Field Measurement of Running Impacts

Final Design Report

May 9, 2007

Team Members: Chelsea Wanta, Amanda Feest, Matt Kudek, Lindsey Carlson, Nicole Daehn

Client: Dr. Bryan Heiderscheit, PhD, PT

Advisor: Paul Thompson

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Abstract:

Dr. Bryan Heiderscheit is a physical therapist whose goal is to identify characteristics of running that lead to stress fractures. The purpose of this project is to create a portable system that records tibial acceleration data to measure the impacts of running. This device will include a lightweight accelerometer which will record data to a data logger. The acceleration data will be used to assess and treat running-related concerns. Three designs alternatives have been considered: a wired system, a wireless system, and a microcomputer. These designs were evaluated using a design matrix, which compared certain design criteria set forth by the client. The best design, the wired system, has been selected and a prototype of this design will be pursued. Future work entails purchasing a data logger and accelerometer, constructing the device, and testing the device to assure accurate data collection.

Design Problem:

The purpose of this project was to create a portable system that records tibial acceleration data to measure the impacts of running. This device includes a lightweight accelerometer which records data to a data logger. The acceleration data will be used to assess and diagnose running-related injuries. The device also required an attachment system to ensure the components are secured to the runner. Finally, a testing system was designed to verify the data from the accelerometer.

Background Information:

Stress fractures are one of the most common running injuries. Around fifty percent of all runners suffer from a stress fracture at some point during their running career (Milner). Tibial stress fractures are very painful and can hinder activity for a period of three to six weeks. Between 33 and 55 percent of all stress fractures occur in the tibia, which is the inner of the two bones in the lower leg (Milner). In adults, these fractures usually occur in the anterior junction of the lower third of the bone, as shown in Figure 1. They occur when muscles become fatigued and are unable to absorb added shock. Eventually, the fatigued muscle transfers the overload of stress to the bone, which is thought to cause stress fractures (American Academy of Orthopedic Surgeons). In order to prevent stress fractures, it is very important to learn about the possible causes and to find a way to prevent them from occurring.

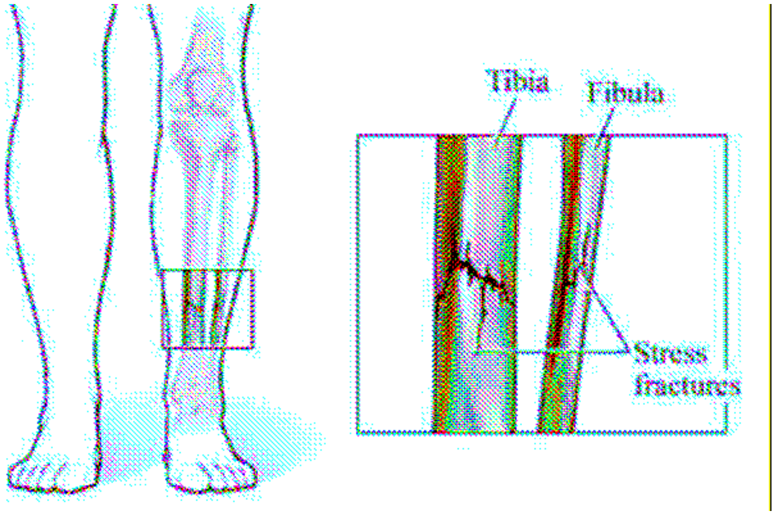

Figure 1: Anatomy of a typical stress fracture (Smith).

Client Motivation:

Our client, Dr. Heiderscheit, is a physical therapist who operates the UW Health Runners' Clinic. One of the goals of his clinic is to identify characteristics of running that lead to stress fractures. Dr. Heiderscheit wants to use acceleration data to measure the peak impacts absorbed by the bone. With this data, he hopes to adjust his patients' running style in order to reduce their risk of stress fractures and other running-related injuries.

Dr. Heiderscheit currently has both a clinical and a research set-up in his lab. In his clinical setting, patients run on a treadmill while their lower body is videotaped (Figure 2). Feedback is then given to the patient based on a visual analysis of their running form. In the research set-up, markers and accelerometers are attached to the subject while he or she runs on a treadmill. Acceleration data is recorded and graphed on a computer, allowing for quantitative analysis of the impacts. Dr. Heiderscheit hopes to incorporate a quantitative analysis into the clinical studies.

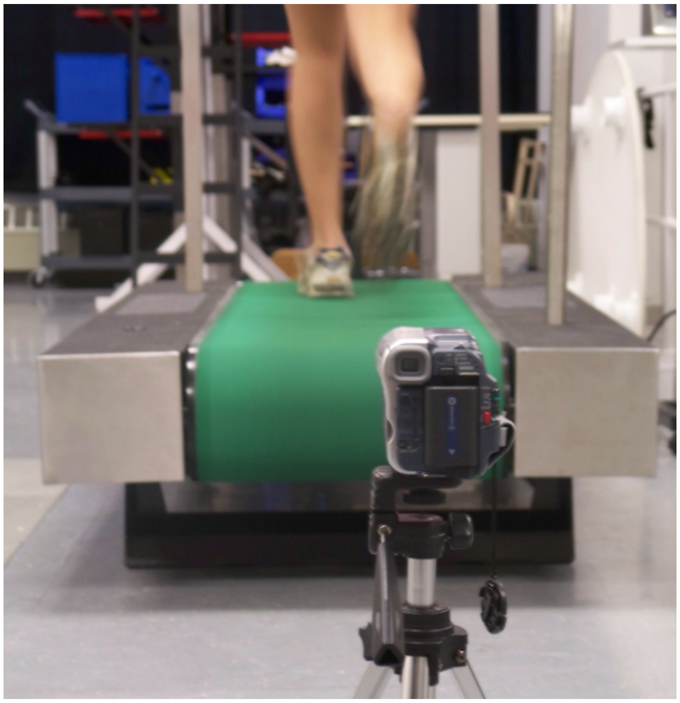

Figure 2: Client’s current clinical set-up

Our design would incorporate the benefits from both set-ups while minimizing the disadvantages. The design would retain the simplicity of the clinical set-up while still allowing Dr. Heiderscheit to collect statistics about the impacts similar to his research studies. Currently, research subjects are hooked up to extensive wiring, a process which can take over an hour. Since the client only sees clinical patients for a half hour, this method of collecting data would not be feasible in the clinical setting; however, our design could be attached to the runner in a matter of minutes. Also, both current methods prevent patients from running in their 'natural' environment. For this reason, our client wants to create a portable device that can measure tibial accelerations on various surfaces. Runners will use the device when they run on their normal running path. After going for a run, the data can be brought back to the lab for analysis. This type of device is necessary for our client to quantitatively diagnose a patient as being susceptible to stress fractures.

Design Constraints:

The most important aspect of our final design is to create a portable and user-friendly data logging system that reliably measures tibial accelerations. This device must consist of a data logger, accelerometer, and system to attach the device to the body. Since this system is used for running, the accelerometer and data logger must be lightweight and not interfere with the runner's gait. The uniaxial accelerometer must be able to read up to 25G peak acceleration. The data logger should be able to collect data at 1000-2000 Hz to make sure all peak accelerations are accurately detected. This system should also be able to store data for at least ten minutes and should have several inputs to allow for multiple accelerometers in the future. Lastly, this system should be completed for use in studies during the summer of 2007. For a complete list of design specifications refer to the PDS in Appendix 1.

Preliminary Designs:

Three alternative designs were developed to meet the design criteria. The first design was a wired device which included an accelerometer connected to a data logger via a wire running up the leg. The data logger would be worn on a belt around the runner’s waist. The accelerometer would be attached to the leg a few inches above the ankle joint on the tibia. The wire connecting the two components would be taped to the outside of the runner’s leg as to not impede the runner’s performance. Power for the accelerometer would be supplied by the data logger. The data logger would have an output that would allow for the data to be easily transferred from the data logger to a computer. See Figure 3 for the first design alternative.

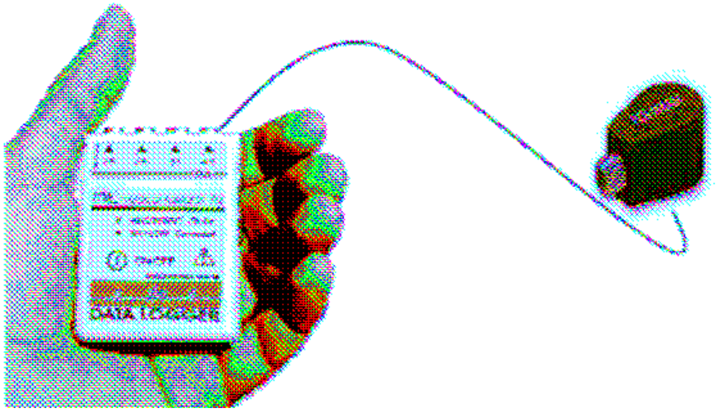

Figure 3 : Data logger (MIE Medical Research Ltd.) (left), accelerometer (PCB Piezotronics) (right)

The second design alternative was a wireless device which used Bluetooth technology to communicate between the data logger and accelerometer. Like the previous design, the data logger would be worn on a belt and the accelerometer would be securely attached to the leg. This design did not require a wiring system between the components; however, additional equipment would be needed to make this communication possible. An RS-232 converter would be necessary to equip the data logger with technology to receive Bluetooth inputs. Since the accelerometer would not be attached to the data logger, it would also need its own power supply. See Figure 4 for the second design alternative.

Figure 4: Wireless accelerometer (Spark Fun Electronics) (left). RS-232 Converter (Tek Gear) (right).

The final design alternative was a device which would be worn entirely on the leg and included an accelerometer, amplifier, analog-to-digital converter, and a microcomputer. All these components would be integrated onto a circuit board. The acceleration data would be sent through the amplifier to an analog-to-digital converter, and then stored to a memory chip. The microcomputer would be used to analyze and store data from the accelerometer which would later be downloaded to a computer. Only one power source would be need for this entire system. See Figure 5 for the third design alternative.

Figure 5: Schematic of the microcomputer device.

Another important component to the final design was creating an attachment system for the data logger and accelerometer. The data logger needed to be worn securely on the runner's waist. Two alternatives were considered to fasten the data logger to the runner: a clip-on pouch and a waist belt. The clip-on pouch would consist of a fabric holder and a clip attached to the back. The data logger would be fastened into the pouch and then clipped onto the runner’s shorts. The other option would be a belt to hold the data logger. The inspiration for this design came from an iPod belt designed for running. This belt would be adjustable for most waist sizes and would securely hold the data logger. These two options are shown in Figure 6.

Figure 6: Clip-on holder (PC Tronix) (left). Belt holder (Proporta) (right).

In order to ensure that data was gathered accurately, the accelerometer must not move relative to the tibia, so a device must be designed to secure it. Two options were considered: a leg sleeve and an elastic band. The sleeve would be made out of a stretchy material, such as spandex, and would be slipped over the leg. The sleeve must be tight to the leg, but not restrict the runner’s blood flow in any way. The other option would include an elastic band with Velcro attached to it. This would allow it to be adjusted to any leg size and would also control how tight the band was on the leg. See Figure 7 for accelerometer attachment options.

Figure 7: Leg sleeve (Germes) (left). Elastic band (right).

Hardware Design Matrix:

	Wired	Wireless	Microcomputer
Signal Reliability (40)	10	7	10
Feasibility (30)	10	6	3
Lightweight on leg (20)	9	7	6
Comfort (10)	6	7	8
Total (100)	**94**	**61**	**69**

Figure 8: Hardware Design Matrix.

The best design was selected based on a weighted design matrix using four main criteria (See Figure 8). The most important (and therefore highest weighted) criterion is signal reliability, since the device is useless if it cannot receive the signal from the accelerometer. A hardwire connection would provide the most reliable signal. The wired design and the microcomputer device received a ten because the accelerometer and the data logger are directly connected. The wireless design received a seven because it involves signal transmission via Bluetooth, which introduces the possibility of interference from other electronic devices.

We also evaluated the feasibility of completing the project within the client's desired time frame. It is important to have a functional prototype by the end of the semester because our client plans on using this device this summer, so this category was weighted second highest. The wired system received a ten because we could buy all of the parts. The wireless design received a seven in this category based on the fact that we cannot find a data logger with wireless inputs. The microcomputer design was the least feasible, receiving a three, because we did not believe it would be possible to design a microcomputer in one semester since none of our members have advanced knowledge of circuits.

The third consideration in the design matrix focused on how much weight would be added to the leg. It is important to minimize the weight worn on the tibia since excessive mass would alter the stride of the runner and result in data inconsistent with the runner’s normal stride. The wired design was the most lightweight because only the accelerometer is worn on the leg, and therefore received a nine. The wireless design scored a seven because an additional power supply must be attached to the leg. Finally, the microcomputer device received a six because all components are worn on the leg.

The final category we judged was the comfort of the device. The wired design received a six since the data logger must be worn on the waist with wires running down the leg to the accelerometer. However, we believe that by securing the wires to the runner’s leg, the wires can be prevented from snagging and this factor can be minimized. The wireless design received a seven because it did not have the same problem with wires, but still required a data logger to be worn on the waist. The microcomputer received the highest score in this category because the device is relatively lightweight and everything is worn on the leg, so it requires no wires. However, since there is added weight to the tibia, it only received an eight in this category.

Accelerometer Attachment Design Matrix:

Criteria (Weight)	**Spandex Sleeve**	**Elastic Band**
Adjustability (70)	**5**	**8**
Comfort (20)	**9**	**8**
Ease of use (10)	**8**	**10**
Total (100)	**61**	**82**

Figure 9: Accelerometer Attachment Design Matrix.

We compared two options when selecting a method to attach the accelerometer to the tibia: a spandex sleeve and an elastic band (See Figure 9). The most important criterion in this choice was adjustability. A size-adjustable design provides a secure attachment while still allowing normal blood flow. A secure attachment is essential for accurate data since slight movements of the accelerometer relative to the tibia can result in incorrect measurements. The spandex sleeve only received a four in the adjustability category because although spandex stretches, that design option did not include any method to account for runners with smaller legs. The elastic band solves this problem because it allows the runner to resize the band to fit his or her leg, and therefore received a nine in this category.

The other two categories are considerably less important, although they are worth taking into account. The comfort of the device is important since the runner must be comfortable while running to maintain their normal stride. While both designs would be sufficiently comfortable, the elastic band received an eight because it would be comfortable and allow air flow to the majority of the leg. However, this design would involve Velcro® or stiff elastic, both of which could cause mild discomfort. The spandex sleeve received a nine because it does not have any irritating materials. Finally, ease of use was considered but weighted the lowest since it would only enhance the quality of the design. The elastic band was considered very user-friendly because it can be fastened and removed without the runner removing his or her shoes. The spandex sleeve, on the other hand, requires the runner to put the sleeve and accelerometer on before putting on his or her shoes.

Data Logger Attachment Design Matrix:

	Clip-on	**Belt**
Secure attachment (60)	**6**	**9**
Adjustability (30)	**10**	**8**
Ease of use (10)	**10**	**10**
Total (100)	**76**	**88**

Figure 10: Data Logger Attachment Design Matrix.

Two major designs were considered to attach the data logger to the waist: a clip-on unit and a belt (See Figure 10). The reliability of the attachment is extremely important in the decision because the data logger is an expensive instrument, so the design must prevent it from detaching from the runner. The belt is considered very secure since it is fitted to the runner's waist. The clip-on design is less secure because running could cause the clip to move around on the runner's shorts and possibly fall off. In terms of adjustability, the clip-on device is the most adjustable because it can be placed anywhere on the waist depending on the runner's preference. The belt design is less adjustable because the size of the belt is limited, but should fit most body sizes. Finally, both designs would be easy to use because the data logger would simply clip in place immediately before the run and would not require any other adjustments.

Final Design:

The final project design chosen has four components. These include a data logger, an accelerometer, a belt to hold the data logger when being used, and a Velcro strap that will be worn around the leg to secure the accelerometer while it is being used. The data logger that was chosen for the system is from Medical Research Limited. This device was strongly preferred by the client. Some features include: eight input channels, a 4000Hz sampling rate, and a mass of 10 grams. Its dimensions are 72mm x 55 mm x 18mm. The data logger also came packaged with a +/- 25G uniaxial accelerometer.

The belt that was chosen for the data logger is the "Proporta Tune Belt." This belt is a neoprene waist belt designed to secure an iPod for someone while running. Since this belt is intended to be used while running, this was one of the primary reasons that this belt was chosen for the project. Because it is expected to normally handle running conditions, it was a good choice to protect an expensive component of the system. Another reason that an iPod belt was selected for this project is that the dimensions of the iPod and data logger are very similar. The belt has a pocket dimension of 4" x 2.75" x .625" (157mm x 108mm x 24mm). The additional height of the pocket allows the accelerometer "Y-connectors" to fit in the pocket without being damaged.

The Velcro® leg band design was made from an elastic band. The band is three inches wide and twelve inches long, which should be long enough to fit around an ankle of most runners. There are four strips of Velcro® attached to the band in order to secure it. By having separate sections of Velcro® instead of one long strip, the band can still stretch in places, making it more flexible and adjustable. A metal loop was attached to one end of the band so that the Velcro® can be fed through so that the Velcro® will attach properly.

Data Acquisition and Analysis:

To assess the quality of the data measured by the system, a testing device was designed (see Figure 11). The testing apparatus consists of a wooden dowel supported by a polypropylene board, a PVC pipe, and a piece of wood to ensure vertical movement. A spring was placed between the board and the bottom of the dowel to increase the downward acceleration of the dowel. The accelerometer was attached to the top of the dowel and the accelerations of the dowel were recorded. As the dowel was pulled up, the spring compressed so that when it was released, higher accelerations were achieved due to the decompression of the spring as well as gravity. A force plate in the client's lab was used as a reference point during testing since it was previously calibrated.

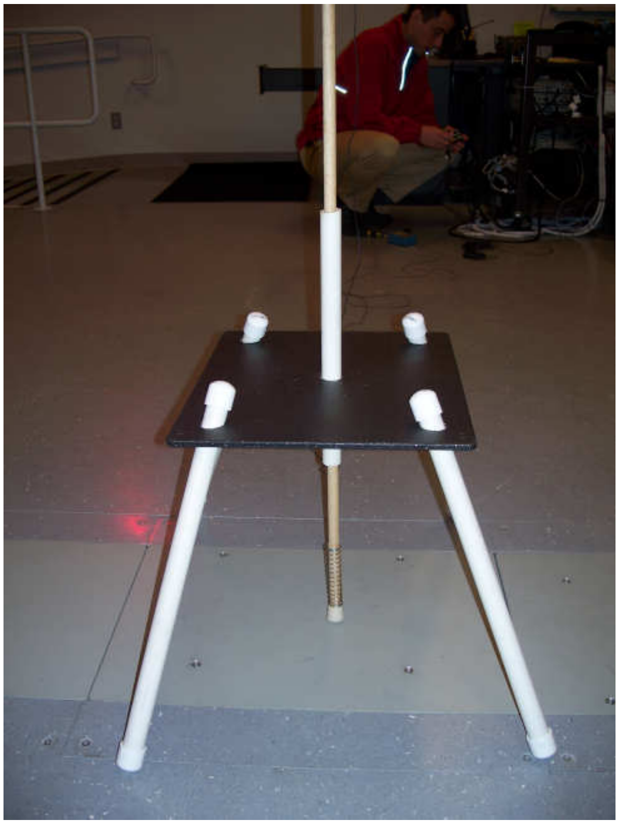

Figure 11: Tester sitting on the client's force plate

Prior to testing, the predicted plots for acceleration vs. time and force vs. time were prepared (Taylor). These graphs helped to identify key points when obtaining measurements from the testing device. On the force vs. time graph, there should be a sharp peak corresponding to the initial impact of the dowel on the force plate and other smaller peaks due to the forces of each bounce of the apparatus. Finally, the graph should level out to an equilibrium value due to the weight of the dowel resting on the force plate. (See Figure 12).

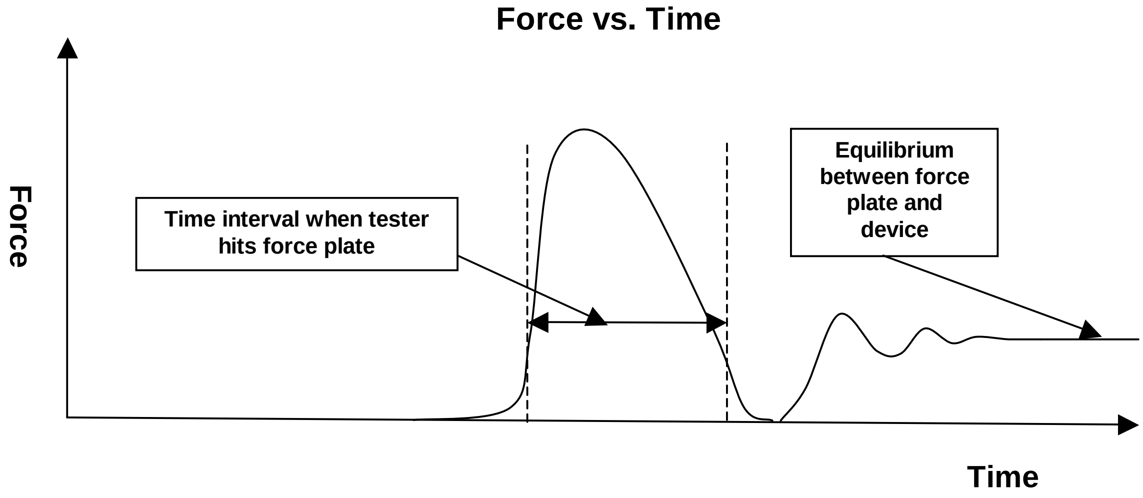

Figure 12: Predicted Force vs. Time

After the dowel was dropped, the acceleration vs. time graph would have an initial acceleration from the force of the spring as well as gravity (Taylor). Once the spring was no longer compressed, the dowel should accelerate solely due to gravity. As the dowel hit the force plate, it should decelerate sharply, creating a sharp decline in the graph. (See Figure 13).

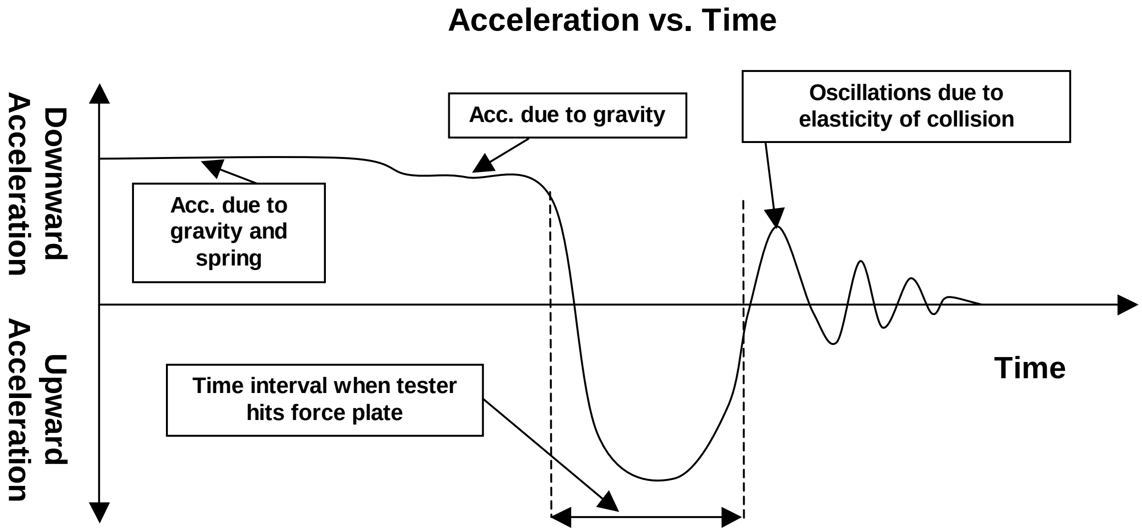

Figure 13: Predicted Acceleration vs. Time

The impulse could be calculated based on the values of the integrals over the time interval that the dowel hits the force plate as shown in the following impulse-momentum equation:

$$\int_0^t F\,\mathrm{d}t = m \cdot \int_0^t a\,\mathrm{d}t$$

These impulse values could be compared to assess the accuracy of the accelerometer against the reading from the force plate.

The data collected from testing was similar to the expected data. A height vs. time graph was obtained using markers to measure the height of the dowel (See Figure 14). This graph was used to relate the data on the other graphs to the events that occurred in testing. From this plot, the time of first impact was between 2.8-2.9 seconds. The smaller peaks after 2.9 seconds correspond to the dowel bouncing on the force plate after the initial impact. Near the end, the dowel rested on the force plate, corresponding to the flat section from 3.5-5.0 seconds.

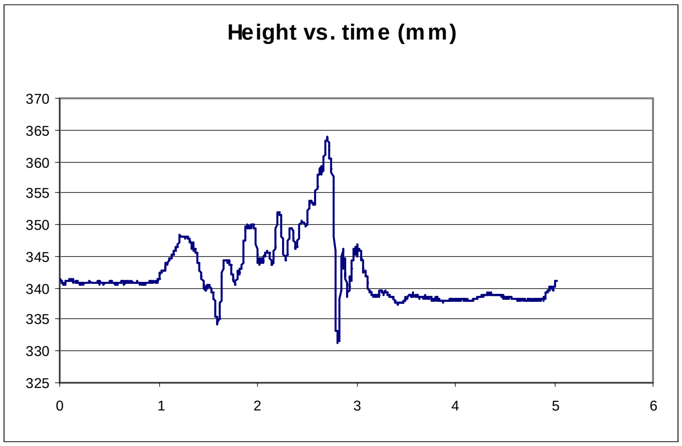

Figure 14: Height vs. Time Graph

A Force vs. Time graph was prepared from the data recorded on the force plate (See Figure 15). The major peaks were the points of interest and the small peaks in between were due to the vibrations of the force plate after impact. There is a general exponential decay with each successive bounce, matching the predicted behavior due to energy dissipating from the system. The initial peak corresponds to the time interval over which the dowel hit the force plate. Furthermore, each point on the force graph corresponds to a point on the acceleration graph.

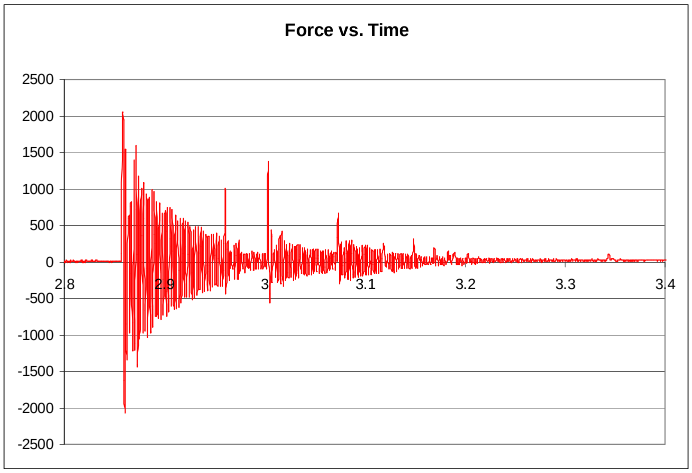

Figure 15: Force vs. Time Graph

Using the data measured by the accelerometer, an Acceleration vs. Time graph was generated (See Figure 16). The initial drop on the graph corresponds to the dowel hitting the force plate. The small oscillations between each peak occur due to the vibrations of the accelerometer. Each successive spike is due to the accelerometer bouncing. Between each peak, the accelerometer decelerates for a longer time than predicted because the collision between the force plate and the dowel is not perfectly elastic. Each successive peak is smaller because the system loses energy. Eventually, the acceleration will reach zero when the dowel is resting on the force plate. From this data analysis, an accelerometer could be calibrated using these values as reference points.

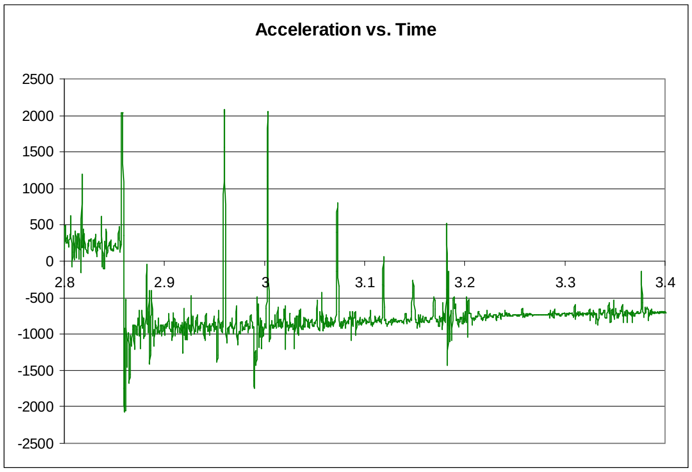

Figure 16: Acceleration vs. Time

To test the attachment system, a mock set-up was used since the hardware had not arrived (see Figure 17). A rectangular block was used in place of an accelerometer and a wire was run up the leg and secured using athletic tape. Marks were placed above and below the leg strap before a run to detect any movement of the leg strap. After the runner had run for five minutes, no movement or discomfort was reported. The wiring did not interfere with the runner's gait and it stayed firmly attached to the runner's leg. The overall system was reported to be very light-weight and ideal for running conditions.

Figure 17. Mock set-up of the leg attachment system.

Conclusion:

Over the course of the semester, our group developed a comprehensive system for measuring the accelerations of the tibia during running. Our design, the first prototype, is a device that consists of a separate data logger and accelerometer. Wires run from the data logger, which is worn on a belt, to the accelerometer, which is mounted on the lower tibia. The accelerometer is attached using medical tape and an adjustable elastic band. The accelerometer can easily be tested to verify the data using the testing device.

Several options could be pursued in future prototypes. One future goal would be to reverse-engineer an accelerometer, modeling it after the ordered part. The testing device could then be used to verify that the reverse-engineered accelerometer is accurate. From there, there are two paths that could be pursued: designing a microcomputer or developing wireless capabilities. A microcomputer design would eliminate the need for a separate data logger since the accelerometer and data logger would be integrated into a unit compact enough to be worn on the tibia. If the wireless route is pursued, there is a possibility of using a device worn on the wrist to display the values from the accelerometer to provide instant feedback.

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Appendix 1

Running Impacts Product Design Specification (PDS)*

Amanda Feest, Chelsea Wanta, Matt Kudek, Lindsey Carlson, Nicole Daehn

5/9/07

Function: The completed prototype will measure the impacts of running using tibial acceleration data. The device should use accelerometers, which will record data to an incorporated data logger. The device must be easily worn by the user, and the hardware should have the ability to do most of the data processing. The design should include a system to attach the hardware to the runner's body. This instrument will be used to diagnose stress fractures and other injuries related to running.

Client requirements (itemize what you have learned from the client about his / her needs):

- $1500 budget excluding data logger
- Durability and battery life are important for field use
- Continuous, solid, reliable signals are required
- Ensure that accelerometer does not move with respect to the tibia
- Data should be processed either by the data logger or software
- Unilateral tibial acceleration measurements will suffice for the first prototype
- System should be portable
- Must have a system to securely attach the device to the runner
- Accelerometer should be calibrated

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements*: Ideally, the runner will take the device into the field and record data from three runs. The battery life and memory must be able to accommodate this criterion. The accelerometer must be secured tightly to the leg to prevent it from sliding on the leg while running, which could result in inaccurate data.

b. *Safety*: The equipment and wiring needs to be secured to the runner.

c. *Accuracy and Reliability*: Data logger should record data at a sampling rate of 1-2 kHz. The accelerometer should be able to record peaks of 25G's, although it should have good resolution for the 0-20g range since this is the normal range. Additionally, a testing system should be developed to ensure that the data collected by the system is accurate.

d. *Shelf Life*: Device should be able to be powered off when not being used to save power.

e. *Operating Environment*: The device will be used primarily outdoors. Therefore, the device must be able to withstand variations in temperature and other weather elements like wind and humidity. The device would be exposed to considerable dirt and dust from the atmosphere. The device will be moving up and down with the runner, so all connections should be secure.

f. *Ergonomics*: Any device pieces that are worn on the leg should be placed on the outside or back of the leg to prevent damage due to running style. The wiring should not interfere with the runner's strides. The individual components should be tightly secured to the runner's body to prevent bouncing.

g. *Size*: Everything must be able to be worn while running.

h. *Weight*: The unit should be as lightweight as possible to maximize comfort. The portion of the device that is worn on the tibia must be especially light so that it does not interfere with the runner's gait

i. *Materials:* The device must be attached to the runner's tibia using a material that will conform to the leg's shape either by wrapping or using a relatively elastic material.

2. Production Characteristics

a. *Quantity*: One.

b. *Target Product Cost*: The budget for the product is $1500, excluding the cost of the data logger.

3. Miscellaneous

a. *User*: The device should be comfortable to wear when running (for example, the device doesn't bounce when running and the wires don't snag easily).

b. *Patient-related concerns*: The device must be able to be wiped with a disinfectant between patients.

c. *Competition*: Current set-ups are stationary, so the patient must come to the lab to partake in the study. The impacts cannot be measured over the runner’s normal paths. No portable devices can be found on the market.

Field Measurement of Running Impacts
Client: Bryan Heiderscheit, PhD, PT
Team Members: Feest (co-leader)
Wanta (co-leader)
Kudek (communications)
Daehn (BSAC)
Carlson (BWIG)

April 20 to April 26, 2007

Problem Statement

Design an instrument that measures the impacts of running using tibial acceleration data. The device should combine the use of accelerometers and gyroscopes, which will record data to an incorporated data logger. The device must be easily worn by the user, and the hardware should have the ability to do most of the data processing. This instrument will be used to diagnose stress fractures and other injuries related to running.

Last Week's Goals

- Buy materials for the tester and build
- Buy materials for the leg band and sew
- Continue looking into waist attachment for data logger
- Set up a time to calibrate accelerometer in the client's lab

Summary of Accomplishments

- Purchased materials for the tester and built the device
- Made the leg band
- Set up meeting on Friday to try out tester

This Week's Goals

- Calibrate the accelerometer using the tester we built
- Create the poster
- Split up sections of the paper

Project difficulties

- Products are not coming in from the UK

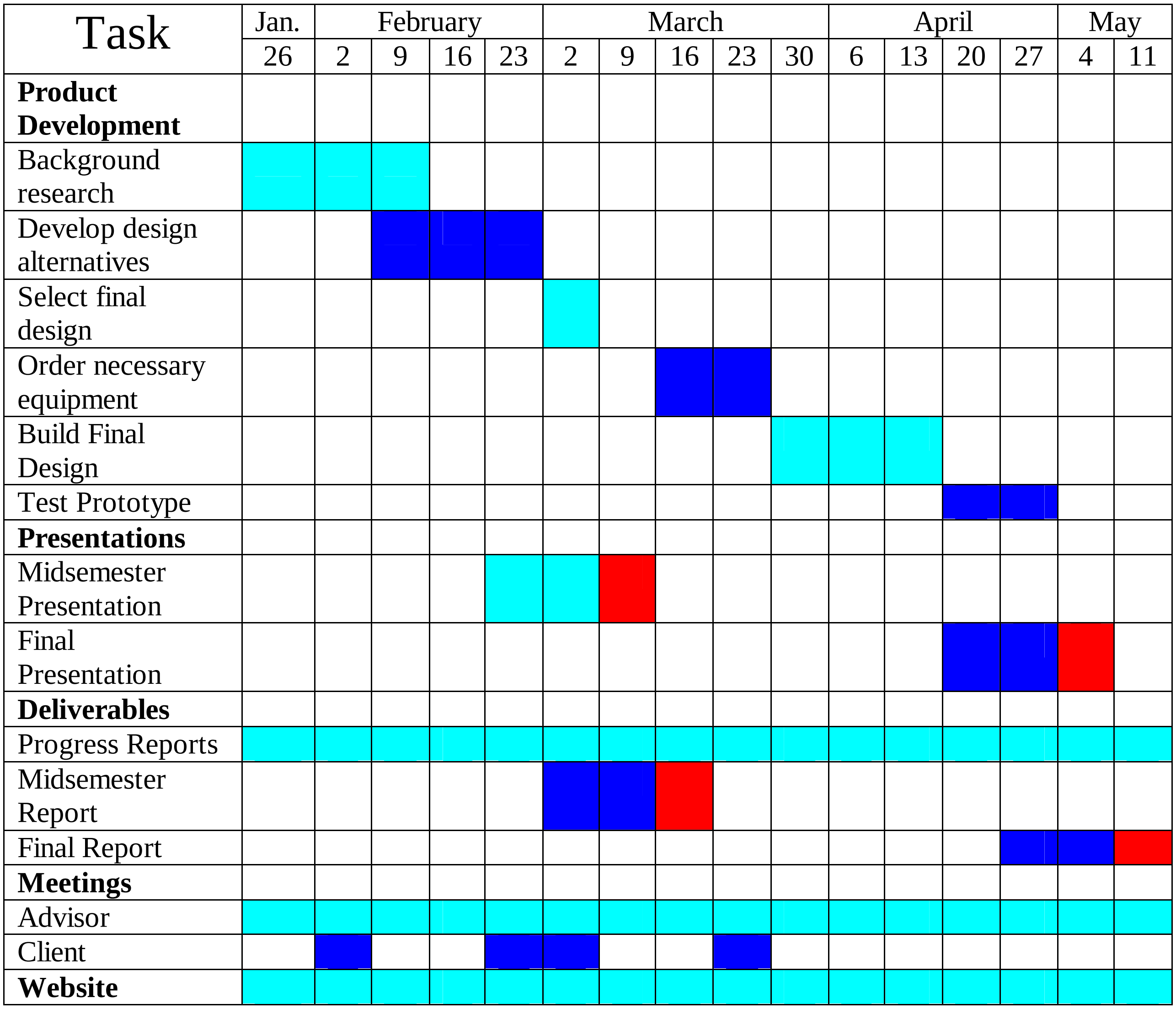
Activities

- Went shopping for the supplies
- Built the tester and leg band

- Amanda-4 hours
- Chelsea-4 hours
- Matt-4 hours
- Lindsey-4 hours
- Nicole-4 hours

Expenses

- None to report so far



Task	Jan.	February				March					April				May	
	26	2	9	16	23	2	9	16	23	30	6	13	20	27	4	11
Product Development																
Background research	▨	▨	▨													
Develop design alternatives			🟦	🟦	🟦											
Select final design						▨										
Order necessary equipment								🟦	🟦							
Build Final Design										▨	▨	▨				
Test Prototype													🟦	🟦		
Presentations																
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Midsemester Report						🟦	🟦	🟥								
Final Report														🟦	🟦	🟥
Meetings																
Advisor	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Client		🟦			🟦	🟦			🟦							
Website	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨