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Step Rate Monitor to be used during Running Analysis

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Abstract

With an increase in the popularity of running, an increase in the occurrence of running related injuries is also apparent[11]. Although many risk factors have been identified, excessive knee joint loading has been recognized as one of the most common when predicting the occurrence of injury[8]. A common outcome for altering joint loads during running is with an increased step rate (number of steps per minute). By achieving a reduction in joint loading, an injured runner may be enabled to continue running without aggravating symptoms, while receiving care for their injuries. Similarly, utilizing an increased step rate may prove beneficial following injury recovery as part of a progressive return to running. Thus, it is important to monitor step rate during a running analysis. We have proposed a design to monitor the resulting vibrations that occur throughout the treadmill as a result of each step taken by the runner. We will use an accelerometer to detect small vibrations in the infrastructure of the treadmill. From there a threshold will be set to identify the largest vibrations, indicating a step. The runner's step rate will be updated and displayed to the runner and clinician in real-time. The step rate monitor will eliminate the need for the clinician to manually count step rate, allowing them to focus more of their time with the runner. Furthermore, by providing the runner with useful visual feedback, the process of learning how to increase or decrease step rate will be simplified.

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BACKGROUND

MOTIVATION

With an increase in the popularity of running, an increase in the occurrence of running related injuries is also apparent[11]. It is expected that approximately 56% of recreational runners will sustain a running-related injury each year[12], with 42% of all injuries occurring at the knee[10]. Although many risk factors have been identified, excessive knee joint loading has been recognized as one of the most common when predicting the occurrence of injury[8].

In the interest of reducing loads to the lower extremity joints during the loading response (LR) of running, several popular strategies have been proposed including minimalist footwear and alterations in running form[3,5,9]. A common outcome from these different strategies is an increased step rate (number of steps per minute). Heiderscheit et al., collected a significant amount of data to characterize the influence of step rate modification on lower extremity biomechanics during running. Kinematic changes that were observed as a result of an increase in step rate include a decrease in all of the following variables: step length, center of mass (COM) vertical excursion, horizontal distance from the COM and heel at initial contact (IC), foot inclination angle at IC knee flexion angle at IC, peak knee flexion and step duration (Figure 1). Therefore running with an increased step rate will require a decrease in step length, which is most often accomplished by striking the ground more underneath one's COM. As a result the foot inclination angle will also decrease, shifting the foot strike pattern from a heel strike to more of a mid-foot strike. In addition COM vertical excursion will also decrease, reducing the velocity at which the runner strikes the ground. With a decrease in COM vertical excursion, a decrease in the peak vertical ground reaction force and the braking impulse is also observed (Figure 2).

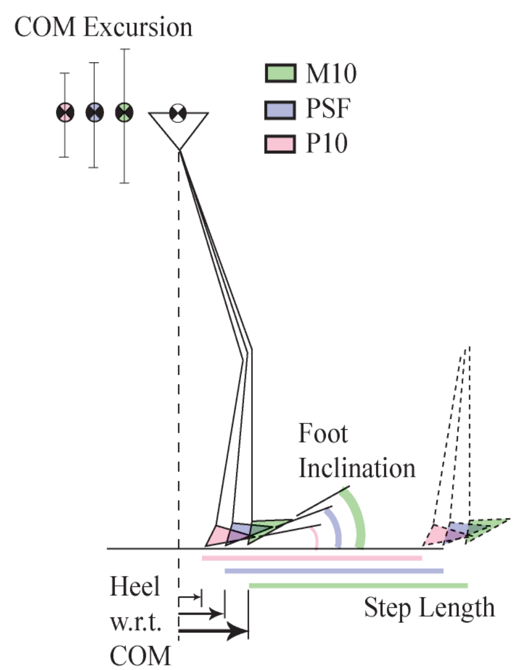

Figure 1. Kinematic changes that occur due to a modification of step rate. PSF is preferred stride frequency, M10 is minus10% from the subjects' preferred stride frequency and P10 is a step rate 10% higher than preferred.

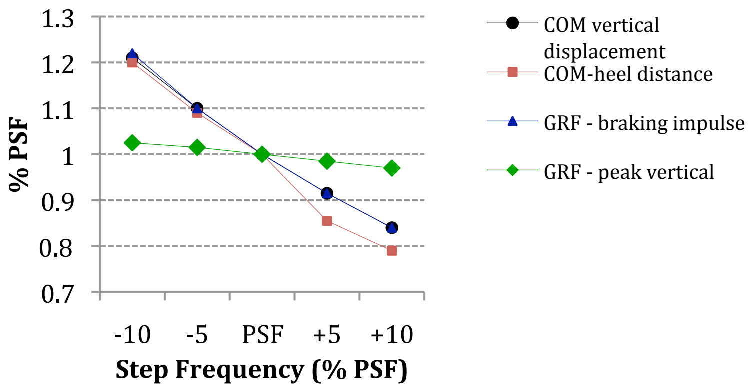

Figure 2. Biomechanical changes that occur due to a modification of step rate. It is likely that a decrease in COM vertical displacement and COM heel distance are two of the biggest contributing factors to a decrease in ground reaction forces (GRF), including braking impulse and the peak vertical GRF.

Kinetic changes associated with an increase in step rate include a reduction in braking impulse, peak vertical ground reaction force and a reduction in the mechanical energy absorbed during loading response (LR) in all lower extremity joints with the most significant reduction occurring at the knee. Thus, adopting a step rate greater than one's preferred may prove beneficial in reducing the risk of developing a running-related injury or facilitating recovery from an existing injury[1,4,6]. The reduced energy absorption at the hip and knee when running with an increased step rate may prove useful as an adjunct to current rehabilitation strategies for running injuries involving these joints and associated tissues. That is, injured runners could be instructed using a metronome to increase their step rate while maintaining the same speed. The associated reduction in loading may enable injured individuals to continue running without aggravating symptoms, while receiving care for their injuries. Similarly, utilizing an increased step rate may prove beneficial following injury recovery as part of a progressive return to running.

Due to the significant impact that step rate has on running mechanics, it is crucial for clinicians to identify the step rate of a patient who is seeking care for a running related injury. A typical visit to the University of Wisconsin's Runners' Clinic consists of a physical assessment to identify any structural or strength and flexibility deficits. Next the patient will run on a treadmill while the clinician conducts a video analysis to determine any asymmetries or imperfections in the individual's running mechanics that may be associated with the patient's symptoms. It is during this portion of the visit that step rate plays an important role in the analysis.

CLIENT INFORMATION

Our design project this semester has been proposed by Dr. Bryan Heiderscheit, a professor for the Doctor of Physical Therapy program at the University of Wisconsin- Madison. In addition to teaching, Dr. Heiderscheit spends a significant amount of time conducting research focused on the analysis of human movement. His emphasis is on the underlying mechanics and how they relate to injury. Dr. Heiderscheit is the co-director of the University of Wisconsin Neruomuscular Biomechanics Laboratory and the director of the UW Runners' Clinic. The majority of his patients are seeking assistance in the rehabilitation of a running related injury.

PROBLEM STATEMENT

Our proposed design project is to create a device that will identify a runner's step rate as they are running on a treadmill. The step rate monitor will be mounted on the treadmill and a step will be identified from a biologically relevant signal. Step rate feedback will be provided to the patient and the clinician in real time to assist in the running analysis. An additional application for this device includes identification of the relative magnitude of the ground reaction forces. It is intended that this device will be used in clinical settings, such as the UW Runners' Clinic. Future adaptations of our design will allow for portability and versatility for implementation in other clinics.

COMPETITION

Currently step rate is visually identified by the clinician. Dr. Heiderscheit must count the number of steps that are taken by the patient over a 30 second time interval. Although it may seem like a relatively short amount of time, it becomes a significant drawback during the visit. It is difficult for the clinician to manually identify a patient's step rate as they must refrain from talking with the patient while they are counting steps. In addition it is often inaccurate because steps may be miscounted, requiring the clinician to recount. Therefore, having a device to automatically update a patient's step rate would be ideal, saving the clinician valuable time.

There are a few different devices currently available on the market that are capable of identifying step rate, including pedometers and force instrumented treadmills. Pedometers can identify the number of steps an individual takes using the technology of an accelerometer. There are a select few pedometers that can identify step rate, one of these being the series of pedometers created by Garmin. Although this would accurately identify step rate there are several complications with these devices as well. Again it is time consuming to outfit the patient with the components necessary to identify step rate with a pedometer. Patients must wear a watch and foot pod, a device that attaches to their shoelaces. In addition step rate is displayed on the watch worn by the patient, preventing the clinician to easily see the patient's step rate. Furthermore, with four different clinicians treating patients in the UW Runners' Clinic, it may become cumbersome to keep track of one device as outfitting all clinicians with a pedometer may become expensive.

The gold standard for identifying step rate is a force-instrumented treadmill. From this device, the vertical ground reaction forces can be monitored and recorded to determine the number of steps taken by an individual. The greatest obstacle in using an instrumented treadmill in the clinical setting is the cost, with these devices costing upwards of $200,000. Although an instrumented treadmill is present in the lab where patients are seen in the UW Runners' Clinic, it is not practical to use it in the clinical setting. Limitations of the mechanical components of the instrumented treadmill in the UW Neuromuscular Lab prevent it from functioning properly when used for longer than 10 min. In addition operation of the treadmill is not a simple task. Another complication of using an instrumented treadmill to identify step rate is the fact that data collected from the force plates of the treadmill would have to be post-processed and analyzed to output the runner's step rate.

Due to the limitations of the devices currently available on the market, we hope to create a solution that will effectively and efficiently identify the step rate of an individual while running on a treadmill. It is our intention that this device will be used in various runners' clinics including the UW Runners' Clinic, to assist in the analysis of a runner's biomechanics.

DESIGN SPECIFICATIONS

Our design must be created to fit several parameters. First our design must be compatible with Dr. Heiderscheit's treadmill, created by Standard Industries. Our device must not comprise the infrastructure of the treadmill. In addition, it must not interfere with the runner on the treadmill in any way. It must accurately identify the step rate of an individual, regardless of the runner's position on the treadmill. Furthermore, Dr. Heiderscheit has asked that the feedback of the runner's step rate is updated frequently. The identified step rate will be displayed in real time so that it is clear to the patient and clinician how many steps the individual is taking per minute.

DESIGN ALTERNATIVES

Our design process began with the consideration of various methods of detecting footsteps on a treadmill. Detection modes we have compared include the use of an accelerometer, optical sensor, and sound sensor.

ACCELEROMETER

The vibrations of the treadmill incurred from each footstep of the runner can be detected by an accelerometer. By securely affixing an accelerometer to the treadmill, the sensor will experience the treadmill's vibrations resulting from each footstep. A properly calibrated accelerometer will allow the conversion of the biologically relevant vibrations of the treadmill to a relative output voltage that can be processed and used to compute step rate. This method of step detection will introduce several new design variables including sensor placement on the treadmill and the method of attachment. Accelerometer placement will influence the magnitude and relevance of the signal detected. For example, placing the accelerometer centrally underneath the runner will likely produce the largest signal and the most noise. At this position, the treadmill and the accelerometer will experience the most deflection and consequently reverberating vibrations leading to increased noise.

An accelerometer can also be superficially attached to the runner's anterior tibia to measure other relevant gait cycle accelerations that could be used to calculate step rate. Although this sensor placement will likely detect less noise in the signal, sensor attachment on each patient will be an inefficient use of clinical time.

OPTICAL SENSOR

Another method proposed to identify step rate may use the technology of an optical sensor. An optical beam spanning the width of the treadmill will be broken each time a runner steps through the beam path. This binary detection of foot placement could then be used to calculate the runner's step rate. This design will require mounting a laser-beam emitter and receiver onto the upper side of the treadmill and will provide signal consistency for various patients. One drawback of this design is its dependency on the positioning of the runner on the treadmill. If the runner strays forward or backward on the treadmill, the beam will be broken at different points of the step cycle and would likely not provide an accurate representation of step rate.

SOUND SENSOR

Our final design alternative is the use of a microphone to detect each step. By attaching a microphone near the runner's position of initial contact on the treadmill, the sound of each footstep can be recorded. This signal would then be processed and used to calculate step rate. Obvious drawbacks of this design include the presence of extraneous audio in the environment and the variation of step force that depends on each runner's size, gait, and speed. In order to reliably use this audio signal to calculate step rate, our processing techniques will need to separate the frequencies of interest from external broadband noise.

DESIGN PROCESING ALTERNATIVES

Data received from any of the previously described sensor modalities will need to be processed and used to calculate step rate. We have several data processing alternatives including Java, Matlab, and LabVIEW.

JAVA

Using JAVA for our data processing software provide programming flexibility and many data presentation alternatives. However, with only limited pre-written code, most of our program will likely need to be written from the ground up. In addition, our analysis program will need to be optimized for the processing power and efficiency necessary for handling live data. Our literature searches have revealed a previously Java platform, IU Sense, designed at the International University in Germany in 2003[2]. This platform has been designed for processing input from multiple accelerometers but would need to be adapted to our parameters.

Furthermore, this software platform was reported to experience lacking display performance based on Java software packages[2].

MATLAB

Matlab offers many built in features and functionalities for data processing that will benefit the design of our software. Moreover, Matlab will have the necessary processing power to handle large data sets. Drawbacks to using Matlab for data processing include its limited data presentation displays. More importantly, live data processing in Matlab will require an infinite processing loop that will need to be terminated by a preset or user-defined break value. Using infinite loops will introduce potential errors and frozen processing states, which are both unacceptable in a time-dependent clinical setting.

LABVIEW

National Instrument's LabVIEW will provide even more built in data processing functionalities than Matlab, including various filtering options. LabVIEW has also been designed with live data acquisition and processing in mind and will be easily interfaced with Dr. Heiderscheit's current data acquisition system. Furthermore, LabVIEW offers many data presentation options that will be suitable for live data feedback for the subject and clinician.

DESIGN MATRICES

Our sensor alternatives have been ranked based on sensitivity, signal to noise ratio, feasibility, cost, and reliability. Based on our client's design requirements we have weighted sensitivity, signal to noise ratio, and reliability the highest in our design matrix. Choosing a design based on these parameters will ensure a clear and biologically relevant signal. As seen in Table 1, the accelerometer design has scored high signal to noise ratio and sensitivity scores. The sound sensor and optical sensor designs have scored low in signal to noise ratio and feasibility categories, respectively. Based on the design matrix results and our client's preference, we will pursue the accelerometer sensor design alternative.

	Weight (%)	**Accelerometer**	Sound	Optical
Sensitivity	20	**16**	16	16
Signal:Noise	40	**34**	16	38
Feasibility	15	**13**	10	9
Cost	5	**4.5**	4.5	2
Reliability	20	**12**	5	9
Total	100	**79.5**	51.5	74

Table 1. Sensor design matrix

After choosing to use the accelerometer detection modality, we had to consider possible accelerometer attachment locations, including attachment to the subject's anterior tibia and attachment underneath the treadmill. Sensor preparation time is the most important parameter in this design matrix (Table 2). Other important factors include signal to noise ratio and biological relevance of the signal. Although placement of the accelerometer underneath the treadmill will provide a lower signal to noise ratio and a less relevant signal, it will require the least preparation time. Based on our client's emphasis on preparation time, we will attach the accelerometer to the underside of the treadmill. This option will offer additional positioning options on the treadmill that will need to be considered after viewing the position's effect on acquired treadmill vibration data.

	Weight (%)	Tibia	**Under Treadmill**
Signal:Noise	25	20	**15**
Preparation Time	40	25	**40**
Biologically Relevant Signal	35	30	**25**
Total	100	75	**80**

Table 2. Accelerometer location design matrix

The most important aspects of data processing for our application are the software's real-time processing and data presentation capabilities. Available built-in functionality is also a beneficial aspect of data processing choice. LabVIEW excels in these categories unlike Java and Matlab and is therefore the clear choice for our data processing needs. Table 3 shows the results of our software evaluation.

	Weight (%)	**LabVIEW**	Java	Matlab
Real-time Processing	40	**35**	25	20
Data Presentation	30	**27**	25	10
Built-in Functionality	20	**15**	10	10
Flexibility	10	**8**	10	5
Total	100	**85**	70	45

Table 3. Data processing design matrix

PRELIMINARY DATA

Preliminary testing of sensor placement on the treadmill has confirmed our design choices. Placement of the sensor on a runner's anterior tibia gives a clear signal and relatively high signal to noise ratio (Figure 3). However, as previously emphasized, this placement method will require an inefficient use of clinical time. We hoped to use the fidelity and relevance of this tibial acceleration measurement as a baseline for comparison to data recorded from an accelerometer placed underneath the treadmill.

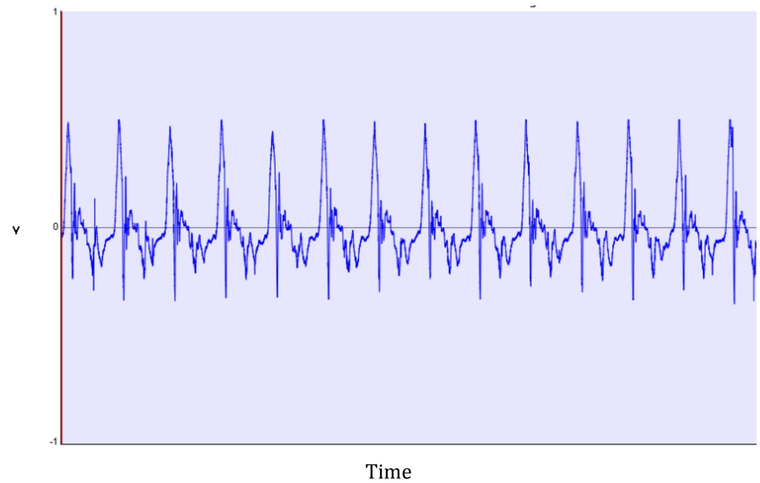

Figure 3. Placement of the accelerometer on the subject's anterior tibia while running.

Next, the accelerometer was fastened underneath the treadmill to a lengthwise support beam. Data from this placement of the accelerometer can be seen in Figures B and C. The signal to noise ratio appears the highest at lower runner speeds, as seen in the data from a walking subject in Figure 4. As expected, the length of reverberating vibrations, and consequently noise, increased with the speed of the runner (Figure 5). This result can be attributed to the increase in step contact force associated with higher runner speeds. Although the undesired vibrations and noise profile increase with runner speed, the desired foot contact signal remains salient and effective for step rate detection.

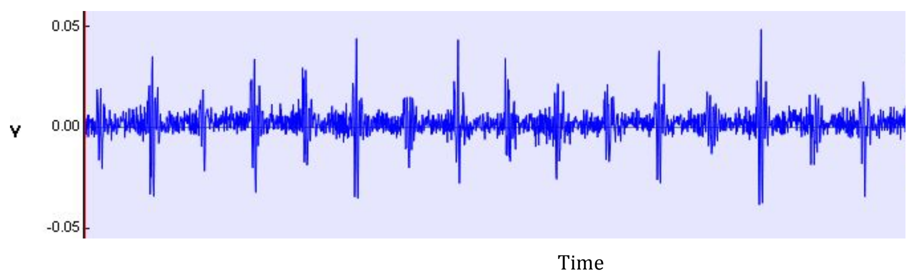

Figure 4. Placement of the accelerometer underneath the treadmill while the subject is walking.

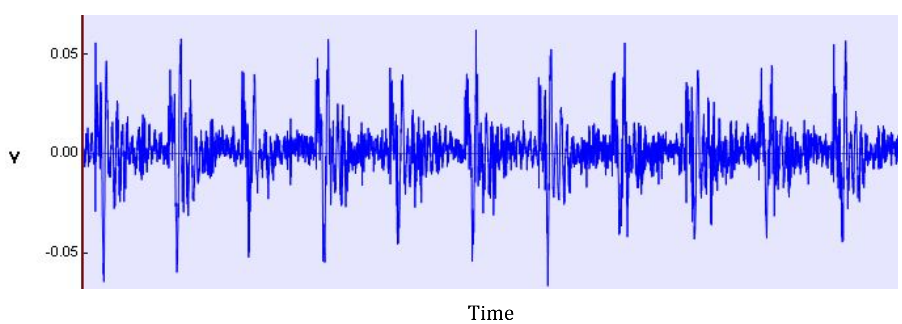

Figure 5. Placement of the accelerometer underneath the treadmill while the subject is running.

FINAL DESIGNS

The final design will include an accelerometer attached securely to the underside of the treadmill. Testing has shown that a usable signal can be extracted and processed. Figure 6 below shows the general block diagram of our final design. More specifically, a U353B16 SN69619 accelerometer, NI CA-1000 data acquisition system, and LabVIEW will be used.

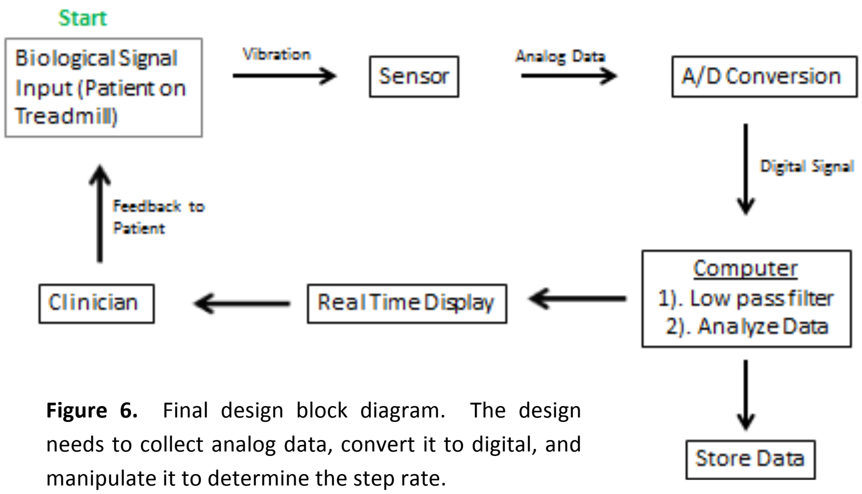

Figure 6. Final design block diagram. The design needs to collect analog data, convert it to digital, and manipulate it to determine the step rate.

The physical components at this point in the semester were chosen primarily due to availability. The accelerometer and DAQ were provided in the lab. The DAQ will remain in the final design, but other types of accelerometers will be considered.

The primary problem that needs to be solved has to do with programming and signal processing. As discussed earlier, LabVIEW was chosen as our programming type due to the ease of use and built in features. Once the data is imported into LabVIEW, data manipulation and collection will occur. First, the data will be filtered with a low pass filter to dampen the high frequency noise of the treadmill and residual vibrations of the accelerometer. Next, a threshold voltage will be determined and set in order to ensure that unwanted noise does not cause a step to be recorded. In addition, a small time delay will need to be set in order to prevent multiple steps to be recorded for one foot strike (Figure 7).

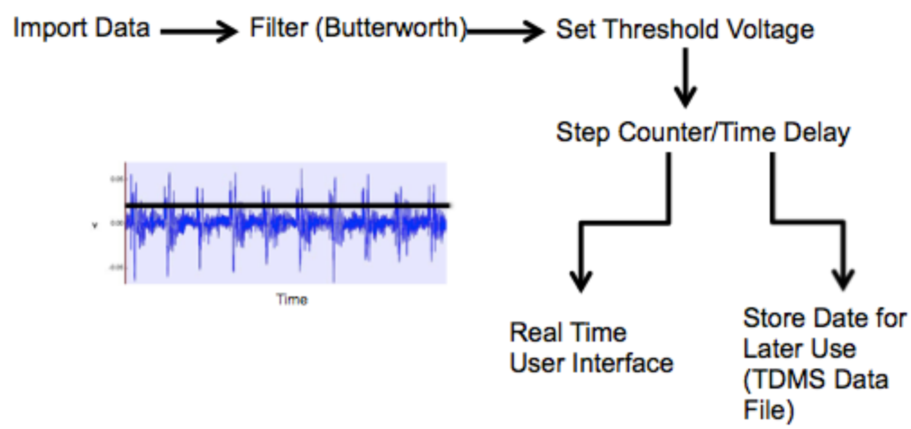

Figure 7. LabVIEW Diagram. After the data is filtered, it will need to be analyzed. This includes setting a threshold voltage to ensure only foot strikes are recorded. In addition a time delay will likely be necessary to make sure more than one steps are recorded for one foot strike.

The recorded steps will be averaged over a time period in order to produce the step rate. An optimal time period has not yet been determined and will require testing. When the step rate is calculated, it will be stored and displayed in real time. Under an initial recommendation of a National Instruments LabVIEW representative, the data will be stored in a TDMS file type. This file type can also be viewed statically and dynamically. The design group has also contacted a NI field engineer and she recommended another method to store the data. Therefore, more consideration is needed before this aspect is finalized.

If all the primary objectives of the design are met, then additional features will be added. These features will include quantification of reaction forces and identifying any asymmetries in the patients' running forms. In order to accomplish this, a significant amount of calibration and testing must occur. Also, the inclusion of additional accelerometers may be required.

FUTURE WORK

The focus of the rest of the semester will be designing and building the hardware and software, acquiring the best signal to noise ratio, altering the system to accommodate each individual, and creating relevant feedback for the runner. In this section, the future development and testing of each component will be discussed.

DESIGNING AND BUILDING THE HARDWARE AND SOFTWARE

Before moving forward to the testing and optimization process, it's necessary to design and set up a system that is functioning properly. The following must take place: (1) mount the accelerometer to the treadmill, (2) properly collect the accelerometer signal with our DAQ system, (3) process the data in real-time using LabVIEW, and (4) create a display in the form of a raw number for the clinician. Once this process is complete and working suitably, we will begin testing to obtain the best signal to noise ratio.

AQUIRING OPTIMAL SIGNAL TO NOISE RATIO

Three main aspects will be tested in order to achieve the best signal to noise ratio including the placement, mounting methods, and orientation of the accelerometer. The assumption has been made that the most sensible place to attach the accelerometer is directly in the center, under the belt. Theoretically, this is where the signal would be the strongest for each foot strike. However, this is also the area that resonates most, resulting in the largest amount of noise. We'd like to test different locations on the treadmill to find the optimal spot where the signal to noise ratio is best. Furthermore, the method of mounting the accelerometer will play a part in the ratio. Our initial data was collected by taping the accelerometer to a support beam. Since this procedure is not a very secure method of attachment, the signal collected may have error; however, for the same reason the noise created may be damped to our advantage. Even so, it's necessary to find a more secure and permanent form of attachment. Options include screws, magnets, or some kind of adhesives. Some current methods of accelerometer attachment utilize a beeswax-like substance. Ideally, the attachment method will assist in damping the noise so that it is minimized. Finally, we'd like to test the effect of accelerometer orientation on the signal. Our accelerometer is uniaxial and we previously positioned it in the vertical direction. We have already observed improvement of signal when altering the orientation of the accelerometer while attached to the tibia of a runner's leg. We hope the same concept can be applied while the accelerometer is placed under the treadmill to achieve the best possible signal to noise ratio.

FITTING THE SYSTEM TO INDIVIDUALS

With each individual, the signal will undoubtedly vary. The signal magnitude recorded when a 300 pound line-backer is running will differ from a 100 pound long distance runner. There are many factors to consider including weight, stride length, step rate, height, etc. We'll have to analyze how the signal differs and determine how to set the threshold and filters for each individual. One option is to have a calibration period to determine the maximum magnitude and set a threshold based on that value.

RUNNER-DEVICE INTERFACE

After the signal to noise ratio is optimized and the device is working properly for each individual, we'd like to provide the runner with useful feedback. To many runner's, the term 'step rate' may not mean much as it can be a difficult concept to understand. Telling the runner to increase or decrease their step rate from a raw number, as given to the clinician, will therefore be meaningless. Instead, giving them visual feedback in the form a speedometer and displaying a "green zone" with limits that they need to stay between will give them better visualization. Furthermore, we'd like to use the accelerometer to quantify relative magnitudes of ground reaction forces. Displaying this information to the runner as they are being taught to alter their step rate and stride length will be useful because they can see how increasing or decreasing step rate corresponds to the load being applied on the joints.

OBJECTIVES

The creation of a step rate monitoring system for running analysis will improve the overall clinical experience. The step rate monitor will eliminate the need for the clinician to manually count step rate, allowing them to focus more of their time with the runner. Furthermore, by providing the runner with useful visual feedback, the process of learning how to increase or decrease step rate will be simplified. For this to be a possibility, the system will be easy to use, as well as provide clear and simple results.

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APPENDIX A. PROJECT DESIGN SPECIFICATIONS

Project Design Specifications

#44- Step rate monitor for treadmill

October 26th, 2011

Team: Carmen Coddington, Joel Schmocker, Bryan Jepson, Christa Wille

Client: Dr. Bryan Heiderscheit

Advisor: Professor Mitch Tyler

Function:

Our proposed design project is to create a device that will identify a runner's step rate as they are running on a treadmill. It is intended that this device will be used in the clinical setting, such as runner's clinics. Additional capabilities of our device will include quantifying the relative magnitude of the ground reaction force. This information can be used as real-time visual feedback for patients as they are being taught to alter their stride to minimize ground reaction forces while running.

Client Requirements:

- Real time identification of runner's step rate while running on a treadmill
- Quantify relative magnitude of ground reaction forces while running on treadmill
- Must not interfere with patient's running mechanics
- Securely mounted to treadmill
- Visually appealing
    - Device should be hidden from view on the internal structure of the treadmill
    - Simple, easily understood display of step rate
- User friendly software that can be used by multiple clinicians

Design Requirements:

1) Physical and Operational Characteristics

  a) *Performance requirements*

    i. Accurately measure step rate

    ii. Display real-time visual feedback

    iii. Easily operated by multiple clinicians

  b) *Safety*

    i. Non-distracting visual display

    ii. Components should not detract from the safety features of the treadmill

    iii. Device attachment should not comprise the durability of the treadmill

    iv. Should not interfere with patient's running mechanics

  c) *Accuracy and Reliability*

    i. Must accurately measure step rate within 2 steps

    ii. Accurately relate resultant vibration magnitudes in the treadmill to ground reaction forces

  d) *Life in Service*

    i. Match or exceed the life of a treadmill

    ii. 10 years

  e) *Shelf Life*

    i. Not applicable

  f) *Operating Environment*

    i. Clinical gait analysis setting

    ii. Biomechanics research lab

    ii. Dry environment

  g) *Ergonomics*

    i. Easily maintained

    ii. Device must not interfere with runner

    iii. Display must not interfere with safety of the runner or cause the runner to alter his/her mechanics to view

  h) *Size*

    i. Contained within treadmill cover

    ii. 3 x 3 x 3 in

  i) *Weight*

i. Testing must be performed to determine if weight will affect vibrations

j) *Materials*

i. Computer

ii. Display screen

iii. Treadmill

iv. Accelerometer

v. Power supply for accelerometer

vi. Data acquisition system

k) *Aesthetics*

i. Accelerometers hidden from view

ii. Visually pleasing display

2) Production Characteristics

a) *Quantity*

i. One complete system

b) *Target Product Cost*

i. $200

3) Miscellaneous

a) *Customer*

i. Runner's Clinics

ii. Home users

iii. Fitness centers

b) *Patient-related concerns*

i. Must not interfere with patients running mechanics

c) *Competition*

i. Pedometers

a) Garmin systems, Olympus

ii. Force-plate instrumented treadmill