Leg Ergometer
for Blood Flow Studies

BME 201
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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 needs a device that will allow a subject to do constant work by kicking one leg while he images the femoral artery to observe blood flow in that same leg. Some of his major requirements include passive return of the foot to the normal position after the kick, a constant kick rate, measurable work output, and reliability. Three design alternatives were developed and the advantages and disadvantages of each were weighed and a final design was chosen. Due to difficulties obtaining the viscous dampener, a temporary solution was constructed. The current design utilizes a bike clutch and resistance system to meet our client's needs. The current prototype will allow the client to perform preliminary research studies this summer, and a final prototype will be delivered to him next fall.

Problem Statement

Dr. William Schrage is researching blood flow through the femoral artery during exercise and needs an ergometer that will allow for a regular kicking motion with a passive return of one leg while providing a constant resistive force against the kick. This device will be used in his research lab as part of his studies. While the subject is kicking, Dr. Schrage will be imaging the femoral artery to determine blood flow.

Background

Blood Flow Research

Dr. William Schrage works in the department of kinesiology conducting blood flow research. He will use this prototype in his experiments to measure blood flow in the femoral artery during exercise. He will infuse drugs into the femoral artery to observe how they are delivered to the microcirculation where they activate the signaling system. The data he obtains will lead to further research on how smaller blood vessels regulate the femoral blood flow.

There are two main questions to be answered by this research. First, what are the neural, metabolic, and vascular signals controlling blood flow at rest and exercise? Second, how do conditions like aging and cardiovascular diseases such as obesity, high blood pressure, and diabetes alter the regulation of blood flow? The wider implications of this research will lead to a better understanding of blood pressure control and how blood flow changes and affects people with obesity and diabetes.

Existing Devices

There are several types of leg ergometers; one example is exercise bikes. Most of them are two-leg cycles with a flywheel and a brake system which gives resistant force to the user. However, there are also leg ergometers for medical use. Most look similar to a normal exercise bike, and are one-leg cycles. These devices are useful in measuring heart rate or endurance.

A research facility in Europe has used a modified bicycle to isolate the right upper thigh by a leg extension motion. This study, which was 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 min of the exercise (Anderson, Saltin).

Previously, the client used a leg ergometer that was designed for studies similar to this at Mayo Clinic. The previous device was composed of a flywheel from an exercise bike and a car seat for the patient's seat. Two different sized rollerblade boots attached the patients foot to the bike pedal through a bar and two ball joints. The larger size 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, and sensors connected to the resistance system measured wattage and kicking rate. Unfortunately, the device was unreliable. The flywheel would occasionally spin backwards, resulting in zero resistive force 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 patient.

Product Design Specifications

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 increase the overall safety of the device. This product 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 device must have a resistant force against the upward kicking motion of the leg, but 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. The force on the leg should be adjustable between tests, and the device should test the subject's right leg.

The device should be easily portable to ensure that it can be moved around the research area as needed. In order to fit in the allotted area, it should be approximately 5' long by 3' wide. The chair of the ergometer should be positioned about 3' above the ground and it must recline. This will 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 ergometer should provide relative comfort and thigh stabilization to the patient throughout the experiment. The leg must be able to fully extend while kicking to 180º, and return to a natural rest position of 90º. The device should also allow for some right-left flexibility to accommodate the different kicking pathway of each patient.

The ergometer must be able to withstand 30-60 kicks per minute, and it should run at 5-100 W of constant power. The kicks per minute and wattage outputs should be read by sensors and then sent to a laptop through an A/D converter. This whole device must be assembled and built for under $2,000.

Alternative Designs

There are certain aspects that each design alternative has in common. Every design includes a seat for the patient that reclines. The boot for the foot of the kicking leg will include a base and straps to hold the shoe of the patient in place. The boot will then be connected to the source of resistance, which will have an adjustable force. There will be sensors attached to the device to measure the wattage and kicking rate of the patient, as well as wheels on the base of the frame to allow for movement of the device.

Gas Spring Shock

The first design possibility employs a gas spring shock as the resistive force against the foot. The gas spring shock works by compressing gasses within a cylinder. When the foot kicks forward, the rod is pulled and the gas compresses (Fig. 1). Gas spring shocks can be purchased commercially in various sizes with adjustable forces at a reasonable price. This flexibility would ensure a device that accurately fits the force requirements of this design. The gas spring shock would be connected to the boot with the use of a cable to allow for more flexibility in the kicking motion. A major disadvantage of this design is that the device would spring back to its initial position when the force of the kick is finished, leading to the active return of the kicking leg to the rest position. This would go against one of the major requirements of the project.

Fig 1. Gas Spring Shock

One-way Clutch

The second and third designs both utilize a one-way clutch, which is a device that freely turns in one direction, while rotation is restricted in the other direction. The clutch would attach to the friction device such that either the entire clutch/friction assembly would rotate when the subject kicked out, or only the clutch would rotate within itself when the leg returned.

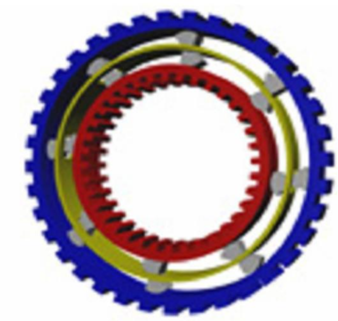

Fig. 2 Sprag clutch

There are two main types of one way clutches, including the sprag clutch (Fig. 2). The sprag clutch employs two rings with several sprags placed between. The sprags are placed at a slight angle from the normal to the rings. When the clutch is turned in one direction, in this case clockwise, the sprags are forced towards their slant and the rotating ring is free to turn. When the clutch is turned in the other direction, the sprags are forced towards the normal and become wedged between the two rings, preventing the mechanism from turning. Another type of one-way clutch is shown in Fig. 3. This mechanism involves the use of four ball bearings which are placed between the hub and ring as shown. When the hub rotates clockwise, it rotates freely. When the hub is rotated counter-clockwise, the ball bearings become wedged between the surfaces of the hub and ring which prevents the device from rotating. The use of a one-way clutch in the following two designs allows for simple, free return of the kicking leg at a reasonable cost (Fronczak, ADCATS).

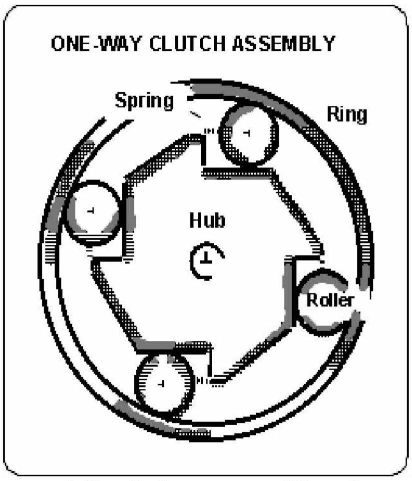

Fig. 3 One-way Clutch

One-way Clutch w/ Drum Brake

This design makes use of the one-way clutch described above and a drum brake as the resistive force. A drum brake is the type of brake that is found on the rear wheels of cars. This

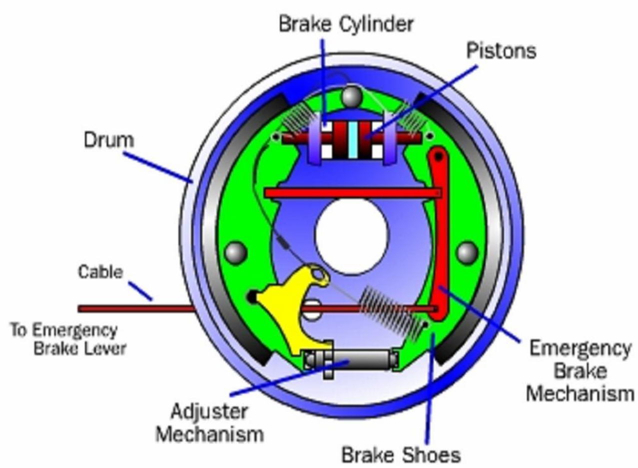

Fig. 4 Drum Brake

design would provide a constant resistive force due to friction that was not affected by the velocity of the kicking leg. The friction would come from two “shoes” pushing against the side of a drum (Fig. 4). The resistive force could be changed by altering the normal force of the shoes to the drum. Some disadvantages of this design are that the properties of the brake pads could change with heat, altering the force of resistance. Also, the brake pads would need to be replaced as they wore down (Fronczak).

Proposed Design

The last design utilizes the one-way clutch as previously described along with a viscous friction device (Fig. 5). This device consists of two metal sheets with a liquid between them. The viscosity of the liquid would provide the resistance as the test subject kicked out. The researcher could change the work output of the test subject by altering the distance between the two surfaces or the distance between them (Subedi, Ace Controls, Sugatsune).

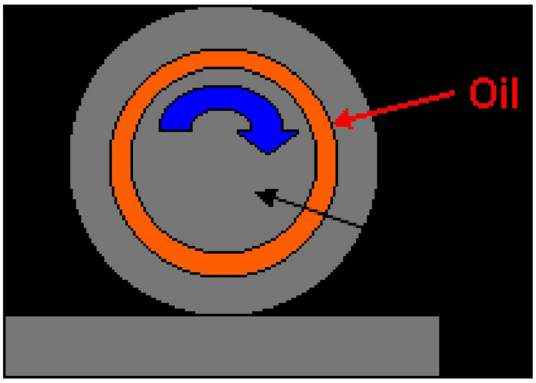

Fig. 5 Viscous Friction Device

There are several advantages to this design. Because the design is dependent on liquid, the work done by the test subject would not change as a result of the small temperature changes of the device. It would also be fairly easy to construct because the viscous friction device could be purchased separately and then attached to the one-way clutch.

There are also some disadvantages to this design. It is difficult to find a commercially produced device with the specified force range and an adjustable force (Taylor Devices).

A design matrix was utilized to aid in choosing one of the three alternative designs. In the design matrix (Appendix 2), the ability of the device to provide a passive kicking return and the overall reliability of the device were given the most weight. Some other considerations included the ease of construction, maintenance required, ease of use, ability to provide a consistent kicking force and flexible kicking motion, and the force adjustability. The gas spring shock design would be easy to construct and would provide a flexible kicking motion, but it would not provide a passive kicking return. Because this is one of the most important requirements of the design, the gas spring shock is not ideally suited for this project. The one-way clutch with drum brake scored higher than the gas spring shock, particularly on the ability to provide a passive kicking return, but it would not be overly reliable, and because this is also one of our largest client requirements, this design was not ideal. The last design, the one-way clutch with viscous friction device, scored very high on both overall reliability and the ability to provide a passive kicking return. Because it meets all of the client requirements, this design was chosen to propose to the client.

Design Progress

The scope of this project is too complex to be completed in one semester. Finding some of the necessary parts, particularly the viscous dampener, proved difficult. Because of this, it was decided that the project will be continued into the fall. However, the client wanted a working prototype for the summer to perform pilot studies and gather qualitative data. To suit his needs, a temporary device was constructed. Because this system is temporary, it was decided to not purchase electronic force sensors to attach to the prototype. The sensor will depend on the type of clutch and resistance system in the final design, and the necessary sensor would not necessarily be the same for the temporary design as for the final design.

Prototype Design

The working prototype for the summer has many aspects of the proposed design. Iron plumbing pipes were utilized to build the frame. These pipes came pre-cut and pre-threaded, and they provide an extremely stable frame to house the rest of the device. The final frame is four feet long, two feet tall, and one and a half feet wide (Figure 6). The frame is slightly smaller than the maximum to allow for easier attachment of the seat to the frame. Wheels were added to the base of the frame to allow for easy transportation from room to room. To meet our client's needs of a reclining, adjustable seat, a car bucket seat was used (Fig. 7). This will make it easier for our client to access the femoral artery on variable test subjects. This seat was purchased from an auto parts store for $45 (Appendix 3).

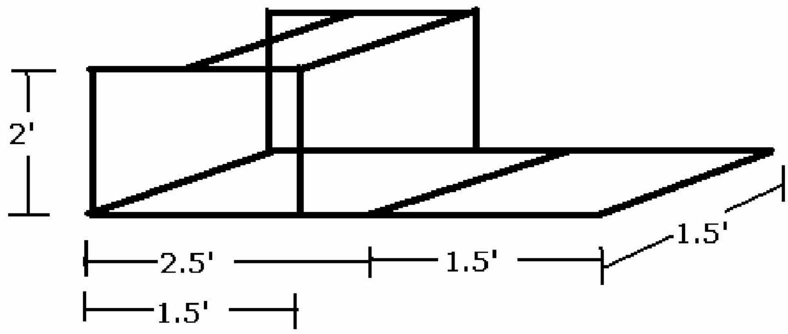

Fig. 6 Frame Dimensions

For a temporary clutch and resistance system, a bike was used to supply variable resistances only while the test subject is kicking out. The bike was halved and flipped upside down to allow for simpler attachment to the iron frame (Fig 7). Then it was wired to the frame with cables and aluminum wire. This will permit the bike to be removed in the fall when a more permanent clutch and resistance system is designed. The bike was purchased from a used bike store for $89 (Appendix 3). The wires and cables also firmly attach the bike to the frame, without letting the bike wobble during tests. To attach the bike pedal to the test subject, aluminum bars were used because of their lightness and adjustability. First, the pedal was fixed in one position and the pedal arm length was increased. This will allow the test subject to fully extend their leg, while not overextending the pedal. Then the pedal was attached by hinges to 2 aluminum bars which were attached with a hinge to snowboard bindings. The test subject's foot buckles into the snowboard bindings. These bindings allow for variable foot sizes, and allow the test subjects to keep their tennis shoes on during the test.

The client will adjust the force by adjusting the tightness of the bike brakes. While this will be a rough adjustment, it will provide variable forces in the range specified by our client. He will then sense the force against the test subject's foot with a spring scale tension sensor. This sensor will hook on to the snowboard bindings at the front of the prototype prior to the test. Once hooked, the client will pull the sensor out as if the test subject were kicking. He can then view the sensor to determine the amount of force the subject is kicking against. He will use a spread sheet calculation to compute the amount of work the test subject is doing based on the resistive force found. Including this sensor, the prototype cost approximately $300, far below the budget of $2000.

Testing

There were several tests performed to ascertain the durability and effectiveness of the final device. The first few tests revealed a few problems with the prototype. One issue was the fact that the bike would move when the person kicked, causing the whole frame to shake slightly. This was fixed by securing the bike more firmly with additional cable and wires, as well as a cotter pin that went through both the base of the bike and the frame that it rested on. Another problem was that the bar would occasionally double back on itself when it was pushed back to parallel with the ground and become momentarily stuck. This was fixed by adjusting the length of the bar.

The device was briefly tested with a variety of tests subjects. These tests were used to make sure the device worked for people of different sizes, ranging from 5’4” to 6’4”. The boot was a success for every foot size, but the bar would hit a protrusion on the base of the seat when some subject’s legs were extended to 180 degrees. This was fixed by first moving the bike, and then transferring the boot attachment to bar from the right side of the bindings’ base to the left. The initial tests were also to ensure that the subject had enough freedom to kick in a comfortable pattern. It was determined that there was enough movement in the hinges to allow all the tested subjects to kick comfortably.

The next tests performed were for an extended period of time ranging from 10-15 minutes of consistent kicking. These tests were meant to ensure the stability and endurance of the design, and to confirm that the resistive force provided by the brakes remained constant throughout the test. Initially, the screws on the hinges began to loosen after just a few minutes of testing. This was fixed by adding washers between the hinge and the bolt for each screw. According to the testers, the force remained constant throughout the test. This was confirmed by the fact that the brakes did not noticeably heat up throughout the test, but remained cool to the touch.

The final tests performed were to see if changing the force the person was kicking against caused any changes in the durability or heat of the break of the prototype. It was found that the increased strain on the device did not cause any additional adverse effects. It was determined, however, that the force needed to be reset between tests. This is necessary because whenever the subject ceased kicking for an extended period of time, the brakes settled, creating a difference in the resistive force.

Future Work

Next semester, the device will be altered to implement a one-way clutch. Two one-way clutches have already been obtained from Formsprag Clutch. For the friction device, both the drum brake and viscous friction will be further researched to determine which is most appropriate. The first choice for the friction device will be the viscous friction. However, as discovered this semester, it has been difficult to find a company which offers a rotary dampener that will provides the required amount of torque. If an effective rotary dampener cannot be found, the drum-brake will be implemented instead.

After deciding which friction device to use, appropriate sensors will be determined. Also, ball joints will be used instead of hinges, to provide more flexibility for the patient's kicking leg, and a lighter, more durable bar material will be used.

Some additional modifications to the device involve both client and patient comfort. Handles will be added on the sides of the base of the seat for the patient to hold throughout the test. Also, a small table will be added on the side of the seat for the client to rest his arm on while imaging the femoral artery.

Finally, the ergometer will be constructed and tests performed to examine the stability and durability of the device, as well as the comfort of both patient and client. According to the results obtained from the tests, the device will be further modified to meet the client's exact needs, resulting in a working device that will be used in the client's research.

References

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

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Yashpal Subedi, Mechanical Engineering Dept., UW-Madison

Mike Travis, Formsprag Clutch

Paul Tutabelli, Taylor Devices

Ace Controls, http://www.acecontrols.com/

Sugatsune, http://www.sugatsune.com/

ADCATS at Brigham Young University http://adcats.et.byu.edu/WWW/Publication/94-1/Paper1-12_6.html

Figure Sources:

Fig. 1 http://www.airoil.com/ai02001.htm

Fig. 2 http://www.mie.utoronto.ca/staff/projects/cleghorn/Textbook/DataFiles/Appendix-B/Appendix-B.html

Fig. 3 http://adcats.et.byu.edu/WWW/Publication/94-1/Paper1-12_6.html

Fig. 4 http://www.howstuffworks.com/drum-brake.htm/printable

Fig. 5 http://galileo.phys.virginia.edu/classes/152.mf1i.spring02/Viscosity.htm

Appendix 1: Project Design Specifications (PDS)

Project Design Specification—Leg Ergometer

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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 at least 5 years
- Adjust for people heights 5’4” to 6’4”
- Maintain a constant wattage throughout testing
- Wattage (5-100 W) and kick rate (30-60 kicks per minute) output to a laptop through an A/D converter
- Flexible range of motion for kicking
- Leg must be able to fully extend when kicking (Range of 90 - 180°)
- Passive return to normal position of the leg after kicking
- Set up for right leg testing
- Minimal lose parts

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 kicks per minute and power output should be measured and sent to a laptop through an A/D converter. The kicking leg should have a range of motion of 90 to 180°. The subject’s chair should be able to adjust the angle from vertical.
   b. *Safety:* The ergometer should be able to hold an average sized person without putting extreme stress on the components. 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. There should be a sufficient amount of enclosed space left in front of the device to allow for full extension of the leg when kicking while ensuring that people in front of the device do not get kicked.
   c. *Accuracy and Reliability:* The device must be able to be set to a single wattage and to run at that setting for at least 20 minutes without deviating. 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. *Shelf Life:* Device should be stored at room temperature in a clean environment.
f. *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.
g. *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 adjustable angle from vertical. The kicking portion of the ergometer needs a little left-right 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 approximately 5' long by 3' wide by 3-4' tall. It should be easily portable (with wheels).
i. *Weight:* The product should contain a comfortable chair for the patient. Also a part which measures the force from the patient is needed. In order to include those parts, the product will be at least few hundred pounds. The ergometer will be placed in a room in a research facility; it is not necessary to move this machine often.
j. *Materials:* If a belt is included in the design, materials other than nylon should be used, since the heat changes the length of the belt. Also, we need to use durable materials and a comfortable seat for the patient.
k. *Aesthetics, Appearance, and Finish:* The previous design was somewhat crude looking. The new 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 budget for this project is $2,000.

3. Miscellaneous
   a. *Standards and Specifications:* Local and national safety standards must be met.
   b. *Customer:* Could have a platform for person holding the ultrasound to rest their arm so that it stays steady. Also the ergometer may be adaptable for use with the left leg in addition to the right leg.
   c. *Patient-related concerns:* The ergometer should provide relative comfort to the user while maintaining stabilization of the thigh while kicking.
   d. *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

	Weight	Gas Spring Shock	One Way Clutch w/ viscous friction	One Way Clutch w/ Drum Brake
Overall Reliability	20	0.75	0.9	0.65
Ease to Construct	5	1	0.8	0.8
Maitenence Required	15	0.8	0.8	0.6
Ease of Use	10	0.7	0.7	0.6
Consistent Force	15	0.6	0.8	0.6
Flexible Kicking Motion	10	1	0.8	0.8
Passive Kicking Return	20	0.25	1	1
Force Adjustibility	5	1	1	0.7
	Total (Out of 100)	68	86	72.5

Appendix 3: Budget

Item Description	Store	Quantity	Cost/Piece	Total Cost
Car bucket seat	Chief Auto Parts	1	$40	$42.50
Iron plumbing pipes	Home Depot	7 x 18” 8x 12” 2x10” 2x 5” 4x4” 16 x “T”’s 6 x “Elbow’s” 16 x “Nipple’s” 6 x “Unions” 6 x “Flange’s” 6 x wheels Hex nuts and bolts		Approx. $110
Used bicycle	Budget Bicycle	1	$89	$89
Seat Cover	Checker Auto Parts	1	$15	$15
Force Sensor	Gander Mountain	1	$20	$20
Extra Hardware – aluminum bars, nuts, bolts	ECB Shop Home Depot	3 bars, many nuts and bolts	$20	$20
Total				$296.5