Leg Ergometer
for Blood Flow Studies

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Abstract

Little is known about the dynamics of blood flow in the femoral artery during exercise due to the difficulty in obtaining reliable and accurate data in a non-stationary person. The goal of this project was to construct an ergometer that would allow researchers to gain access to a subject's femoral artery while providing a resistive force that the subject will actively oppose. An ergometer is simply a machine that measures the amount of work a given muscle does. This project involved the construction of a one-leg ergometer to determine the work done by the quadriceps during exercise and allow for ultrasound imaging of the femoral artery during use. With this data, a deeper understanding of blood flow may also lead to more accurate information about factors that influence conditions such as high blood pressure and vascular diseases. Some of the major requirements for the leg ergometer include a passive return of the foot to the resting position after a kick, a constant kick rate, measurable work output, and reliability. The major design decision concerned the resistance generator. Some possible mechanisms included the use of a regular bicycle brake system, the use of the braking system of a commercialized exercise bike, or the use of an adjustable magnetic brake and servo-motor design. Each alternative was considered in terms of ease of construction, client use, cost, resistance adjustability, and constant power output. Based on the available time, budget and client requirements, the servo motor design was chosen as the best option and constructed.

Problem Statement

While there are many ergometers available commercially, these do not meet the requirements of researchers who wish to study blood flow in the femoral artery to the quadriceps during exercise. The femoral artery is best imaged with Doppler ultrasound (see figure 1) at the conjunction of the hip and the leg; however, this area is not always accessible during normal exercise (cycling, running, stair climbing, etc.). We propose building a one-leg ergometer which will allow subjects to have a regular kicking motion with one leg against a constant resistive force while still allowing a researcher access to image the femoral artery. A reliable mechanism must be implemented to deliver the resistive force. The ergometer will allow the subject's leg to return passively to the resting position before kicking out again. The subject will sit at an incline to allow better access to the femoral artery. A Doppler ultrasound probe will be placed over the femoral artery during the exercise, as well as before and after exercise to compare blood flow and velocity at rest, during exercise, and during recovery. The information gathered using this ergometer will further the understanding of blood flow during exercise and may lead to better diagnosis of blood and vascular diseases.

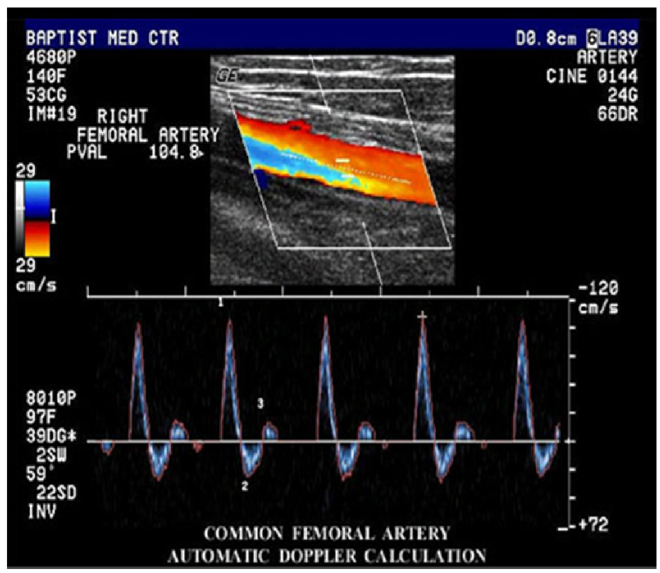

Fig. 1: Ultrasound image of femoral artery

Background

Blood Flow Regulation

During exercise, the blood flow through vessels increases in order to increase the amount of oxygen to muscles. Muscles use the oxygen carried by the hemoglobin in blood to produce ATP, the chemical energy that fuels muscles. The sympathetic division of the autonomic nervous system signals the brain that more blood needs to flow to the muscles to exercise. This causes the blood vessels to dilate and allows more blood to flow. One study showed that exercise, even moderate, slowed the aging process of blood vessels (Gilbert, 2000). The study concluded that exercise maintained the production of nitric oxide (which controls the aging of blood vessels); however, they did not have concrete support. Very little information is actually known about the mechanics of blood flow during exercise. Researchers do not know what neural, metabolic, or vascular signals control blood flow at rest or during exercise. Also, not much is known about the effects of conditions such as aging and cardiovascular diseases (obesity, high blood pressure, diabetes, etc.) on the regulation of blood flow. If the mechanisms and factors that influence blood flow are better understood, the information can be used to help treat cardiovascular diseases. For example, tests could be conducted to discover whether exercise can restore normal blood flow. Furthermore, drug companies could develop drugs that mimic the effects of exercise and correct dysfunction.

Existing Devices

There are several types of leg ergometers available, one of which is an exercise bike. While commercial bikes used in fitness centers and homes are two-leg cycles, ergometers used for medical and research uses are typically one-leg cycles. These exercise bicycles use a flywheel and a brake system to generate a one-way resistive force. In addition to measuring the power output, these devices also display other information, such as heart rate, kick rate, and distance traveled.

A research facility in Europe has used a modified bicycle to isolate the right upper thigh by a leg extension motion. This study used work outputs of 20-60W and measured pulmonary oxygen uptake, heart rate, leg blood flow, blood pressure and femoral arterial-venous differences for oxygen and lactate between 5 and 10 min of the exercise (Anderson, Saltin).

A study of vascular diseases at Stanford University also used a leg ergometer to study blood flow during exercise. The custom MRI cycle was created to allow researchers at the medical center to determine the rate and force at which blood flows through arteries during pedaling. Since MRI machines use magnets, this custom ergometer was made mostly of wood so that it would function during the scan. The seat of the ergometer is placed inside an MRI that opens vertically while the large flywheel that provides the resistance remains outside the machine. As the subject pedals, the MRI images the blood flow in the femoral. An addition coil is wrapped around the subject to measure the blood flow in the thoracic and abdominal aorta. Using this data on blood flow, researchers will examine and compare healthy adults to people with vascular diseases to improve their diagnostic and treatment techniques. In addition, researchers will be able to extend their understanding of normal blood flow during exercise (Selis, 2003).

Finally, researchers at Mayo Clinic also developed a leg ergometer to facilitate their research of blood flow during exercise. This device also used a flywheel from an exercise bike to provide resistance. A car seat was placed on the ergometer for the subject to sit on and two different sized rollerblade boots attached the subject's foot to the bike pedal through a bar and two ball joints. The larger boot had the toe cut out to allow for various foot sizes. A Doppler ultrasound probe measured the blood flow while sensors connected to the resistance system tracked the wattage and kicking rate of the subject. Unfortunately, the device was unreliable. The flywheel would occasionally spin backwards, resulting in zero resistive force being applied when the patient kicked forward. Also, the nylon belt, which was attached to the flywheel, became hot as a result of friction. This altered the length of the nylon belt and the work output by the subject.

Spring 2007 Design

The prototype from the Spring 2007 semester was used as the starting point of this project. Pre-cut and pre-threaded iron plumbing pipes were utilized to build the frame of the ergometer. The final frame was four feet long, two feet tall, and one and a half feet wide. This frame was extremely stable (Figure 2). The frame was slightly smaller than the maximum dimensions to ensure the seat, once attached, would not exceed the maximum height desired. Wheels were added to the base of the frame to allow for easy transportation of the ergometer from room to room. An adjustable car bucket seat (shown in figure 3) was used so that subjects would be able to recline and give researchers better access to the femoral artery at the junction of the subject's hip and leg.

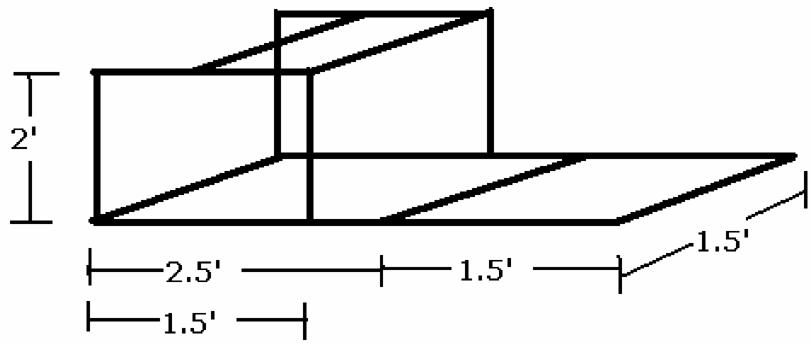

Fig. 2: Dimensions of steel pipe frame

Due to time constraints, a bicycle was used as a temporary resistance mechanism to supply variable one-way resistance to the ergometer. The bicycle was cut in half, flipped upside down and attached to the iron frame using cables and aluminum wire (shown in Figure 3). These temporary attachments were used so that the bicycle could be easily removed in order to

Fig. 3: Spring 2007 prototype

implement a new resistance mechanism this semester. Light weight aluminum bars were used to connect the bike pedal to the subject's foot. The necessary length of the bar was the distance from the foot to the pedal when the leg is fully extended and the pedal is forward. The pedal bar was attached to the bike pedal on one end and a snowboard binding on the other end. The snowboard binding was attached with hinges to allow for a wide range of foot motion.. The binding could adjust to various foot sizes. The force created by the bicycle could be changed by adjusting the tightness of the brakes. The prototype cost approximately $300, far below the total budget of $2000.

Product Design Specifications

The ergometer must be able to withstand 30-60 kicks per minute, and it should run at 5-100 W of constant power. The lower half of this range corresponds to moderate exercise. The upper half of the range corresponds to steady state, which is the amount of exercise that the body can sustain for extended amounts of time while undergoing aerobic respiration. The resistive force and work done by the subject should remain constant throughout a test. The kick rate and power output should be read by sensors and sent to a computer through an A/D converter.

The ergometer should provide relative comfort and thigh stabilization to the subject throughout the experiment. The leg must be able to fully extend to 180º, and return to a neutral rest position of 90º. The device should also allow for some lateral flexibility to accommodate different kicking paths of each subject.

To fit in the allotted lab space, the device should measure no more than 5' long by 3' wide. The chair of the ergometer should be positioned about 3' above the ground, and it must recline to at least 30˚ from vertical. This will increase the subject's comfort and allow a researcher to access the femoral artery with an ultrasound probe. The device must be able to accommodate test subjects of heights ranging from 5'4" to 6'4". This range includes the average height for males and females, so information obtained using the device can be applied to the average person.

The device must provide a resistive force against the kicking motion of the leg and zero force as the leg falls to the rest position. This allows for a passive return to the rest position of the leg after kicking and gives the quadriceps a chance to rest before being activated during the next kick. The force on the leg should be adjustable between tests.

The final product should have a streamlined, compact design that encloses any loose parts. This will prevent anything from becoming caught in the moving components and increase the overall safety of the device. This product should also have a minimum lifetime of five years. To accomplish this, it must be built of durable materials that will withstand the subject's weight and vigorous testing. The whole device must be designed and built for less than $2,000.

Alternative Designs

There are certain components of the leg ergometer that are common to all three considered designs. Three of these components were used in last semester's prototype, while the remaining common components are new to the current design. The first of the elements from last semester is the car seat, mentioned above. All three designs also use the same snowboard boot binding from last semester's prototype to attach the subject's foot to the ergometer. The snowboard binding boot provides a secure fit for a wide variety of foot sizes and allows the subject to wear his/her own shoes during testing. One difference in the snowboard binding from its previous use is that the back was removed to allow for a more comfortable kicking pattern. The final element from last semester's prototype that will be used in the current design is the steel pipe frame.

The first of the new components is a lightweight pedal bar to attach the pedal to the boot. The new pedal bar will be an aluminum rod attached to a ball joint at either end. The ball joints will be bolted to the boot at one end and the resistance mechanism at the other. These ball joints allow for some lateral motion during the subject's kick. The final new element common to all three alternative designs is a kick rate sensor used to record a spike in PowerLab every time the subject kicks out. This sensor input allows the computer to output the subject's kick rate by averaging the number of voltage spikes (number of kicks) over a period of time.

Modification of Bike Design

One design option was to improve the reliability of the prototype from Spring 2007. While the bike wheel, brake system, and pedal would be retained, some new improvements would be added to improve the stability and reliability of the ergometer. The handlebars from the bicycle would be removed so that there are no excess parts in the device and the seat would be welded to the frame rather than tied with wires to improve stability and ensure the safety of the subject. The wires that anchored the bike wheel to the frame would be replaced with sturdier metal bars. Additionally, sensors would be placed in the wheel so that a computer program would be able to convert the force applied into power used. Finally, the strength of the resistive force could be altered by either tightening or loosening the bicycle brakes. While this design would be easy to construct and does not involve a lot of expenses, it still would not provide an easy and reliable method to produce the same amount of resistance for different levels since the brakes may also be prone to loosening. This would mean that the operator would frequently be required to readjust the brakes to maintain a constant work output.

Monark Exercise Bike

Another option would be to purchase a Monark cycle ergometer (see Figure 4) and adapt it to the specifications of this project. Various models of the bicycle are produced exclusively for medical research or rehabilitation and have features that satisfy our specifications. As previously mentioned, a leg ergometer was built using the brake system of a Monark bike at Mayo Clinic; however, that device was unreliable and had variable forces. Since that ergometer was built a few years ago, these errors and unreliability would be corrected by using the resistance mechanism of a newer Monark model.

Fig. 4: Monark Exercise Bicycle

The Monark bicycle utilizes a frictional braking system regulated by a belt on the internal flywheel in which a constant force is applied for the subject to cycle against. The Monark can store data and display outputs such as heart rate, RPM, distance traveled, calories burned, and work expended in Watts. This monitor is capable of digital and analog signal output and would supply the necessary data in a convenient interface directly to PowerLab.

The desirable attributes of this design include the pre-assembled flywheel resistance mechanism, the convenient data display, and the overall aesthetics of the machine.

Some of the downfalls of the modified Monark bike design include high costs and the necessary disassembly of the seat and handlebars. Monark ergometers range from $900-7,000 and weigh approximately 120 pounds, which would create a sizeable shipping bill.

Final Design: Servo motor and magnetic brake

The implemented design (figure 5) incorporates a brake and pulley resistance mechanism that can be adjusted with a servo motor. A pedal bar connects the boot to the rest of the device and consists of three separate aluminum bars that are both sturdy and lightweight. Ball joints attached at either end of the pedal bar allow for any lateral movement that a subject's natural kicking pattern would require.

Fig. 5: Final leg ergometer

The pendular motion of the kick is allowed by a crank arm attached to a pulley that rotates 360°. The crank arm starts just below a 180° position, horizontally pointing away from the subject when the kicking leg is at rest. When the subject begins to kick, the crank arm rotates below the center axel of the pulley. The momentum created during the outward kick propels the crank arm back over the center axel to the starting position without any effort exerted by the subject. This allows the kicking leg to be lowered passively between kicks.

This semester's prototype involves a magnetic brake which is attached to the pulley by a belt to generate resistance (Figure 6). The belt is secured to the brake with grooves to prevent lateral slipping and a tensioner prevents the belt from slipping along the brake and pulley.

The brake consists of four magnets attached to an inner, stationary plastic piece. The outer portion of the brake, which the belt is connected to, is able to rotate about the inner portion as the subject kicks. This portion of the brake is metal, and therefore resists motion due to the magnetic field created by the magnets.

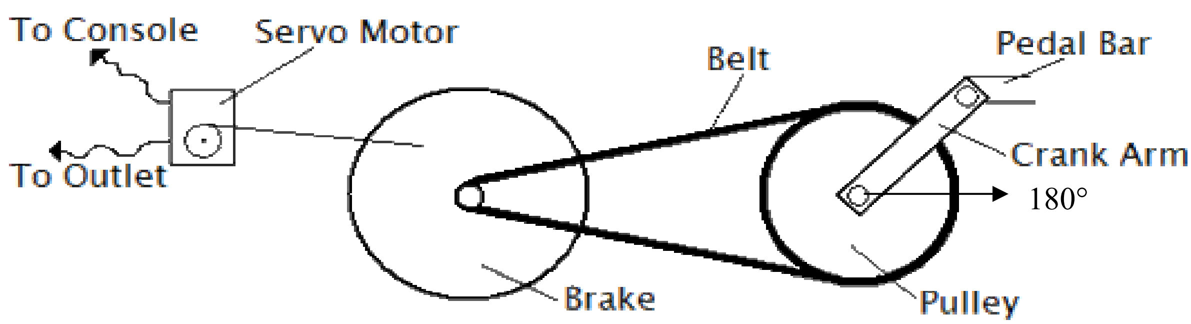

Fig. 6: Servo motor design components

The resistance of the brake is adjusted by a servo motor, which is connected to the break by a short cable that winds around a portion of the servo motor on one end and attaches to the magnets of the brake at the other. By winding the servo motor, the cable pulls on the magnets of the brake, moving them farther from the outer edge of the brake, and reduces the resistance. The servo motor tightens or loosens the brake based on the amplitude of the voltage sent to it by the console, which is preset to levels 1 through 20 with 1 corresponding to the smallest resistance and 20 corresponding to the largest resistance.

The kick rate of the subject is interfaced to Powerlab through a BNC cable that connects to a kick rate sensor. A voltage of 5 V is sent to the sensor by the console and the output voltage of the sensor changes based on its proximity to a magnet. The sensor is mounted next to the pulley, which contains a magnet. Every time the subject kicks, the magnet passes by the sensor and the output voltage changes. The kick rate can be calculated by determining the time between consecutive voltage changes.

Safety and Ethical Considerations

The largest safety concern when using this type of ergometer is the risk of the test subject kicking against zero resistive force when expecting a force to act against the kick. If this happens, the subject could damage the tendons and ligaments of the knee. Because the magnetic brake provides a force in two directions (it is not a one-way clutch), it is impossible to kick against zero resistance. If the subject attempts a second kick before the crank arm reaches the top of its rotation, the rotation of the brake will reverse, but it will still provide a force. The operator should also be sure the area in front of the ergometer remains clear of all obstructions, including other persons in the lab space.

Testing

After the device was constructed, tests were performed to ensure that the product specifications were met. Three different tests were performed to ensure stability, suitability for different sizes of users, and passive return of the leg.

To test for stability, the device was used for several tests of five to ten minutes and the status of the components was evaluated after each test. From this test, it was determined that the tensioner does loosen with use. To account for this, the placement of the tensioner should be checked at the beginning of each test to guarantee the belt stays tight. This test also revealed that the horizontal movement of the pulley causes the belt to slip off of the grooves on the brake. This only became a problem when the tensioner was not tight. To correct this problem, the pulley was secured to prevent lateral movement.

The device was also tested on a range of possible users. The desired subject height range is 5'4" to 6'4". Subjects at the top and bottom of that range were tested, as well as several others within. The device works well for users on the short end of the range, but the range of motion is not large enough for taller subjects. The best way to resolve this problem is to design a new crank arm with adjustable length. The length of the crank arm is what determines how far the foot can be extended. Other than the limited range of motion for taller users, the tests for size were successful.

The third test performed was an electromyography (EMG) test to determine if the leg return is passive. Electrodes were placed on three muscles of the quadriceps, the rectus femoris,

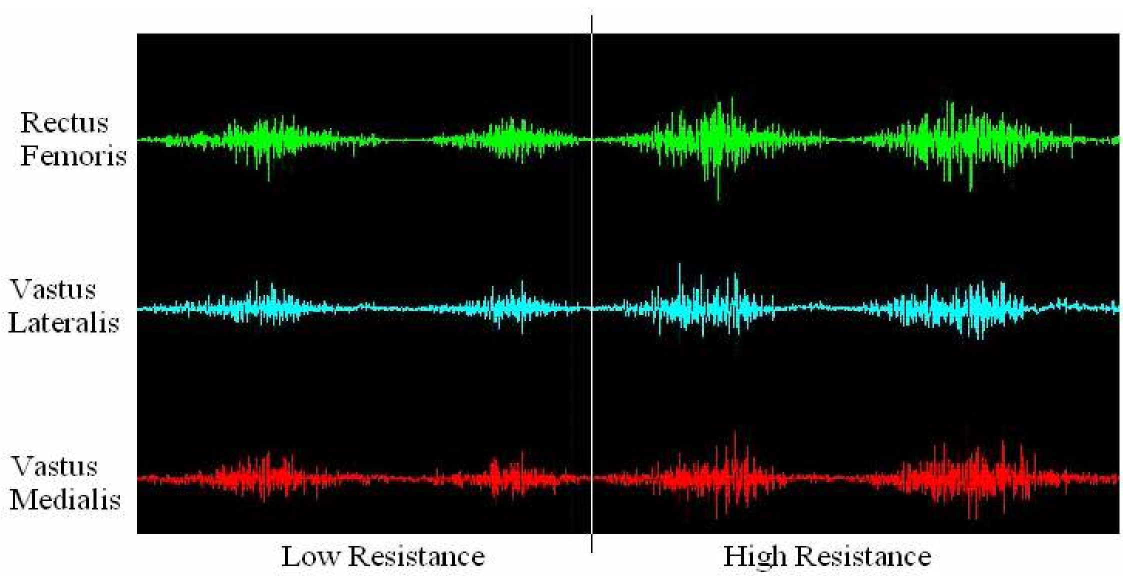

Fig. 7: EMG image of quadriceps during testing

vastus lateralis, and vastus medialis. The activity of the muscles was observed at various resistances. The data image of the lowest and highest resistances is shown in figure 7. Areas of high amplitude indicate muscle activation during the outward kick. Between these areas, there is little to no amplitude indicating no muscle activity and a passive leg return.

Budget

The total allotted budget for this project is $2000. The total expenses for this semester amounted to $315.28 resulting in a grand total for the project of $650.28 (see appendix 3 for complete budget). Expenses were less than our mid-semester estimates due to the donataion of key components from Octane Fitness including the magnetic brake, servo motor and console.

Future Work

There are two main pieces of the device that need to be completed before it can be used for quantitative research. A new crank arm (figure 8) must be added to accommodate a wider range of subject heights. The new crank arm will be 12” long (current crank arm is 8” in length) and have four holes to adjust the range of motion.

A force transducer will be integrated into the pedal bar. The transducer will collect force data throughout the subject’s kick and send the information to PowerLab. Work done by the subject can be

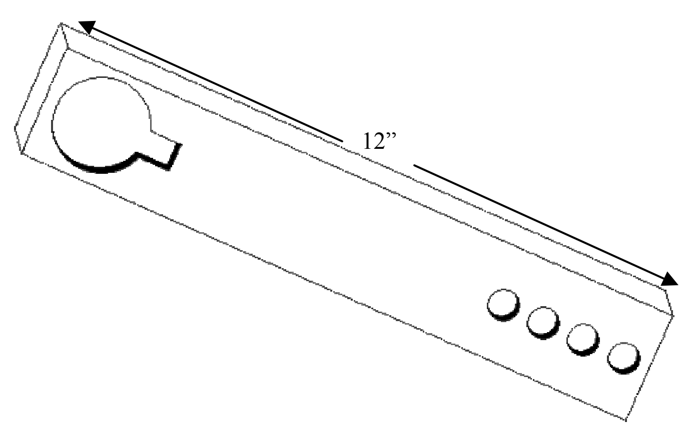

Figure 8: New crank arm to allow for height adjustability

calculated using this force data and the length of the crank arm. Further calculation can be done to find the subject's power output (see appendix 4 for calculations).

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Figure Sources:

Fig. 1 http://www.gehealthcare.com/usen/ultrasound/images/cmeadi_fig3_500.jpg

Fig. 4 http://www.elitefitness.co.nz/Product.aspx?CategoryId=2534&pageId=0&ProductId=391

Appendix 1: Project Design Specifications (PDS)

Project Design Specifications—Leg Ergometer

Amy Weaver, Laura Bagley, Lacey Halfen, Deborah Yagow, Lein Ma

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Function: The goal is to design a leg ergometer to measure power output of a subject who is kicking against a resistive force. The test subject will use the ergometer to maintain a constant kicking motion while the femoral artery is imaged using an ultrasound. The information is used to determine blood flow velocity during exercise.

Client Requirements:

- Must be sturdy, last at least five years
- Adjustable for subject heights 5'4" to 6'4"
- Boot to attach foot to the device must be adjustable for different foot sizes
- Maintain a constant wattage throughout testing
- Wattage (0-100 W) and kick rate (30-60 kicks/sec) output to a laptop through an A/D converter
- Flexible range of motion for kicking
- Leg must be able to fully extend when kicking
- No resistive forces against the leg during return to resting position after kick

Design Requirements:

1. Physical and Operational Characteristics
   a. *Performance Requirements:* The ergometer should be able to be used at a rate of 30 to 60 kicks per minutes (kpm) and output 5 to 100 W of constant power. The kpm and power output should be sent to a laptop through an A/D converter. The kicking leg should have a range of motion of 90 to 180º from the horizontal and allow for some lateral movement. The subject should sit in the chair 30º from vertical. The boot attaching the foot to the resistance mechanism should be adjustable to different foot sizes.
   b. *Safety:* The ergometer should be able to hold a person of average build (height range 5'4" to 6'4") without putting extreme stress on the components. There must be no possibility of the resistance failing to act against the kick. Also, any elements under tension should be enclosed such that if they come lose, they do not cause harm to any persons near the device. The whole device should be as enclosed as much as possible so that nothing can get caught in the moving elements. The kicking path must remain clear of any components of the device.
   c. *Accuracy and Reliability:* The device must be able to be set to a specific resistance and run at that setting for at least 5 minutes without deviating.
   d. *Life in Service:* Product should have a lifespan of at least five years.
   e. *Operating Environment:* The ergometer needs to be durable enough to withstand the test subject's weight. It also needs to withstand numerous tests with variable force levels and minor transportation.

f. *Ergonomics:* The device must accommodate test subjects from 5’4” to 6’4” with variable weights. The subject should also sit 3’ above the ground at an angle of 30º from vertical. The kicking portion of the ergometer needs slight lateral flexibility to accommodate different test subjects. Overall, the device should be comfortable for the test subjects as well as the researchers to use.
h. *Size:* The ergometer needs to be no larger than 5’ long by 3’ wide by 4’ tall.
i. *Materials:* Materials used should be able to withstand heat and friction without changing performance. Also, materials that can withstand the weight of the device must be used.
j. *Aesthetics*, *Appearance, and Finish:* The design should be streamlined and compact, with as few extra parts as possible.

2. Production Characteristics
   a. *Quantity:* The client only requires one unit at this time, although there is the possibility of additional units used in the future.
   b. *Target Production Cost:* The total budget for this project is $2,000.

3. Miscellaneous
   a. *Standards and Specifications:* Not applicable.
   b. *Subject-related concerns:* The ergometer should provide relative comfort to the user while maintaining stabilization of the thigh while kicking.
   c. *Competition:* Ergometers are available in many different styles including ellipticals and stationary bicycles. There are examples of ergometers similar to this proposed design in use in several research facilities. One example of this type of ergometer was used in a research study published in the following article: P. Andersen and B. Saltin, Maximal perfusion of skeletal muscle in man. J Physiol.

Appendix 2: Design Matrix

Criteria	Weight	Servo Motor	Monark	Modified Bike
Ease of Use for Client	35	0.9	0.6	0.4
Constrant Power Output	25	0.8	0.6	0.5
Force Adjustability	20	0.9	0.5	0.1
Ease of Construction	10	0.6	0.3	0.8
Cost	10	0.7	0.1	0.8
Total	**100**	**82.5**	**50**	**44.5**

Appendix 3: Budget

Item	Dimensions	Units	Unit Price	Total Cost
Smooth-Band Worm-Drive Hose & Tube Clamp Kit, screw assemblies		1	$36.10	$36.10
Pack of 5 Screws for Smooth-Band Worm-Drive Hose & Tube		1	$9.98	$9.98
Steel tube (pulley support)	1.5" x 1" x 3'	2	$41.81	$83.62
Steel tube (brake support)	0.75" x 0.75" x 3'	1	$33.14	$33.14
Carbon Steel 90 Degree Angle Perforated (brake support)	1.5" x 1.5" x 3'	1	$4.94	$4.94
Steel sheet (brake support)	0.109" x 8" x 12"	1	$30.47	$30.47
Right-Hand Threaded Connecting Rod, 3/8"- 24 female threads (pedal bar)	18"	1	$9.68	$9.68
Right-Hand Threaded Connecting Rod, 3/8"- 24 female threads (pedal bar)	12"	1	$8.70	$8.70
Right-Hand Threaded Connecting Rod, 3/8"- 24 male threads (pedal bar)	6"	1	$6.00	$6.00
Inline Booted Ball Joint Linkage 3/8"-24 Male Shank with Stud		1	$8.56	$8.56
PTFE-Lined Ball Joint Rod End Linkage, 3/8"-24 Rh Thrd Male Shank W/Rh Thrd Stud		1	$19.89	$19.89
Hex Nut, Packs of 100	3/8"-24 Screw Size, 9/16" W, 7/32" H	1	$1.93	$1.93
Aluminum Flat Washer, Packs of 5	3/8" Screw, .391" ID, 5/8" OD	1	$6.40	$6.40
Aluminum Rectangular Tube (crank arm)	1" X 1-1/2", .125" Wall, 1' Length	1		
Right-Hand Threaded Connecting Rod, 3/8"- 24 male threads (pedal bar)	12"	1	$7.84	$7.84
Right-Hand Threaded Connecting Rod, 3/8"- 24 male threads (pedal bar)	18"	1	$8.74	$8.74
Right-Hand Threaded Connecting Rod, 3/8"- 24 male threads (pedal bar)	24"	1	$8.41	$8.41
Shipping and Handling				$30.88
Brake, Pulley, Servo motor, console, belt, tensioner, connecting wires				(donation)
Semester Total				**$315.28**
Spring 2007 Total				**$335.00**
Grand Total				**$650.28**

Appendix 4: Work and Power Calculations

$$W = Fd$$

Where F is the force given by the force transducer and d is 2(length of crank arm) which depends on the hole-setting of the pedal bar.

$$P = \frac{W}{t}$$

Where W is the work taken from the above equation and t is the time required for one kick.

Time, t in seconds is given by 60/(kick rate) where kick rate is in kicks per minute.