Treadmill step rate monitor device for use during gait analysis

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A B S T R A C T

With an increase in the popularity of running, an increase in the occurrence of running related injuries has become evident. 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. 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 created a design to monitor the vibrations that occur throughout the treadmill as a result of each step taken by the runner. A uniaxial accelerometer is used to detect small vibrations in the infrastructure of the treadmill. This signal is fed back to the computer where it is processed to identify step rate in real-time. The runner's step rate is be updated and displayed to the runner and clinician every 5 seconds. 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. Upon completion of data analysis with 11 subjects, it was identified that our step rate monitor had an average percent error of 4.7%, above the specified level of accuracy for this design.

1. Introduction

With an increase in the popularity of running, an increase in the occurrence of running related injuries has become evident[12]. It is expected that approximately 56% of recreational runners will sustain a running-related injury each year[13], with 42% of all injuries occurring at the knee[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[9].

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[3,5,10]. A common outcome from these different strategies is an increased step rate (number of steps per minute). Heiderscheit et al., characterized 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[8] (Figure 1). Therefore running with an increased step rate will require a decrease in step length, thus decreasing the distance to the heel with respect to the COM at IC. 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[8].

Changes in kinematic variables may also be used to explain kinetic changes that occur with an increase in step rate. For example, with a decrease in COM vertical excursion the runner will strike the ground at a decreased vertical velocity. Therefore, a decrease in the peak vertical ground reaction force and the braking impulse is observed[8] (Figure

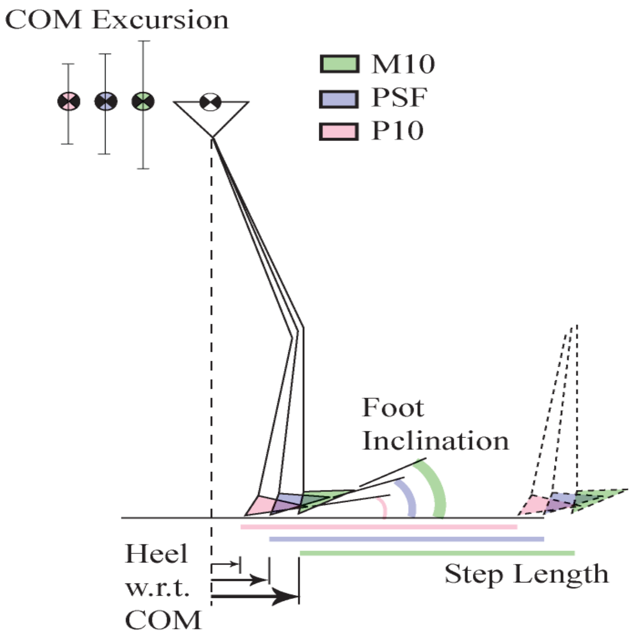

Figure 1. Kinematic changes that occur due to a modification of step rate, a comparison between preferred stride frequency (PSF) and 10% above (P10) and 10% below (M10) PSF. With an increase in step rate a decrease in stride length, foot inclination angle, center of mass (COM) vertical excursion, and the distance from heel to COM at initial contact will be observed[8].

2). A decrease in braking impulse is advantageous during running as the runner can devote a larger portion of energy expenditure towards the propulsive impulse instead. Furthermore, an increase in step rate is associated with 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[8] (Figure 3). 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 forward velocity. 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

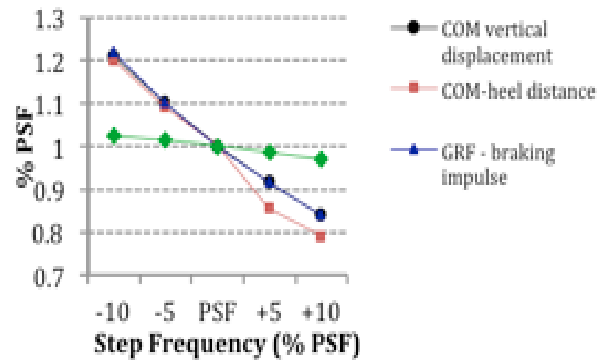

Figure 2. Biomechanical changes that occur due to a modification of step rate. It is likely that a decrease in center of mass (COM) vertical displacement and COM heel distance are two of the biggest contributing factors to a decrease in ground reaction forces (GRF), including braking impulse and the peak vertical GRF. All data are reported as a percentage of preferred stride frequency (PSF).[8]

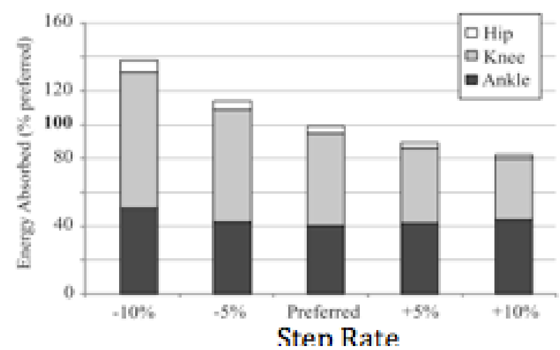

Figure 3. Changes in mechanical energy absorption during loading response with changes in step rate. All data are reported as a percentage of the preferred step rate condition.[8]

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.

2. Methods

2.1 Design Specifications

2.1.1 Equipment

The final design utilizes a uniaxial accelerometer created by PCB Piezotronics, model U353B16. The accelerometer is then connected to an aluminum angle bracket which is then attached to a center support beam that runs parallel to the length of the treadmill with four neodymium magnets (Figure 4). The accelerometer is attached approximately 1/3 the length of the treadmill from the front and lies below the treadmill belt. The accelerometer monitors the vibrations that occur throughout the treadmill as a result of each step taken by the runner. A wire runs from the accelerometer to a signal conditioner followed by a DAQ system created by National Instruments, NI USB-6212. The DAQ is connected to the computer where the data is processed in real-time, where step rate is calculated and displayed.

Figure 4. Method of attachment. 4 neodymium magnets were used to secure the accelerometer to an I-beam below the belt of the treadmill. An aluminum angle iron was used to maintain a vertical position of the accelerometer.

2.1.2 Calibration

Once a patient steps onto the treadmill and begins to run, the clinician will click the "Calibrate" function. This function acquires a 10 second data sample for the calculation of the threshold. After collection of this preliminary data set, the program sends the signal through a low-pass Butterworth filter with a corner frequency of 25 Hz. Although ground reaction forces are generally filtered with a cutoff frequency of 100 Hz during running[8], we are confident that 25 Hz is an appropriate cutoff frequency as we are not interested in the rapid changes at initial contact, but rather the occurrence of a step. Even if someone runs at a step rate of 200 steps per minute, their step frequency would be 3.33 Hz, well below our cutoff of 25 Hz. Therefore, this filter will attenuate any unwanted noise that could result from accelerometer resonance following a foot strike. After the data is filtered, the program determines the maximum and average voltages. With these values calculated, the threshold is identified according to equation 1:

$$Threshold = Average\ Voltage + (Max\ Voltage - Average\ Positive\ Voltage) * 0.4 \qquad \text{(Equation 1)}$$

The factor of 0.40 in this equation was determined from a pilot set of data from 9 subjects. In this data set the ideal threshold for each subject was manually identified. Using this value as well as the average and max voltages from the respective subject, the ideal multiplication factor was determined for each subject and then averaged across all subjects (0.04±6.97). The calibrated threshold values are saved into the GUI and passed into the "Monitor" function when the clinician is ready to monitor the patient's step rate.

2.1.3 Monitoring step rate

After identifying the threshold parameter through the calibration function, the clinician is able to click the "Monitor Step Rate" button on the user interface. This function continuously reads in 5-second data sets to be processed and used to calculate step rate in real-time. Therefore, the clinician and patient receive a step rate update approximately every 5 seconds. Each 5-second data sample is processed in the same way. First, the data is filtered through a low-pass Butterworth filter with a corner frequency of 25 Hz. Next, all data points less than the calibrated threshold value are set to zero. After this processes, several large peaks still remain above the threshold (Figure 5). In order to prevent each of these peaks from being counted as a step, we have implemented a time delay that is initiated immediately after the first peak in that subset crosses the threshold. The algorithms used to identify the time delay first identify where each peak crosses the threshold as the signal is increasing as well as where the signal crosses the threshold as it is decreasing. Next, the difference is found between each of these time points. If this difference is below 0.1 sec, it is assumed that there are more peaks that are within that subset and code will move to the offset of the next consecutive peak until the time from the onset to the offset exceeds the minimum required time delay of 0.1 sec. This time was identified because even if an individual were running at an extreme step rate of 200 steps per minute, their total step duration would be 0.3 seconds, significantly greater than our required minimum time delay. Next, each of the time delays are compared from each set of peaks occurring from one step and the maximum time delay is identified. Once identified, all data falling within this time delay after the first peak that cross the threshold are set to zero, leaving only one peak for every step. From here the number of peaks are summed and the duration between the first and last step is recorded. By dividing the number of steps by the duration, step rate is identified. In order to report data in real time, data is collected in 5 second intervals, and immediately processed and analyzed to report the runner's step rate every 5 seconds through a graphical display.

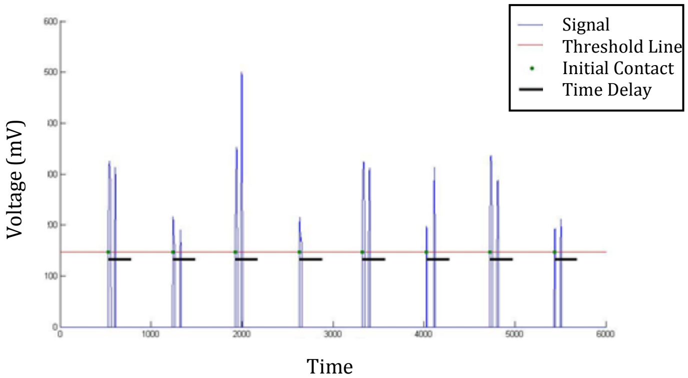

Figure 5. Step rate calculations. Data is displayed in sets of peaks occurring as a result of one step. The red line indicates the identified threshold and the short black lines indicate the duration of the time delay. For visual representation of the sets of peaks, data within the time delay is not set to zero.

2.1.4 User interface

In order to give complete control of the step rate monitor to the user, a graphical interface was created through MatLab so that users would not have any interaction with the complicated algorithim used to identify step rate (Figure 5). Two separate buttons are activated on the user interface. First, The user must click the 'Calibration' button. Upon completion of calibration, the 'Monitor Step Rate' button is activated and once selected the runner's step rate will be updated and displayed in the given text box. This display will be updated approximately every 5 seconds.

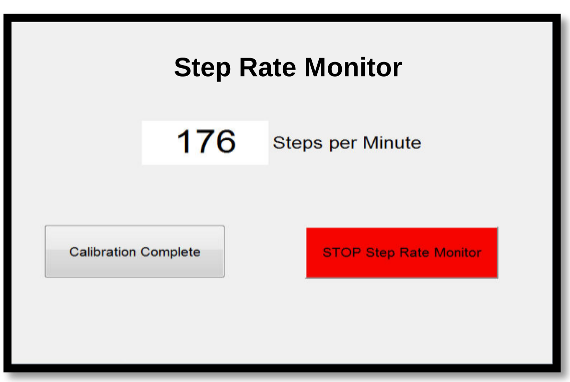

Figure 5. User interface displayed while step rate monitor is in progress, after calibration has completed.

2.2 Testing

Eleven subjects (Table 1) were recruited to participate in preliminary testing of our design. Subjects were given a sufficient amount of time to warm up and become comfortable running on the treadmill. Next, the preferred step rate of each subject was identified. In order to ensure that they remained at that step rate, a digital audio metronome was set to match their preferred step rate and data was not collected until subjects were able to consistently match and maintain the step rate set by the metronome. Data was collected from a uniaxial accelerometer; model U353B16, by PCB Piezotronics that was magnetically attached to a support beam underneath the belt of the treadmill. Data collection lasted for 30 seconds at a sampling rate of 2000 Hz. Data was then filtered with a 4^{th} order low-pass Butterworth filter with a cutoff frequency of 25 Hz. From the given data, each runner's step rate was identified and compared to the known step rate of the subject. Requirements for accuracy of our design were set to within 3% difference. This value was chosen as it has been previously identified that a runner's step rate naturally vary approximately 3%.[14]

Table 1. Subjects with a wide variety of anthropometric data were chosen to ensure that our design works for all types of runners.

Subject Characteristics	
Males:Females	5:6
Height (ft)	5.2-6.4 (±0.27)
Weight(lbs)	128–205 (±26.2)
Speed(min/mile)	7-10 (±1.04)
Preferred Step Rate (steps/min)	146-174 (±10.5)

3. Results

Upon completion of data analysis, it was identified that our step rate monitor had an average percent error of 4.7%, above the specified level of accuracy for this design. Individual subject results can be seen in Figure 6. It is interesting to note that subject 7 can be considered an outlier as the percent error for that subject lays 2 standard deviations outside of the average percent difference. After removing this subject, the average percent difference is 2.88%, meeting our criteria for an accurate design.

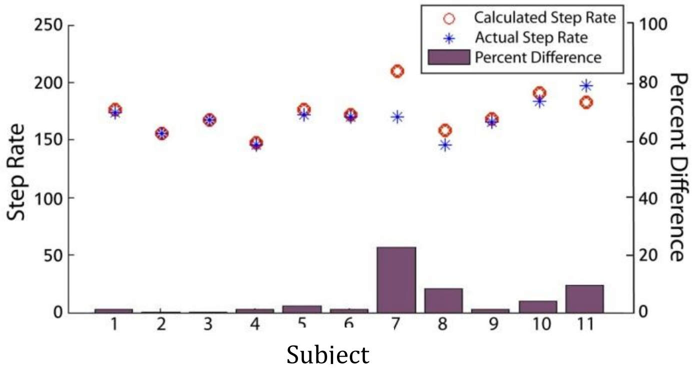

Figure 6. Comparison of each subjects' known step rate to the calculated step rate identified by our step rate monitor. Step rate values are plotted on the left hand y-axis while percent difference for the respective subject is plotted on the right hand y-axis.

4. Discussion

The next steps in improving the design will be improving the accuracy and usability of our device through optimizing signal filtering, creating a visual display for the runner, and performing further testing. Once the design has been close to perfected, we would also like to make the product more accessible outside of the clinical setting.

This has been the only study conducted with the treadmill step rate monitor. The study was limited in the number of test subjects. The subjects covered a wide range of heights, weights, genders, and speeds; however, 11 subjects does not represent the running population well. It will be imperative to conduct more tests with a larger sample size to ensure the validity of the device. Furthermore, the tests will assist in finding weaknesses in the algorithms to determine the step rate. After collecting data from enough subjects, the algorithms can be made more robust to improve accuracy with diverse body types and running styles. The test is also limited because only one treadmill was utilized. The future product will be marketable and will be able to be implemented in various running clinics. For this to be the case, the device will be tested on different clinical treadmills to assure that it can be easily step up in a spectrum of clinics.

Error may have also been in the determination of actual step rate. A digital audio metronome was set to the frequency of a runner's step to identify actual step rate. The runner was then asked to do their best to stay on beat with the metronome. Theoretically, it should be effortless since the pace was set to their preferred step rate. However, since running to a metronome was new to most of the subjects it may have been more complicated than anticipated especially if the metronome was off by even one beat. To improve the identification of actual step rate, a video should be taken and steps visually counted to guarantee the correct value of actual step rate is being used.

It will also be useful to research different filters to find a way to reduce the noise while retaining biologically relevant signal. Future improvements to the signal filtering process have the potential to greatly simplify the step rate calculation algorithm. If optimized, a filtering sequence could resolve each step into a single voltage plateau, which would eliminate the need for a time delay to handle multiple voltage peaks per step.

After the signal to noise ratio is optimized with the improved filtering and the device is working properly for each individual, a visual platform will be created to provide the runner with useful feedback. The visual display is currently only providing visual feedback for the clinician with step rate in the form of a raw number. To many runners, the term 'step rate' may not bear much significance, as it can be a difficult concept to understand when first introduced. Telling the runner to increase or decrease their step rate from a raw number will therefore be difficult. Instead, giving the runner visual feedback in the form a speedometer and displaying a "green zone" with limits representing the values of step rate to stay within will give them better visualization. Displaying this information to the runner as they are being taught to alter their step rate and stride length will be useful because the runner can easily identify if they need to increase or decrease their step rate.

To make our device more accessible to runners outside of a clinical setting, integrating the system into a treadmill or creating a SmartPhone application is possible. The treadmills could be used in fitness centers or home gyms. The interface could either be built into the treadmill similar to the heart rate function or calorie burning function. Additionally, a SmartPhone could be hooked up to the pre-instrumented treadmill. With the knowledge of step rate, runners may be able to alleviate undesirable painful symptoms that are associated with running by trying to increase their step rate by the recommended 5-8%. To make all of this possible, our goal is to reduce the price of our step rate monitor. One way this can be done is by using a different method of programming to eliminate cost of a MatLab license such as C++. Furthermore, we would like to determine the effectiveness and accuracy of a microcontroller to identify step rate.

5. Conclusions

The creation of the treadmill step rate monitor device 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. This study presented the treadmill step rate monitor device to be within the desired 3% error criteria for an accurate design. The accuracy of the study with 10 subjects was 2.88%. An improved method of this study could now be applied to more test subjects of different body types and running styles to ensure the accuracy of the device.

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