

Leg Ergometer for Blood Flow Studies

BME 200/300
University of Wisconsin-Madison
October 24, 2007

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Abstract

Dr. William Schrage of the kinesiology department at UW-Madison is conducting research studies involving blood flow through the femoral artery during exercise. He requires a device that will allow test subjects to do constant work by kicking one leg while he images the femoral artery and observes blood flow in the active leg. Some of his major requirements for the device include a passive return of the foot to the start position after each kick, a constant kick rate, a measurable work output, and reliability of the device. Three design alternatives for a resistance mechanism were developed, and the advantages and disadvantages of each one were weighed in order to choose a final design. Because of its relatively low cost, its high reliability, and its ease of use, a servo motor design was chosen over a Monark bicycle design and the proposed improvements on last year's resistance device.

Problem Statement

Dr. William Schrage, who is researching blood flow through the femoral artery during exercise, needs a one-legged ergometer that will provide a constant one way resistive force against a test subject's kicking motion. The force should be applied while the leg kicks out and absent while the leg returns to the starting position. This device will be used in his research lab as part of his studies. While the test subject uses the ergometer, Dr. Schrage will image the subject's kicking leg femoral artery to determine blood velocity.

Background

Blood Flow Research

Dr. William Schrage conducts blood flow research with the UW – Madison Department of Kinesiology. He plans to use the proposed ergometer in his experiments to examine the effects of exercise on blood flow. A Doppler ultrasound probe angled against the upper thigh provides an image of the blood vessels (Figure 1). The data obtained by Dr. Schrage will lead to further research about how smaller blood vessels regulate the flow of blood from the femoral artery.

Two main questions will be investigated during this research.

First, what are the neural, metabolic, and vascular signals controlling blood flow at rest and exercise? Second, how do conditions such as aging and cardiovascular diseases (i.e. obesity, high blood pressure, and diabetes) alter the regulation of blood flow? The answers gained from this research will lead to a better understanding of what controls blood pressure. This will also provide more information about how blood flow affects people suffering from obesity and diabetes. Once normal and abnormal states of blood flow are understood, tests can be conducted to discover whether exercise can be used to restore normal blood flow. Furthermore, drug

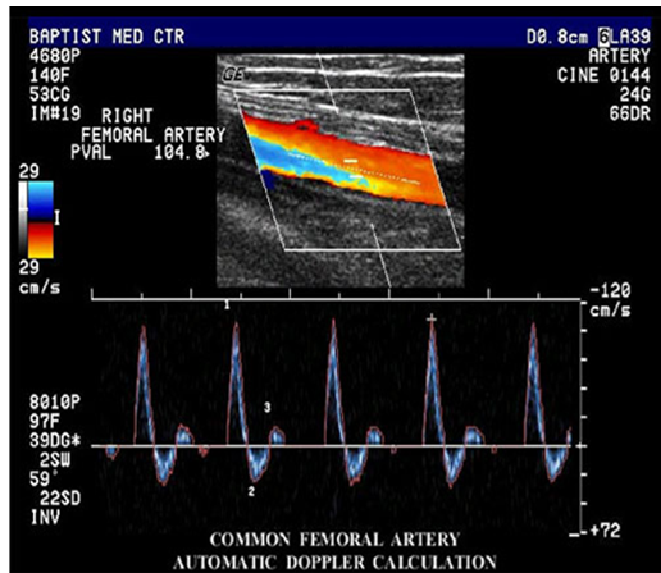


Fig 1: Doppler Probe Image

companies may then be able to develop drugs to mimic the effects of exercise and possibly correct dysfunction.

Existing Devices

There are several types of leg ergometers, one of which is an exercise bike. Most of these bicycles are two-leg cycles with a flywheel and a brake system that provides resistive force. In addition to these personal exercise machines, there are leg ergometers designed for medical use. While most look similar to a normal exercise bike, they are one-leg cycles. These ergometers have a simple monitor that displays useful information such as heart rate, distance traveled, or work output.

A research facility in Europe used a modified bicycle to isolate the right upper thigh by means of a leg extension motion. This study, which is related to the client's research, 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 minutes of the exercise (Anderson, Saltin).

Previously, Dr. Schrage used a leg ergometer at Mayo Clinic that was designed for similar studies. The device was composed of a flywheel from an exercise bike and a seat from a car. Two different sized rollerblade boots attached the patient's foot to the bike pedal through a bar and two ball joints. The larger rollerblade boot had the toe cut out to allow for various foot sizes. A Doppler ultrasound probe held by the researcher was used to observe and measure the blood flow while sensors connected to the resistance system measured wattage and kick rate. Unfortunately, this device was unreliable. The flywheel would occasionally spin backwards, resulting in zero resistive force being applied when the subject kicked forward. Also, the nylon belt attached to the

flywheel became hot as a result of friction. The heat altered the length of the nylon belt and changed the work output by the patient.

Last Semester's Design

Last semester's prototype had many aspects of the proposed design. Iron plumbing pipes were used to

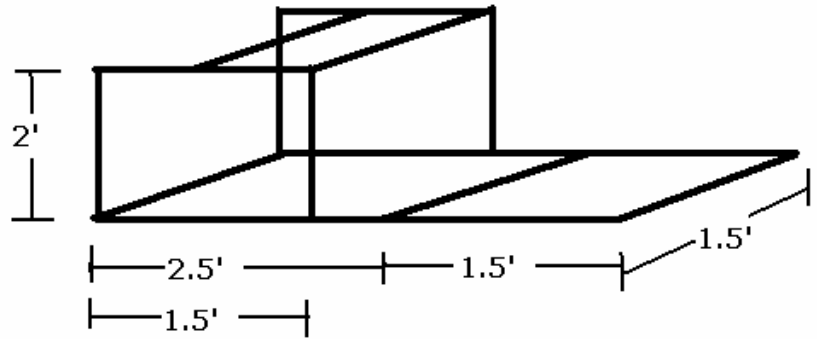


Fig. 2 Frame Dimensions

build the frame of the

machine. These pipes came pre-cut and pre-threaded, and they provided an extremely stable frame to house the rest of the device. The assembled frame is four feet long, two feet tall, and one and a half feet wide (Figure 2). The frame is slightly smaller than the maximum allowed dimensions to allow for easier attachment of the seat to the frame.

Wheels were added to the base of the frame to provide easy transportation from room to room. To meet the client's requirement for a reclining, adjustable seat, a car bucket seat was used (Fig. 3). This adjustable seat allowed the client easier access to the femoral artery of the test subjects.

For a temporary resistance mechanism, a bike was used to supply variable one-way resistance when the test subject's leg kicked out. The bike was halved and flipped upside down to allow for simpler attachment to the iron frame (Fig 3). Then it was wired to the frame with cables and aluminum wire. These temporary attachments were used to allow for easy removal bicycle this semester when the new resistance mechanism is implemented. Aluminum bars were used to attach the bike pedal to the test subject's foot

because of their lightness and adjustability. First, the pedal was fixed in one position and the pedal arm length was extended to allow test subjects to fully extend his/her leg



Fig. 3 Last Semester's Prototype

without overextending the pedal.

Next, the pedal was attached using hinges to two aluminum bars. These bars, in turn, were attached using a hinge to a snowboard binding. The snowboard binding buckles the subject's kicking foot into the ergometer. These bindings adjust to variable foot sizes and allow the test

subjects to keep their tennis shoes on during the test. The resistive force was changed by adjusting the tightness of the bike brakes. Last semester's prototype cost approximately \$300, far below the total allotted 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 power should not vary by more than ± 2 W in five minutes. The kicks per minute and power should be read by sensors and then sent to a laptop 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 when kicking to 180° and return to a natural rest position of 90° to the ground. The device should also

allow for some lateral flexibility to accommodate the different kicking pathway of each subject.

In order to fit in the allotted area, the ergometer should be approximately 5' long by 3' wide. The chair for the test subject should be positioned about 3' above the ground and it must recline at least 30° from vertical to increase client comfort and access to the femoral artery. Also, the entire device must be adjustable to accommodate test subjects of heights ranging from 5'4" to 6'4".

The device must provide a resistive force against the upward kicking motion of the leg, but zero force as the leg falls back to the rest position. This means that the subject will not have to oppose a force when returning the foot to the starting position. The force on the leg should be adjustable between tests and the device should test the subject's right leg.

The final product should have a streamlined, compact design that encloses the loose parts as much as possible. This will prevent anything from becoming caught in the moving elements and it will increase the overall safety of the device. The ergometer should also have a minimum lifespan of five years. To accomplish this, it must be built of durable materials that will withstand the patients' weight and vigorous testing. The whole device must be designed and built for under \$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 and three will be new to the current design. The first part that will be retained from last

semester is the car seat. The seat is comfortable for subjects and it provides the 30° angle that allows Dr. Schrage access the femoral artery with the ultrasound probe. All three designs will also use the snowboard boot binding from the old prototype to attach the subject's foot to the leg ergometer. The binding provides a secure fit for a wide variety of foot sizes and allows subjects to wear their shoes during testing. The final retained element is the leg ergometer frame. The frame is assembled from pipe and supports the seat, boot, and resistance mechanism.

There are three components in each of the proposed designs that are new additions or changes from last semester's prototype. The first new component is a lightweight pedal bar that will replace the aluminum bar that attached 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. The ball joints allow for some lateral motion during the subject's kick. The final new element is a force transducer placed inside the pedal bar. The force transducer will record a spike every time the subject kicks out, which will allow the computer to determine the subject's kick rate. Dr. Schrage will be able to set a threshold level in PowerLab on his computer. PowerLab will be able to determine the number of force spikes above the threshold (number of kicks) over a period of time to output kick rate.

Modification of Bike Design

The first design option is simply to update and improve the prototype assembled last semester. This design still employs the bike wheel, brake system, and pedal used in the previous prototype; however, the handlebars will be removed. To improve the stability of the device, the seat will be welded to the frame rather than tied with wires.

The wires that currently anchor the bike wheel will be replaced with sturdier metal bars. Sensors will also be placed in the wheel in order for the client to determine the subject's power output. The client will be able to adjust the resistive force by tightening or loosening the bike brakes. While this design would be easy to construct and does not involve a lot of expenses, it still does not provide Dr. Schrage with an easy and accurate way to adjust the device's resistance. Once the resistance is set, the brakes may also be prone to loosening. This means that the client would frequently be required to readjust the brakes to maintain a constant work output.

Monark Exercise Bike

Another option that would satisfy Dr. Schrage's requirements would be to purchase a Monark cycle ergometer (see Figure 4) and adapt it to the specifications. There are various models that are produced exclusively for medical research and rehabilitation and have features specific to this



Fig. 4: Monark Exercise Bicycle

project. As previously mentioned, Dr. Schrage worked at Mayo Clinic, where he used a modified Monark for similar research. That device was unreliable and had variable forces. But if a newer and more reliable model is used, these errors may be eliminated, especially with Dr. Schrage's experience.

The Monark utilizes a frictional braking system where a constant force is set for the subject to cycle against, regulated by a belt on the internal flywheel. The Monark can store data and it has a display unit that outputs heart rate, RPM, distance traveled, Calories used, 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, which is the program used by the client.

In order to comply with the client's requirements, some changes would need to be made to the ergometer. The existing top plate, which consists of the handlebars and the seat, would need to be removed. In its place, the car seat from last semester will be attached to the flywheel inside the Monark bicycle. The seat must also be positioned to obtain the necessary 30° angle from vertical to allow easy access of the Doppler probe. Other change to the Monark bike would be that a kick bar is connected from the ergometer's pedal to the snowboard binding holding the subject's foot. The bar will use ball joints to allow the subject a free range of kicking motion due to natural curvature in the leg. Since a reasonably constant kick rate by the subject is required, Dr. Schrage will train the subject at his discretion in order to achieve that rate. A metronome would also be provided to serve as a guide.

The desirable attributes of this design include the pre-assembled flywheel/resistance mechanism, the convenient data display, and the overall aesthetics of the machine. With the efficient design of the Monark pedaling system, less time for assembly would be required and more focus would be placed on tailoring the prototype to the client's needs.

Some of the downfalls of the modified Monark bike design include high costs, the necessary disassembly of the seat and handlebars, and cost and addition of supplementary parts. The cost of Monark ergometers range from \$900-7,000 and they weigh approximately 120 lbs, creating a sizeable shipping bill and overspending the budget.

Proposed Design

The proposed design for the resistance device involves a brake and pulley adjusted by a servo motor (see Figure 5). The pulley has a crank arm that connects to its

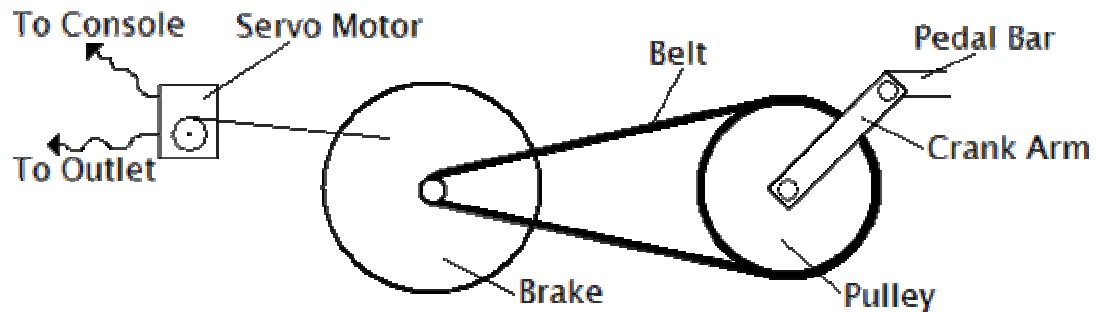


Fig. 5: Servo Motor Design

center axle to the pedal bar. This arm rotates 360° along with the rotation of the pulley. It rotates below the pulley from a 180° position to a 0° position when the test subject kicks outward. The momentum from this kick then propels the crank arm the rest of the way around, back to the initial 180° position, with no effort exerted by the subject. This allows the kicking leg to be lowered passively between kicks.

The pulley in this design is connected to the brake via a belt. The belt and the components it is attached to will all have grooves to prevent slipping and the loss of any resistance from the brake. The brake's resistance is provided by two internal magnets, which can be adjusted by changing the distance between the magnets using the servo motor. The servo motor, which winds a cable connected to the magnetic brake, will adjust the distance between the magnets based on the voltage sent to it. This voltage will be controlled with a console that is connected to the servo motor. The console will have 15 settings that will each correspond to a particular brake resistance given the kick rate of the subject. Even though the resistive wattage will be set before each experiment, there

will still be a sensor used to measure and display the resistance in the client's pre-existing PowerLab program.

Budget and Time estimates

The total budget allotted for this project is just under \$2000. While the servo motor design appears to be relatively low cost, most of the budget will be used to purchase sensors. The servo motor will cost approximately \$50 while the sensors will cost around \$100. Other possible expenses include the ball-socket joints, the poster for the final presentation, and any materials needed to construct attachments to the frame. Now that the resistance mechanism design has been finalized, the rest of the semester will be spent fixing the problems from last semester's prototype to ensure that the device meets the client's specifications. The servo motor and most of the parts for the resistance mechanism should arrive in approximately one week, which will allow enough time to assemble the resistance mechanism and test the ergometer. The project construction is scheduled to be completely two weeks before the end of the semester to allow sufficient time for testing, modification, and re-testing.

Future Work

Work will be done to implement the servo-motor design during the rest of the semester. The servo motor, other parts of the resistance mechanism, and a force transducer for the pedal bar will be ordered. While these parts are being obtained, new attachments for the car seat and servo motor will be built and added to the frame. Finally, once all the parts have arrived and the ergometer has been assembled, several

trials with test subjects will be performed with the client present to ensure that all specifications are met. The major specifications to be verified include passive leg return and constant wattage. Once the prototype has been modified to the client's need, the final product will be delivered to Dr. Schrage.

References

Maximal Perfusion of Skeletal Muscle in Man (Per Andersen and Bengt Saltin) 1984

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
September 20, 2007

Function: The goal is to design a leg ergometer to be used by William Schrage in his lab. 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 to the leg during exercise.

Client Requirements:

- Must be sturdy, last more than a few 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 for return to normal position of the leg after kicking
- Should be set up for right leg testing

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 5 to 100 W of constant power. The kpm and power output should be measured and sent to a laptop through an A/D converter (supplied by the client). The kicking leg should have a range of motion of 90 to 180° from the horizontal and allow for some lateral movement. The subject should sit in the chair 30° 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 an average sized build with 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 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 single wattage and run at that setting for at least 5 minutes without deviating more than + /-- 2W. Any data collected from the machine should be consistently accurate.
 - 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 subjects' 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 30° 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