stroke length. It was determined that most strokes are between 2.5 and 3.5 feet with a 4’ paddle. These numbers will provide a minimum constraint for the amount of rope needed to complete a stroke.

Stroke Distance of 4' Paddle			
Height	Starting Stroke Distance (feet)	Final Stroke Distance (feet)	Minimum Required Stroke (feet)
59"	4	6.5	2.5
5'11"	3.25	6	2.75
6'0"	3	6.5	3.5
59"	4	6.25	2.25
57"	4.25	6.5	2.25
			MIN
			2.25 feet
			MAX
			3.5 feet

Table 3 – Stroke Distance of a 4' Paddle

Figure 16 shows the stroke length and depth requirements from a test with the Dansprint machine. The maximum depth they encountered was 1.3 feet, and the stroke lengths were measured at 4.5 feet. The Dansprint machine uses a paddle length of about six feet, which explains their greater paddle depths and stroke lengths. [4]

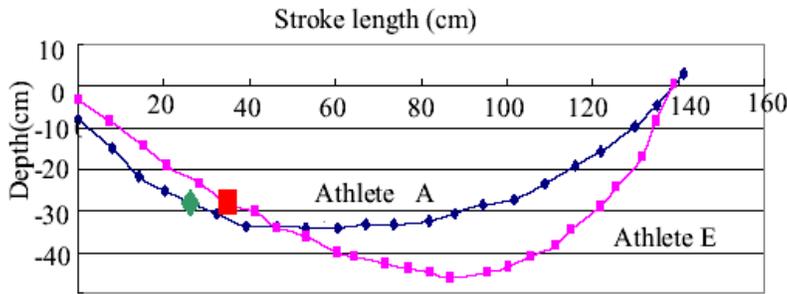


Figure 16 – Dansprint Stroke length vs. Depth Graph

Biomechanical Conclusions

The biomechanical forces and motions detailed above will drive the design of the kayak exercise machine project. A pulling of force of around 20 lb will supply the resistance through the paddle which will simulate a speed of about 5 m/s. It would also be desirable to make the arm resistance variable through the use of a fan with an opened-closed grill assembly. The seat assembly will be limited to a rotation of about 5 degrees, mimicking the motion of an average size kayak. The two-part frame design will allow greater rotation and stressing of the torso. A FitBall™ will be incorporated into the seat to mimic the balancing involved in kayaking into the design by forcing the exerciser to center their mass while exercising.

Stage 3: Mechanical Design

The design criteria for our machine were as follows:

- accurately recreate the motion and forces of a real kayak
- safety of the user
- ease of manufacture
- reasonable cost
- unique design
- ability to sell to target market

By considering these factors, we were able to create a prototype that exhibits these criteria.

Initial Concepts and Design Issues

To mimic the motion of an actual kayak the exercise machine will have to rotate about the Y-axis. The paddling motion of a kayak causes a moment about the Y axis and results in a slight turn on each side, which current machines neglect to include in their designs. The rotation of the kayak exercise machine will mimic the side to side turning of an actual kayak and will provide a more thorough, accurate workout. When the machine rotates, the user will need to utilize their abdominal and oblique muscles to resist this rotation, which is accurately representative of real life kayaking. This Y axis resistance will limit the rotation in either direction to about five degrees. The rotation will differentiate the kayak exercise machine from any other currently available machine.

In addition to the rotation of the boat, we designed our machine to recreate the slight bobbing motions about the x- and z-axis. To accomplish this we used a FitBall™ as our seat. A FitBall™ is a disc version of a swiss ball, and when used as a seat forces the user to contract their core muscles to balance. This extra contraction of the core muscles adds another dimension to the workout the user of our machine will encounter. We believe that the combination of the seat being a FitBall™ and having the ability to rotate elevates our machine above the competition in terms of accurately recreating the kayak experience in a gym or home setting.

Safety is another important concern when developing design concepts for the kayak exercise machine. The frame must be structurally sound when supporting a wide range of users. The frame will be made from high strength structural framing and will need to have finite element analysis conducted in order to ensure the user's safety. The kayak exercise machine is being designed to handle a high rate of use, such as in a gym environment. Fatigue considerations will need to be factored into the design due to the cyclic loading and moving parts. A reasonable lifespan can be sustained with these same fatigue considerations.

Comment [d2]: add more about accurately recreating the motion and forces of a real kayak

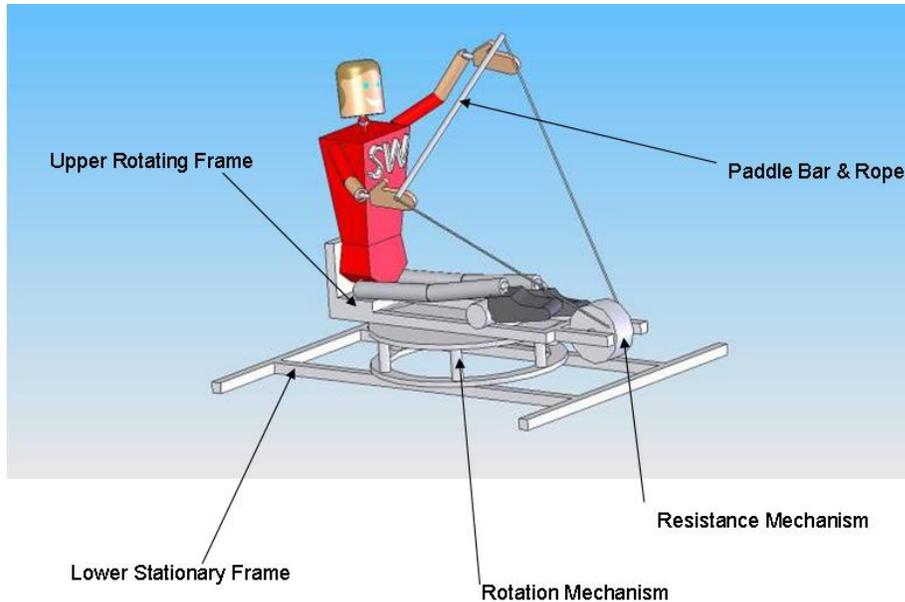


Figure 17 – Initial Design Concept

There are five major parts of the design, see figure 17, that will have to be expanded on as the kayak exercise machine is designed in more detail. There is a resistance mechanism, a rotation mechanism, the rotational resistance mechanism, the lower, stationary part of the frame, and the upper, rotating part of the frame.

The resistance mechanism will be the part of the kayak exercise machine that delivers resistance when the user moves the paddle. The mechanism will need to generate the resistance in a way that mimics the forces of a paddle moving through water and air in a real kayak. Potentially, the resistance mechanism could be a permanent magnet electric generator connected to a variable resistor. The variable resistor would allow an adjustable method of changing the resistance of the kayak exercise machine on the fly. Other possible solutions are a flywheel, a fan, or a cam-spring assembly. As examined in Table X.

The rotation mechanism will allow the upper frame to rotate approximately 5 degrees in either direction. This degree of rotation should be more than adequate to mimic the rotation of an actual kayak. The rotation mechanism should be sufficiently wide as to spread out the weight of the user and the upper frame. If the rotation mechanism is too narrow, the pressures applied to the parts of the rotation mechanism will be much greater, and could lead to fatigue or catastrophic failure. The rotation mechanism will need to have some resistance in order to mimic the actual kayak experiences due to inertia and friction of the water. Potentially, this resistance could come from either springs, dampers, bungee cords, or something akin to a constant torque hinge.

The lower part of the frame which remains stationary will be the base to the entire kayak exercise machine. This part of the frame will bear the weight of the rest of the machine and the user. The base will provide stabilization and transfer all the forces to the floor of the exercise room. This part of the frame will be designed to reduce the chance of the user overturning the machine.

The upper part of the frame supports the seat, user and footrest assembly. The upper frame will need to rotate about the seat center. This means the upper frame will need to be integrally attached to the rotation mechanism through either a bearing or turntable. The upper frame may contain additional safety features to prevent any falls such as a padded safety bar.

Initial Frame Development

The frame part of the project will act as the stationary base. The job of the frame will be to support the weight of the user and seat, as well as provide the necessary space off the ground. The proposed frame is made from Bosch-Rexroth™ structural framing. Bosch-Rexroth™ framing is a widely used aluminum framing, known in the industry for its strength and various selection of mounting fixtures and accessories. A turntable will be mounted to the stationary frame in order to provide the turning motion around the Y plane.

Initial Seat Development

The seat part of the design consists of a seat and foot rest. This section will mount to the turntable of the stationary frame via a mounting plate. The seat will be a FitBall™, which will provide the balancing part of the kayak exercise. A beam extending from the lower part of the seat will act like a foot rest. A locking fixture will be attached to this beam in order to make adjustments for different users.

Initial Shaft/Resistance Development

The shaft and resistance assembly will be the third major part of the design. The design must allow for an accurate reproduction of resistance, and should allow for a variable resistance. The design matrix below, in table X, shows the criteria and possible solutions that were considered for this segment of the design project.

Criteria	Cost x1	Weight x1	Size x1	Availability x2	Maintenance x2	Complexity x2	Totals
fan	5	3	3	4	4	4	35
generator	1	1	4	4	3	1	21
cam/spring	3	2	2	2	3	3	23
flywheel	3	2	2	2	4	4	27

Table 4 – Energy Absorption Design Matrix

It was obvious from this exercise that a fan would be the best choice for the project with a score of 35. Since a fan was already available from a previous project it would not add to the cost. A fan also has the ability of a variable resistance through limiting airflow and increasing air pressure. As the fan spins faster, the more air resistance is generated. This change in force due to the air resistance vs. rotational speed is supposed to mimic the feel of a paddle in water. The fan for this project was taken off a Concept II rowing machine. As for the other criteria, the generator was deemed too complex, costly and heavy for this application. The cam spring assembly would not be readily available and would require several custom parts. The flywheel came in second place with 27 points. The flywheel is similar to a fan, except that no air resistance is generated and the forces are set by change in inertia. A flywheel would have been the next logical energy absorption device if the fan had not been readily available.

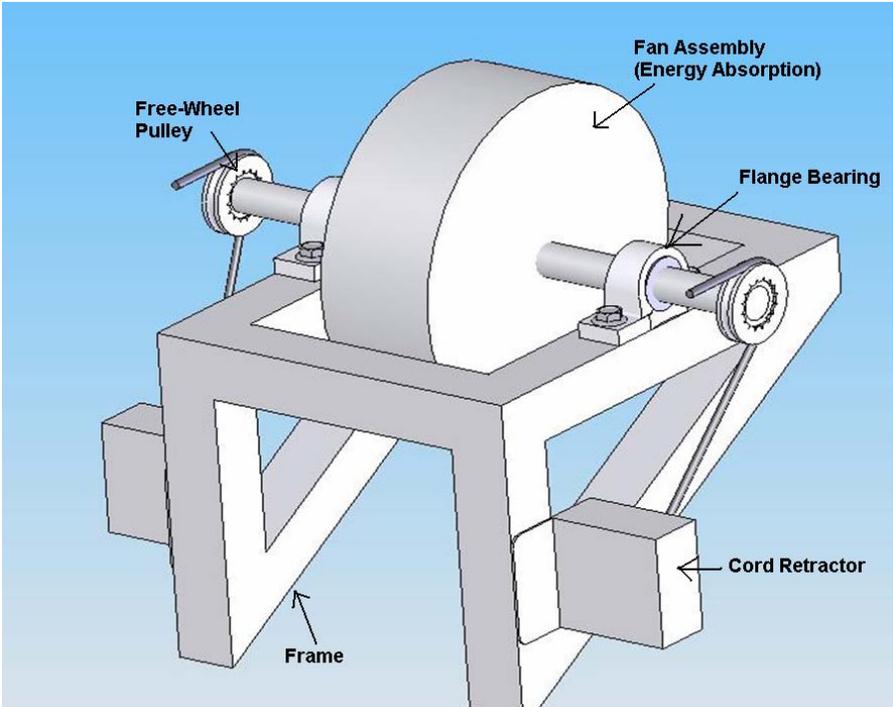


Figure 18 – Proposed Shaft Assembly

Figure 18 shows the development of the shaft assembly. A frame supports two bearings that have a shaft running through them. The fan wheel is in the middle of the assembly, hard mounted to the shaft. Left and right hand freewheels are attached on either end of the shaft. The freewheels will engage when pulled in one direction, but spin freely in the other direction. A pulley/cord retractor assembly will provide the returning force once the stroke has been completed. The fan will spin, resulting in air resistance as well as inertia resistance. The target baseline resistance for the project is 20 lbf.

Final Design Solution

The final design of the kayak exercise machine can be broken down into three primary categories: the framing, the energy absorption mechanism, and the rotation mechanism. The framing supports all of the other components and provides a stable platform to exercise on. The energy absorption mechanism accurately reproduces the forces that occur on a kayak paddle as it moves through the water. Finally, the rotation mechanism mimics the twists experienced while paddling a boat through water.

A big part of our design criteria was ease of manufacturability and low cost. In order to accomplish this we decided to design our machine using as many off the shelf parts as possible. The selection of Bosch-Rexroth™ aluminum framing, while not the cheapest option for manufacture, gives the ability to make framing changes and adjustments on the fly. Almost every other part that makes up our machine is a standard off the shelf part, with a few custom machined parts, which were necessary for the functionality of our design.

Figure 19 shows the final design prototype, while figure 20 illustrates the CAD model used for the design.

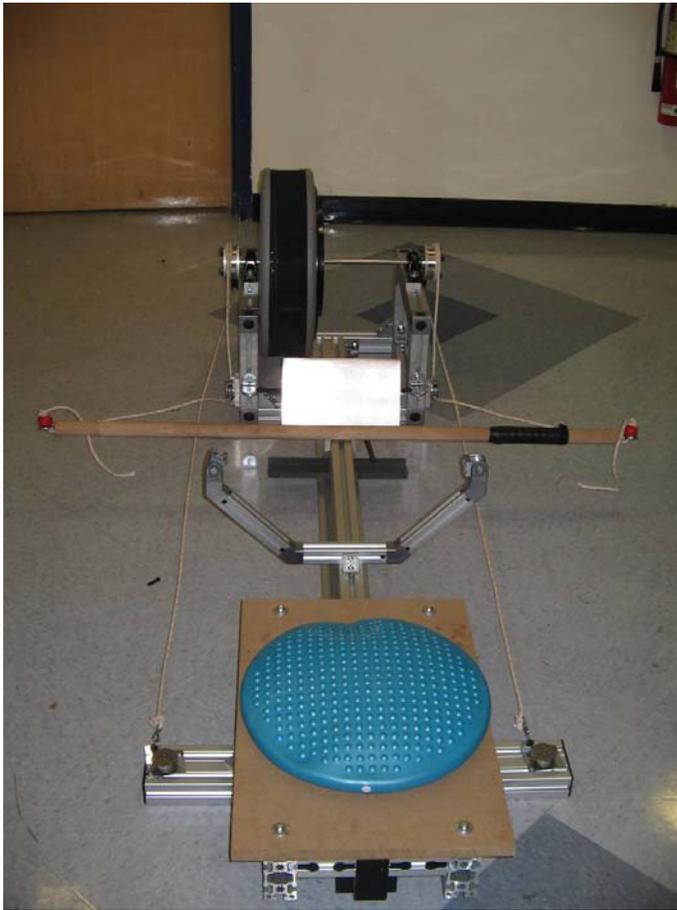


Figure 19 – Picture of Prototype

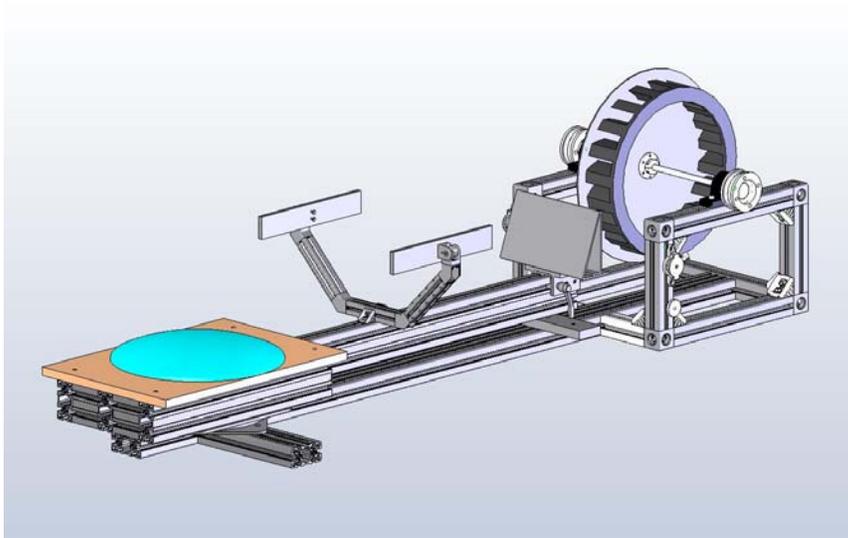


Figure 20 – CAD of Final Prototype Design

Final Frame Design

The structural framing, produced by Bosch-Rexroth™, consists of extruded aluminum beams with standard cross-sections, which allow for multiple pieces to be easily assembled into a larger structure. The extrusion profile has 6 slots along the sides for easy mounting and adjustment of other frame members and accessories. The framing system also uses specially manufactured bolts, nuts, and supports which allow it to be easily configured and manipulated. No welding, hole drilling and tapping, or cutting is needed because the parts can be ordered with the necessary modifications performed at the factory, which saves a lot of time. Using engineering data available on the Bosch-Rexroth™ website, designs were drawn up, calculations were performed to check for the necessary safety factors, and parts were ordered.

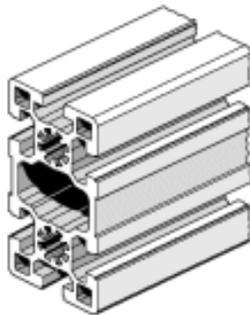


Figure 21 - Bosch-Rexroth™ Aluminum Extrusion Framing

The framing consists of a lower frame, an upper frame, and the support for the rotational components. The lower frame was designed wide enough to prevent the machine from tipping over. The lower frame and upper frame are connected by a turntable that allows for the upper frame to rotate as the user paddles. Special mounting plates were fabricated to match the bolt patterns of the turntable to that of the structural framing. The upper frame is designed to support the weight of the user while still being able to rotate freely about the lower frame. Also attached to the upper frame are a seat, an adjustable footrest,

and thigh braces. The framing that supports the rotational components and flywheel were designed to provide optimal structural support while minimizing space and cost. See figure 22 for the final frame solution.

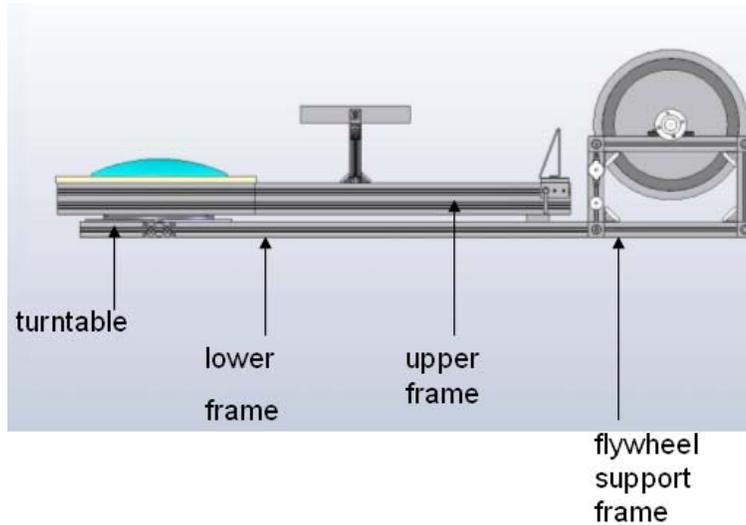


Figure 22 - Frame Design, Final Solution

Final Energy Absorption Design

Another primary category is the energy absorption mechanism, which mimics the forces on a kayak paddle as it moves through the water. This mechanism consists of a series of pulleys that transfer the force of the user paddling to a shaft with a flywheel/fan combination mounted to it. A four foot long Oak shaft was chosen to mimic a kayak paddle. After looking at various kayak paddles it was determined that the average diameter of a paddle was 1.25" and the average weight of the paddles was 2 pounds. Various materials were looked at to determine which would closely match the weight of a normal kayak paddle while being 1.25" in diameter and 4 feet long. Oak was chosen because in those dimensions the paddle would weigh 1.8 pounds while having high strength, high fatigue resistance, and low cost.

Both ends of the paddle have a length of rope attached to them through eye hooks. The rope wraps around pulleys before being wound around the driving part of the energy absorption mechanism. The rope was chosen with the appropriate strength to support the forces exerted by the user while paddling, but with the necessary flexibility so that it could be wrapped around the pulley system. The rope that met the requirements was a 0.25" diameter rope with cotton outer surface and a nylon core. The rope's cotton outer surface gives the rope greater friction when interfacing with the resistance mechanism. The rope's nylon core gives the rope high tensile strength at a 100 pound working load and 1500 pound breaking load.

The rope winds around an adaptor which drives a shaft and provides resistance similar to that of a paddle moving through water. Included in the resistance mechanism is the driving freewheel adaptors, the freewheels, the freewheel to shaft adaptors, the shaft, the bearings, the fan and flywheel, and the flanged shaft collar used to hold the flywheel. Most of these components are off the shelf parts with a few, the driving freewheel and freewheel to shaft adaptors being custom parts.

The part that translates energy from the rope to the shaft is the driving freewheel adaptor. While designing the whole kayak exercise machine it was decided to use off the shelf freewheels from a bike that would allow the rope to be retracted during the return stroke of the user. Because the freewheels were designed to be used with a bike chain, some adapter was needed to allow it to interface with rope. The rope

to freewheel adaptor was one of a few custom machined parts in the kayak exercise machine. The rope to freewheel adaptor consists of two halves that encase the bike freewheel and has four specially sized holes that match the inner radii of the teeth of the freewheel. When two adapter halves are placed around the freewheel the holes of the adaptors are lined up and allow for a bolt to be placed through the adaptors to mesh with the teeth of the freewheels and hold the two halves together. When held together, the rope to freewheel adaptors look like a pulley encasing a bike freewheel.

The free wheels are off the shelf components originally designed for BMX bicycles that were chosen to maximize performance while minimizing costs. When force is applied to the freewheel in the drive direction, the freewheel will engage the shaft. When force is applied opposite the drive direction, it will 'freewheel,' or spin freely. The combination of a left and right hand drive freewheel located on either end of the shaft allows one side to retract while the other is driving the shaft. Both freewheels were purchased on the bike supply website BikeParts.com.

Another adapter was needed to interface the inner threads of the freewheels to the tapped ends of the drive shaft. The thread on both freewheels was non standard, 1.370" diameter by 24 threads per inch, so a custom part was needed to connect the freewheel from the specialized thread size to the ¼" by 20 threads per inch holes tapped on the ends of the shaft. This part was made from aluminum stock due to ease of machining and existing stock in the shop. If brought to market, this part would be made out of hardened steel to ensure durability and fatigue resistance.

The drive shaft is a ½" diameter hardened steel shaft, 18" long, ordered from McMaster Carr, the source of most of our parts. The shaft was chosen because it has a very high yield strength, 295,000 psi, relatively low cost, and two tapped ends to accept the freewheel to shaft adaptors. The shaft also provided enough space for all the components while keeping the overall dimensions relatively compact.

Mounted bearings were chosen to support the ½" shaft, and fasten into the Bosch-Rexroth™ framing. Each bearing interfaces with the shaft by tightening two set screws on each bearing. The bearings are rated to withstand over 2,100 pounds of dynamic force, which is more than enough for our rotational components.

The shaft and bearings support the flywheel/fan assembly, which are what actually produce the resistance felt by the paddle. The fan and flywheel were taken from a commercial rowing machine, the Concept II. The rowing machine was used by a previous capstone design group in their efforts to make a kayak exercise machine. The fan and flywheel were used as the resistance device because it had no associated costs, it is a proven resistance unit, it is easily modifiable, and is robust enough to handle the work load. The flywheel is a circular sheet of steel, and the fan, a ring of angled pieces of plastic, is mounted to the flywheel. The flywheel provides inertia to the system while the fan creates air resistance as it rotates.

The last part of the rotational mechanism is the flanged shaft collar that connects the fan and flywheel to the shaft. The flanged shaft collar is an off the shelf part and has a ½" bore to accept a ½" shaft. Two screws on the shaft collar tighten the bore around the shaft. On the flange of the collar are 6 evenly spaced holes which were used to attach the flywheel and fan to the shaft collar. The process of mounting the shaft collar required drilling precise mounting holes to center it on the center point of the flywheel.

Centering the shaft collar on the flange was crucial so as to keep the rotation of the fan and flywheel centered around the shaft so as to avoid creating uneven forces during rotation. To center the shaft collar, the fan and flywheel were placed on a milling machine and the center of the flywheel was found. A bolt circle was drilled using the milling machine's numerical outputs.

To ensure the shaft collar and flywheel would stay attached during high speed rotation, high strength bolts were selected. The bolts have a 180,000 psi yield strength, and are made of alloy steel. Securing the bolts to the flywheel/fan assembly are vibration resistant, nylon insert, lock nuts.

After spinning the resistance mechanism, the two ropes go through a pulley system and terminate at an elastic cord. The elastic cord was chosen to replace our original design to increase the force required to rotate the fan and to increase the rate at which the cord is returned on the back stroke. Furthermore, the cords provided more than the needed 4 feet of stroke length, and were readily available.

Image 23 shows the shaft assembly and table 5 is the labeling. Image 24 is a close up picture of the final result.

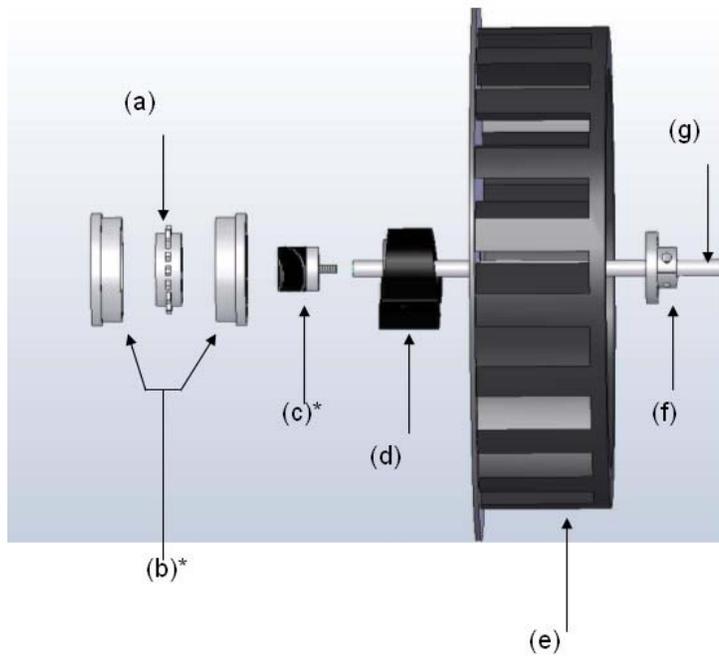


Figure 23 – Shaft Assembly

- (a): Bike freewheel
- (b): Freewheel to rope adaptor
- (c): Shaft to freewheel adaptor
- (d): Bearing
- (e): Flywheel with attached fan
- (f) : Flanged shaft collar for flywheel
- (g): Steel shaft with two tapped ends

Table 5 – Shaft Assembly



Figure 24 – Close up Image of Shaft Assembly

Final Seat Design

The last two components of the kayak exercise machine, the turntable, and the plastic support block, are what allow the upper frame to rotate. The upper frame is connected to the lower frame through an off the shelf, 12” diameter turntable. The turntable rotates by sitting on steel ball bearings, and is load rated for a capacity of 1000 pounds. To attach the turntable to both the upper and lower framing it was necessary to fabricate two mounting plates out of aluminum sheet with unique bolt patterns to allow for ease of assembly and maintenance.

Once the turntable was mounted to the lower frame, the upper frame was cantilevered over the lower frame. It was determined a plastic block would be necessary to prevent the framing from putting too large a moment on the turntable, deforming it. Furthermore, the plastic support block has rubber stops in a precise location to limit the rotation of the upper frame to exactly 5 degrees in either direction. The actual seat that the user sits on, as mentioned earlier, is a FitBall™ inflatable disc. It provides the user a degree of instability that necessitates a greater use of the torso, increasing the effectiveness of the workout.

Final Cost Analysis

The final cost of this project prototype was approximately \$1,400. The price seems high initially, but the fact that much of the budget was spent on structural framing leaves room for some major cost cutting. By substituting the Bosch-Rexroth™ structural framing for a box-frame, or tube-frame and weld design the costs could be reduced substantially. In a mass production setting it does not make sense to order all the pre-fabricated parts from Bosch-Rexroth™, but rather pay for raw materials which would be shaped and welded in a factory.

The cost of the new Design seems to be more affordable then the Kayakpro and Dansprint machines as seen in Table 5. The R80APM row machine is significantly cheaper then any of the other machines. Rowing machines, especially home models, tend to be smaller and cheaper than most gym models.

	New Design	Dansprint	Kayakpro	R80APM
price (\$)	1,400	5,000	2,000	600
footprint (ft ²)	24	75	55	7.33

Table 5 – Price vs. Footprint

Final Design Footprint Comparison

The final footprint of the design solution is the smallest of any of the current kayak exercise machines. Table 6 shows a visual plot of the total square footage of several kayak exercise machines. By comparison the Dansprint and KayakPro machines are significantly larger. The R80APM rowing machine has the smallest footprint available, but it does not use a paddle like the kayak exercise machines do. The table below shows the difference in footprint. Units are in ft².

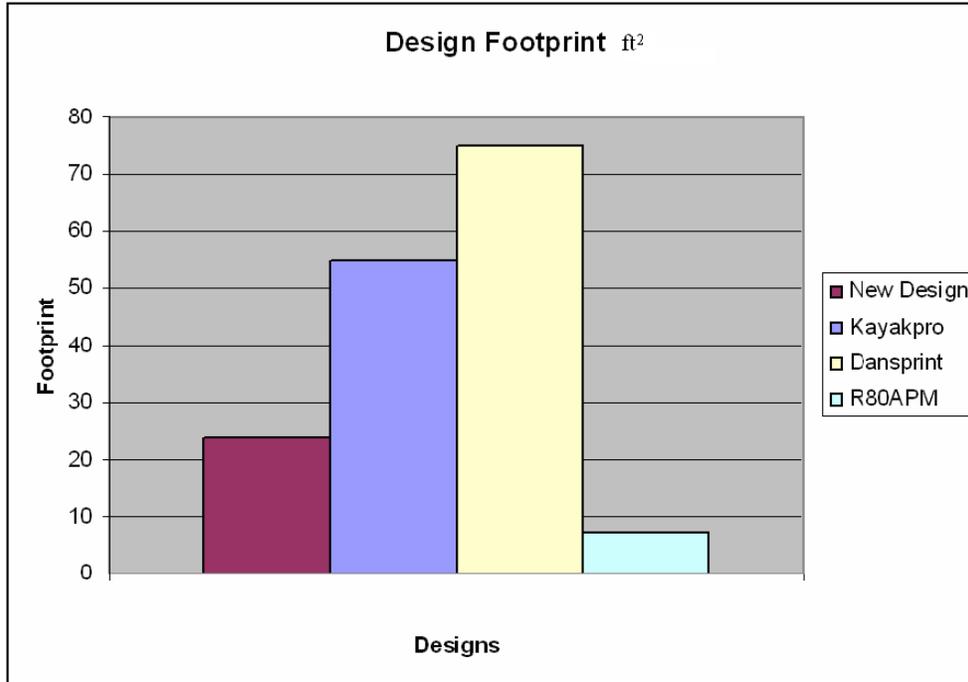


Table 6 – Design Footprint Comparison

Calculations

Since this is an exercise machine to be used by people it needs to be safe. The machine must be able to support a max weight of 300 lbs and avoid fatigue for premature failure. Calculations also needed to be performed for analyzing frame motion. See image 25.

Padding Angle Analysis

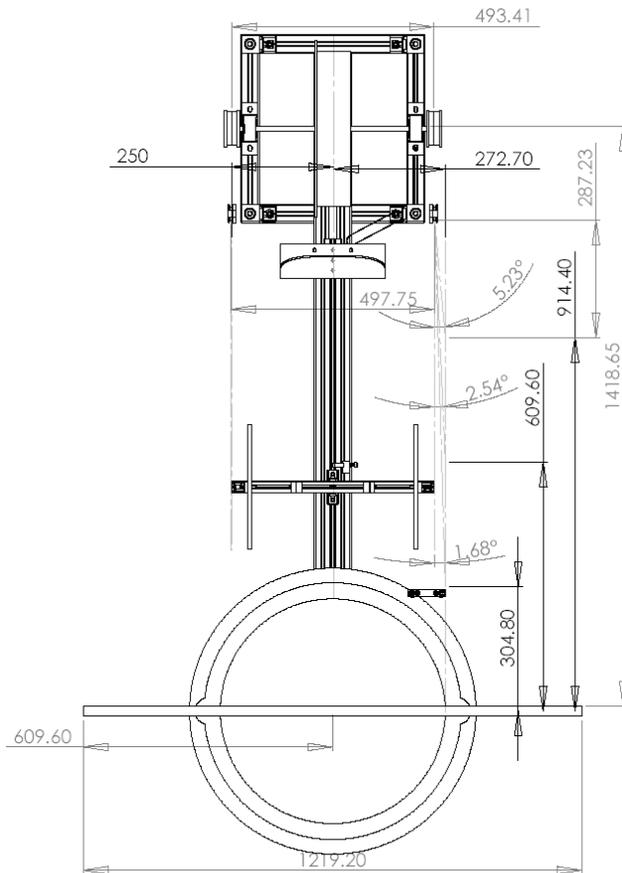


Figure 25 – Paddling Analysis

Assumptions:

1. Avg. Paddle L = 220cm
2. Our Paddle L = 120 cm
3. Paddle angle = 40°
4. x-axis = vertical
5. y-axis = horizontal
6. 10 lb return force

Paddle Ratio:

$$120/220 = .5454$$

Dist. from center of rotation to end of Paddle:

Correct Paddling: 50 cm

Machine: 25cm

ratio: .500

Y-axis components of force:

$$3ft: 10lb * \tan(5.23) = .9153lb$$

$$2ft: 10lb * \tan(2.54) = .4436lb$$

$$1ft: 10lb * \tan(1.68) = .2933lb$$

$$0ft: 10lb * \tan(0) = 0 lb$$

Conclusions:

It turns out that as currently configured, there is a force pulling the users arm towards the center of the machine, though it is very small.

At the same time, this should not be happening, as it does not occur in real kayaking.

The solution:

To mount the rollers from previous group in a manner that minimizes the problem angle, ensuring a distance from center of rotation of $.5454 * 50$ cm, or 27.3 cm. I will have this modelled and send you a drawing of the new configuration this week.

Shaft Calculations

Analysis of the shaft was necessary to insure safety of the operator. Static analysis as well as torque analysis was performed to determine factors of safety. A 20lb pull force and the resultant torques were used to make the calculations.

Stress at Shaft:

$$\tau = 20\text{ lbf} \cdot 4.21\text{ in}$$

$$\tau = 82.4\text{ in} - \text{lb}$$

$$\sigma = \text{stress}$$

$$\sigma = (\tau / Z)$$

$$Z = \text{cross-sectional-area}$$

$$Z = \pi r^2 = 3.13 \cdot (.0625/12) = 0.0163\text{ in}^2$$

$$\sigma = 82.4\text{ in} - \text{lb} / 0.0163\text{ in}^2 = 5055.21\text{ psi}$$

$$Y_{\text{strength}} = 66700\text{ psi}$$

$$N = Y_{\text{strength}} / \sigma$$

$$N = 66700 / 5055 = 13.19$$

Units = mm

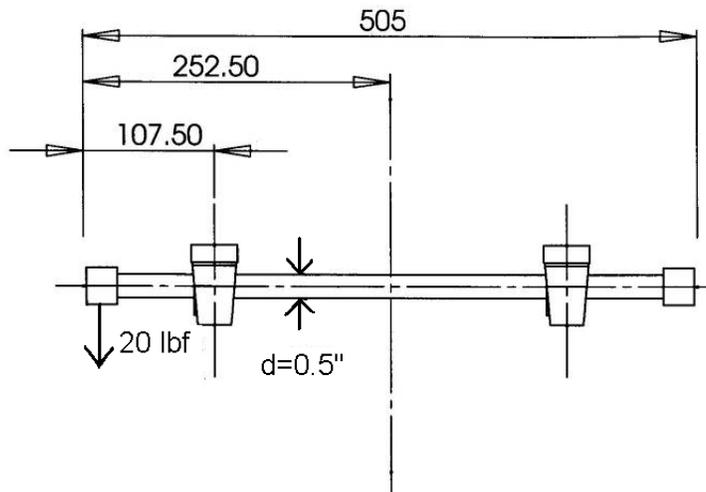


Figure 26 – Shaft Assembly Dimensions

Shaft FEA

Finite element analysis was performed on the proposed shaft assembly to determine potential stress concentrations. Figure 25 illustrates the static Von Mises stress due to a static load applied normal to the shaft direction. The factor of safety for the static load from these calculations is around 30. Figure 26 depicts the Von Mises stress due to an applied torque. The factor of safety for the torque calculations is around 300. The highest stress concentrations occur at the shaft – bearing interface.

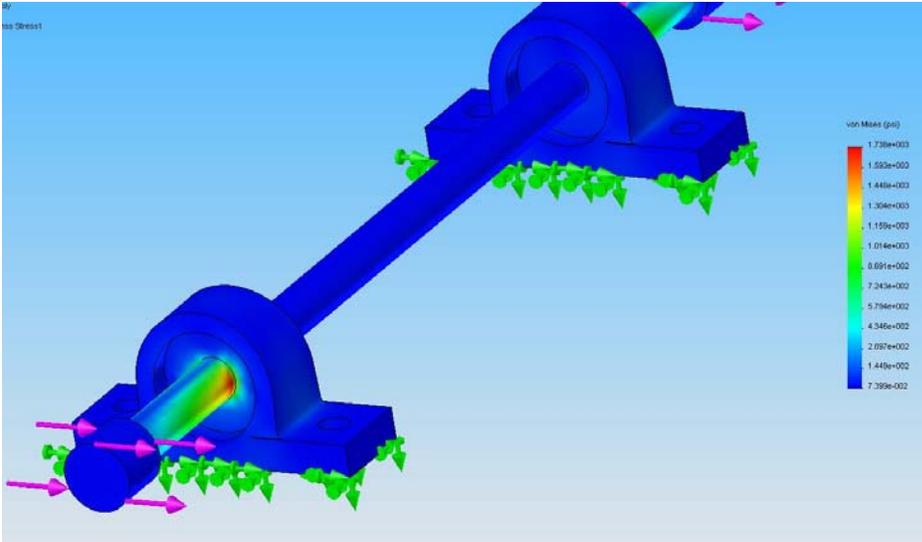


Figure 27 – Static Von Mises Stress Concentrations

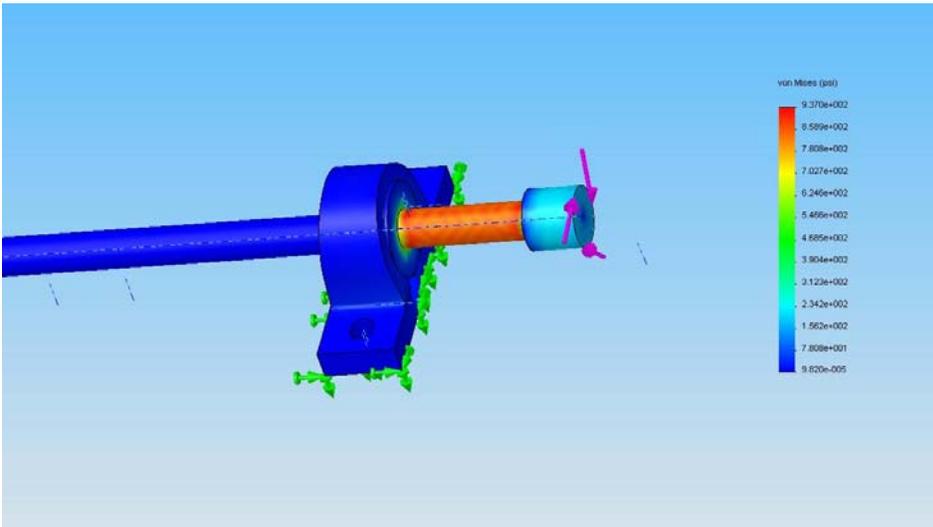


Figure 28 – Torque Von Mises Stress Concentrations

Base and Seat Frame Calculations:

Calculations to find the bending stress and factor of safety for each beam in the assembly were completed under the assumption of a 300 pound user and the seat assembly weighing 100 pounds. For most frame members, the factor of safety was very good. For example, the factor of safety for the short beam in the base frame is 25.414, and 6.75 for the long beam. The beam used for the footrest assembly, however, has a factor of safety of 1.675, which is unacceptable for human use. In order to improve this, the seat frame will have to be redesigned using higher strength framing to get the factor of safety up.

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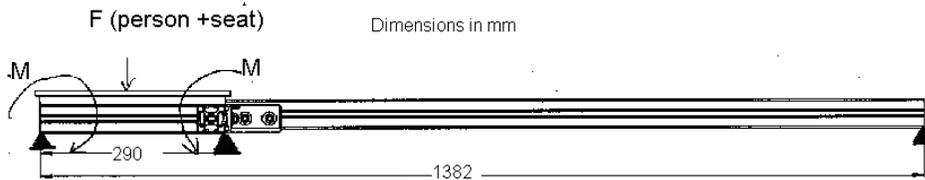


Figure 29 – Base and Seat Calculations

Base and Seat Calculations (Worst Case Scenario)

Person (Static Load)

$$\sigma = stress$$

$$F_{total} = 1334N$$

Small :

$$\sigma = (1335N \cdot 145mm) / 4 \cdot (6.147 \cdot 10^3)$$

$$\sigma = 7.86Pa$$

$$Y_{strength}(Bosch - Connectors) = 100Pa - each$$

$$N = Y_{strength} / \sigma$$

$$N = 200 / 7.86 = 25.4$$

Long :

$$\sigma_{max} = (1335N \cdot 546mm) / 4(6.147 \cdot 10^3)$$

$$\sigma = 29.6 Pa$$

$$Y_{strength}(Bosch - Connectors) = 100Pa - each$$

$$N = 200 / 29.6$$

$$N = 6.75$$

Person and Seat (moment)

$$F_{\text{total}} = F_{\text{person}} + F_{\text{seat}}$$

$$F_{\text{person}} = 300 \text{ lb} = 1334.5 \text{ N}$$

$$F_{\text{seat}} = 100 \text{ lb} = 444.8 \text{ N}$$

$$F_{\text{total}} = 1779.3 \text{ N} \cdot 0.145 \text{ m} = 257.9 \text{ N} \cdot \text{m}$$

$$N = 4000/1779.3 = 2.24$$

$$N = 4000/444.8 = 9$$

Connections

$$M = F_{\text{total}} / 4 \cdot 0.145 \text{ m} = 64.5 \text{ N} \cdot \text{m}$$

$$M_{\text{max}} = 140 \text{ N} \cdot \text{m}$$

$$N = 140/64.5 = 2.17$$

Fatigue Calculations

Fatigue calculations were performed on the key aspects of the kayak exercise machine knowing that those were the sections most likely to fail. The calculations below in tables 8, 9 and 10 show the allowable force for a 45 x 45 mm beam, a 45 x 90 mm beam, and a 1/2" diameter rotating shaft. After analyzing the forces involved in the system it was concluded that the force on the rotating shaft and the moment it caused on the beam below were the two most significant forces involved. The force on the shaft end is 20 lbs which is well below the acceptable values. The moment it creates is approximately 55 lb-in on a surface area of 1.16 in². The resultant stress on the beam is 47.5 psi, while the safe limit for the Bosch framing is 12.5 kpsi, well within the acceptable safety range.

Rate (Cycles/min)	Cycles in 30 mins	Cycles for 36 users a day	Cycles for 4 years 365 days a year
20	600	21600	4.73E+07
40	1200	43200	9.46E+07
60	1800	64800	1.42E+08

Table 8 – Fatigue Calculations for Non-Rotating Beams

Beam Size (mm)	Surface Area(in ²)	ka (kpsi)	kb	kc	kd	ke	kf	Se' (kpsi)
45 x 45	1.16	1.045	0.8442	0.59	1	1	1	18.144
45 x 90	2.39	1.045	0.8134	0.59	1	1	1	18.144
		Se (kpsi)	σF' (kpsi)					
45 x 45		9.443798	86					
45 x 90		9.099248	86					

Table 9 – Fatigue Calculations for Non-Rotating Beams Continued

For the 45 x 45 beam

$$b = -\frac{\log\left(\frac{86}{9.4438}\right)}{\log(2 \cdot 10^7)} = -0.1314$$

$$f = \frac{86}{36} (2 \cdot 10^3)^{-0.1314} = 0.8800$$

$$a = \frac{(0.88 \cdot 36)^2}{9.4438} = 106.25 \text{ kpsi}$$

$$S_{f(10^7)} = 106.25 (10^7)^{-0.1314} = 12.7 \text{ kpsi}$$

For the 45 x 90 beam

$$b = -\frac{\log\left(\frac{86}{9.099}\right)}{\log(2 \cdot 10^7)} = -0.1336$$

$$f = \frac{86}{36} (2 \cdot 10^3)^{-0.1336} = 0.8653$$

$$a = \frac{(0.8653 \cdot 36)^2}{9.099} = 106.65 \text{ kpsi}$$

$$S_{f(10^7)} = 106.65 (10^7)^{-0.1336} = 12.38 \text{ kpsi}$$

Calculations for rotating shaft						
ka (MPa)	kb	kc	kd	ke	kf	Se' (Mpa)
0.6601	0.9447	1	1	1	1	710.7257
Se (kpsi)	$\sigma F'$ (kpsi)					
443.206	1755.17					

Table 10 – Fatigue Calculations of Rotating Shaft

For the rotating shaft

$$b = -\frac{\log\left(\frac{1755.17}{443.2}\right)}{\log(2 \cdot 10^7)} = -0.0819$$
$$f = \frac{1755.17}{1410.17} (2 \cdot 10^3)^{-0.0819} = 0.6679$$
$$a = \frac{(0.6679 \cdot 1410.17)^2}{443.2} = 2001.38 \text{MPa}$$
$$S_{f(10^7)} = 2001.38 (10^7)^{-0.0819} = 534.6 \text{MPa}$$

Future Work

Although we are quite satisfied with our final design, as with any design, there is room to improve. Future work on the design includes; outfitting of a workout monitoring system, design of rounded frame components, a custom seat design, and a resistance mechanism that varies the resistance force based on the segment of the stroke. The outfitting of a work out monitoring system would improve the overall appeal of the machine as well as assist the user in fine-tuning their workout. An assessment of the seat's rotational resistance mechanism may also be necessary as the current design may not be a cost effective system.

As mentioned previously, the Bosch-Rexroth™ framing was chosen for its adjustability and flexibility in setup. It would not be a proper, cost effective solution for manufacture. A standard extrusion, rounded or oval, similar to usual gym equipment would be a desirable framing solution. The framing would also be welded instead of bolted together. In addition to the framing changes, it would be necessary to make a custom seat assembly similar to the FitBall™ used, but with an injection molded base to install it in.

The energy absorption mechanism should also undergo analysis for the possibility of improvement. The adaptors used for the freewheels should be made of hardened steel instead of aluminum to increase fatigue resistance. It would also be necessary to increase the effectiveness of the resistance adjustability. As is, the fan's adjustable intake and exhaust does not come into effect as much as in the concept II due to a lack of gearing. In all, it would not take much more time to complete the analysis and design changes needed to put the machine into manufacture.

Conclusion

Kayaking is an increasingly popular sport and both enthusiasts and amateurs need a way to train during the off season. There are very few kayak exercise machines that are commercially available and those that exist are oversized, expensive, complicated and do not work all of the correct muscle groups required for kayaking. They are not designed for high volume use, such as in a gym setting, or compact enough for the home environment. The approach for the design was to simulate the basic paddling motion, as well as the motions and forces the kayak encounters from water resistance. Rotation of the torso and water resistance is simulated through the use of a two part frame design, a lower stationary frame and an upper rotating frame. The energy absorption mechanism is from a Concept II™ rowing machine and is an accepted form of energy absorption in watercraft exercise machines. Overall, the kayak exercise machine prototype was successful in reaching the goals outlined in this paper, and given proper demand could be commercialized into a viable product.

Comment [d4]: Steal from Executive Summary.

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Appendices:

Bosch Rexroth Aluminum framing provided a chart which can be used to determine safety limits in a given design. These charts and numbers were used to determine acceptable parts for a safe design. Mechanical drawing also included.