Portable Instrumentation to Detect Gait Instabilities

Mid-Semester Design Report

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Problem Statement

The project seeks to measure various spatio-temporal parameters suitable for accurately detecting gait instability in elderly individuals. We base our design on two important results from recent studies: trunk acceleration and stride/step length/duration. Trunk accelerations are proven to be accurate in the detection of imbalance normal walking habits (Zijlstra & Hof, 2003[1]; Cho et al., 1998[2]). Stride/step length and duration were found to positively correlate with the risk of falling (Hausdorff, 2005[3]; Hausdorff et al., 1995[4]). Combining these two techniques of analysis, we can encompass all known aspects of measurement regarding the probability of elderly gait instability. To achieve such analysis we will develop the necessary software and instrumentation solely using 2- and 3-dimensional accelerometry. We envision a device combining 2 dual-axis accelerometers and 1 tri-axial accelerometer interfaced to a data logger that is user-friendly and suitable to be worn over clothing.

Background Information

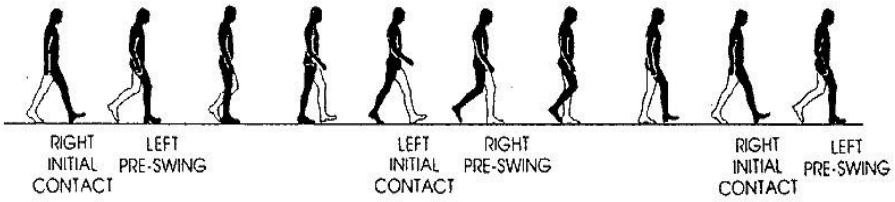

Figure 1: The gait cycle

Figure 1 shows the gait cycle of an average human being. One stride is defined as the heel-strike from one foot to the heel-strike of the same foot in sequence. One step is scientifically defined as the heel-strike of one foot to the next heel-strike of the other foot. By securing 1 dual-axis accelerometer to each heel, the linear accelerations of each heel can be recorded and manipulated to give the length and duration of each step and stride. The data need not show exact fluctuations corresponding to each phase in the gait cycle, but must at least be able to display distinct spikes that indicate impact of the heel with the ground. Variability in step/stride length and duration shall be assessed to determine the degree of imbalance during normal gait.

Dual-axis accelerometers are required for the heel, due to the increased age of the target audience. Because elderly persons walk gingerly or with a 'shuffle' instead of a pronounced walking stride, the change in acceleration is much more subtle for a 'shuffling' stride. Thus, the second axis needs to be incorporated for accurate stride identification.

Gait instability can also be measured using the degree of sway of the body's center of mass. By anatomical definition, the body's center of mass is located at the 2nd sacral vertebra (commonly abbreviated as the "S2 level"), which is about 4 cm along the spine from the superior aspect of the hip bone. As mentioned in the problem statement, the body's degree of sway can be determined using trunk acceleration. Therefore, securing a tri-axial accelerometer near the hip can provide a good estimate of the 3-dimensional acceleration of the body's center of mass, from which the degree of gait instability can be identified.

Design Specifications

The client had several specifications that he required to be included in the design. The main considerations that needed to be addressed during the design process were portability, accuracy, and safety. The device needs to include: a data logger, acceleration sensors, internal data processing capabilities, and enough memory to complete the sampling duration.

The design specifications need to incorporate strict size and weight limits, so as not to inhibit any normal bodily movements. And inhibitions of movement will reduce the accuracy of the data and thus introduce undesirable and caustic variables into the experiment. The data logger needs to be of small dimensions and less than 500g. The logging system can not be connected to a computer or other processing machine via wires, to ensure relatively free motion. The data logger also needs to have a sampling rate of 60Hz. This sampling rate is needed for an accurate plot of the changes in acceleration intended to fulfil future research objectives. The logger will need to record information for a minimum of two minutes. This information must be stored in memory either hardwired into the logger, or onto a removable memory source for analysis at a later date.

Accelerometers will be used to detect the changes in acceleration made while the patient is walking. Three accelerometers will be used in total, two dual-axial and a tri-axial. A dual-axial accelerometer will be attached to each heel of the patient's foot, while the tri-axial accelerometer will be attached at the second sacral vertebra position, the approximate position of the human body's center of mass. These accelerometers must have a low-g (±10g) range and high sensitivity. The low-g range was necessary to ensure accurate data collection. If the g range was too low, then there would be too much interference

[1] "Assessment of Spatio-Temporal Gait Parameters from Trunk Accelerations during Human Walking" published by Zijlstra W and Hof Al, on October 18, 2003

[2] "Detecting Balance Deficits in Frequent Fallers Using Clinical and Quantitative Evaluation Tools" published by Chiung-Yu Cho and Gary Kamen, in "JAGS" Volume 46, Number 4, April 1998

[3] "Gait Variability: Methods, Modeling and Meaning" published by Jeffrey M Hausdorff, on July 20, 2005

[4] "Footswitch System for Measurement of the Temporal Parameters of Gait" published by Jeffrey M Hausdorff, Zvi Ladin and Jeanne Y Wei, in "J Biomechanics" Volume 28, Number 3, 1995

picked up simply from moving the leg. If the g range was too high, then the impact from the heel wouldn't be a large enough change in acceleration to be detected by the accelerometers.

In the future, this device could be worn by the patient as he/she when about his/her daily routine. The machine will also be programmed to detect different activities the patient is performing. These activities can range from standing to bending over to walking. This will allow the client to collect even more data to be used in determining a trend between falling and the activity responsible for it.

While brainstorming, we focused on four main areas of the design: the type of data logger, the sensor signals, the memory storage, and the attachments to the body. We needed to determine whether we were going to custom build the data logger from scratch or buy one that's commercially available. We also needed to determine how to connect the accelerometers to the data logger. The two options available are either using accelerometers that are hardwired to the data, or using accelerometers that transmit their signals via Bluetooth or some other wireless signal. The means of storing the data was another area with several options. We narrowed the decision down to either having using internal memory available in the data logger, or using a removable memory device, such as a jump drive or SanDisk (SD drive). The final point of focus was how to attach the accelerometers and data logger to the patient. The attachments would have to allow for maximum mobility and be strong enough to keep the device from falling off or moving and creating false data readings.

Design Configurations

Model 1:

Using the design specifications agreed by our client and ourselves, we created three potential models for the completion of our project. One such model was the purchase of a commercial data logger from Medical Research Limited with facilities located in the United Kingdom. This company produces a 90g, 1000Hz sampling rate for 8 ports, and has several customizable features.

The logger will need to be connected to our accelerometers via LEMO wires, micro-wires that are used in cases where extremely precise connections must be made (LEMO[5]). Medical Research Limited will collaborate with our needs and they will connect our desired accelerometer specifications from Analog Devices using their technology. This is extremely convenient for our purposes, being that our team has limited electronic experience. Also, being that the connections will be manufactured at their facilities there is more precision in the device's construction, which will lead to less erroneous data collection in the future.

The logger has a built in 512MB memory and can run at our sampling rate for 10 minutes. We only need sampling for 2 minutes, so this covers that data collection design specifications completely. However, this does limit our ability to adapt this to a home environment where sampling would be desired for longer periods of time. Though our project doesn't immediately adhere to the long term goal of the use of this device, it is good to keep this in mind for the sake of what the client will have to deal with in the future.

This data system will be attached accordingly. The two duel-accelerometers will be taped, using surgical tape to the heel columns of each shoe. The tri-axial accelerometer will be taped to the S2 vertebra. The data logger will fit in a belt of sorts for support of the system. This configuration might hinder the patient, though not enough to impede movement. The wires might be difficult to get used to, but we can tape the wires at reference points on the leg so as not to largely hinder any movement.

Model 2:

Our second proposed design entails a self-built microcomputer. This design would lay largely on our ability to order all the proper/compatible parts and configure them on a specialized evaluation board in a static free environment. This would be extremely difficult with our limited abilities, though not completely out of the question, being that we have commendable resources and mentors to help us through the process. However, this design does have a heightened margin of error that might affect our data collection precision.

This model would be constructed using wireless/Bluetooth components, so that we could eliminate all restricted hindrance from the patient. This would be the best way to go about monitoring any patient in their natural stride, because they will have no wires attaching the components; however the accelerometers and evaluation boards would have an increase in weight, because a power source would have to be directly attached to each wireless component.

The memory storage would be supplied by a removable SD card, which would collect the information and plugged respectively into a computer to analyze the data. This would be acceptable as long as the data wasn't lost in transition. Such memory cards, however, are becoming increasingly reliable through advancing technology specifications.

This model would be attached to the body by tape and adhesive patches. This technique of attachment would increase freedom of movement and promote standard stride calculations.

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[5] "LEMO." *Wikipedia, The Free Encyclopedia.* 28 Feb 2007, 15:57 UTC. Wikimedia Foundation, Inc. 11 Mar 2007 <http://en.wikipedia.org/w/index.php?title=LEMO&oldid=111596356>.

Model 3:

The third model that was constructed with our design specifications in mind was a NIKE/iPod configuration. NIKE and iPod currently have collaboration intact to measure distance and stride information. The accelerometers are placed in a cavity designed into the NIKE running shoes and the data is wirelessly transmitted to the memory card inserted into the iPod the patient is carrying[6]. This is primarily dependant upon buying both NIKE and iPod products. This is not favourable due to the incredibly important design specification that patients must be wearing their own shoes to determine unique stride patterns. By changing the footwear of the subject, stride length or stability would change and add variation into the research that would affect the validity of the data for publication.

The system is, however, a wireless system, thus giving the subject maximum freedom of movement. The wireless system is dependant upon a modified RFID configuration.

The memory of this model is completely iPod dependant. The accelerometer data is processed through the iPod and stored on a removable memory drive, which can then be inserted into the computer system for further data retrieval and analysis.

The attachment to the body is driven on the fact that any patient will need this specially designed and commercially supported NIKE running shoe system. The information will be communicated to the corresponding iPod, which can be strapped with an iPod exercise band to the arm.

Model Analysis and Design Matrix:

These three models were ranked according to the following criteria, with the weight documented in parenthesis: Cost Efficiency (5%) being that the device can't be outrageously expensive, but our budget allows freedom to create an efficient and reliable system. Portability (20%) is incredibly important because the patient needs complete freedom to walk with ease simulating their normal gait and not an altered one due to the clinic and logging system that we create. Any alteration in the normal gait of the patient will deviate the data and invalidate it for future publication. Ease of Analysis (15%) must be taken into consideration, because the clinician must be able to work with the system we create and assemble it repetitively for many different collection situations. Data Storage/Transmission (15%) must be reliable. Any data that is lost is data that was never collected. We need to be able to transport the data from the collection system and into a visualization program on a computer efficiently, safely, and accurately. Numerical Accuracy (20%) is very important because of the nature of the data collect. This data collected results from a voltage difference outputted by the accelerometers; we need to be able to quantify the data collected and in an efficient and reliable way. Inaccurate data is unpublishable data, and the nature of this project requires long term study evaluation, which in turn requires data consistency and collection accuracy. This device must be adaptable (5%) to our client's future ambitions with this project. Though his future goals are not our immediate concern, it is imperative and our responsibility to keep his goals in mind so that he can expand what we do and apply it to many facets of his work. Safety (20%) is important, because if our device is unsafe, it can not be used for its purpose, which is to evaluate human subjects.

The pros and cons have been discussed in the appropriate sections in each design descriptions; however, for summary: Model 1, the commercially purchased logger, exhibits accuracy, light weight, adaptability in purpose, customizable options, manufactured customization thus exhibiting maximal safety to the user, complete data transmission from the internal memory board. This system does require wires and external connection, which could interfere with normal gaits; however this can be minimized in the length of the wires connecting the accelerometers and the logger. This system is also the most expensive of our proposed models.

Model 2, the self-built microcomputer exhibits among the highest adaptability, because of our ability to create whatever we need through our individual design requirements. Due to the need for us to construct this design from scratch, it is the most cost efficient of our designs. However, human error would be greatly increased in our limited experience with electronics, accelerometers would be greatly weighted due to the need of a power source on each evaluation board from the wireless property.

Model 3, NIKE/iPod combination, has the least variability due to licence agreements and the need to use NIKE and iPod restrictive products. The system is extremely portable and safe, but the constraints on the configuration are extremely great. Not every person will have this specific shoe model, nonetheless NIKE affiliated, and it has been discussed that the patient needs to maintain his/her footwear of normal wear. Any alteration in the footwear will result in a change in gait and the data becomes tampered, inaccurate, and less fit for any publication or future studies.

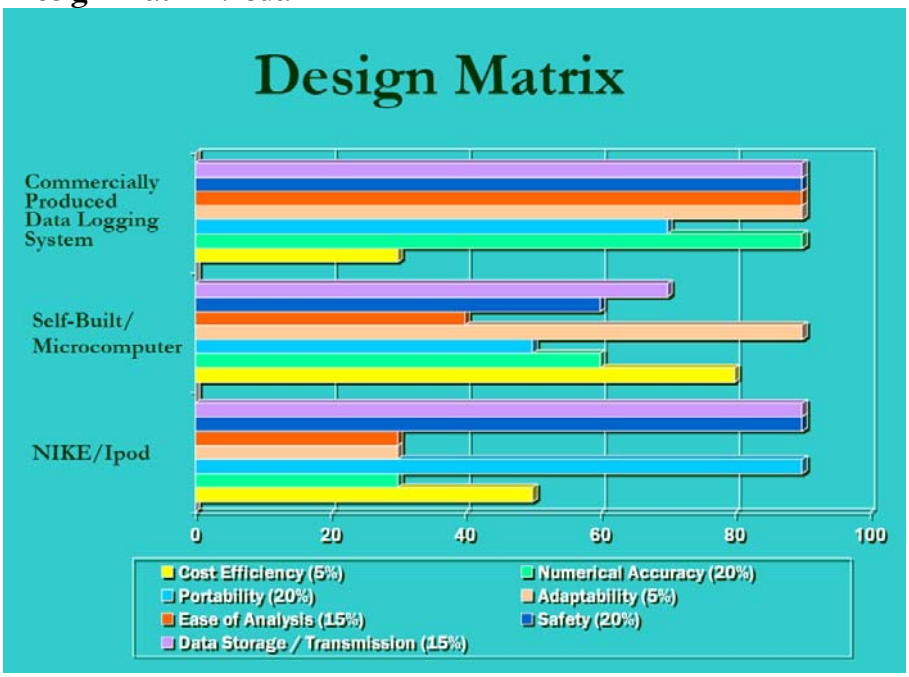
With these designs in mind, the following design matrix (Figure 2) and visual chart (Figure 3) was created, which denoted that Model 1 fit our design specifications the best and maintained the most feasible properties for this semester's Gait Device project.

[6] "Devices That Tell On You: The Nike+iPod Sport Kit" published by T. Scott Saponas, ET. Al. , on November 30, 2006

Figure 2: *Design Matrix*

CRITERIA	WEIGHT	MODEL #1 Medical Research Ltd.	MODEL #2 Self-built	MODEL #3 NIKE iPod
Cost Efficiency	5%	30	80	50
Data Storage / Transmission	15%	90	70	90
Numerical Accuracy	20%	90	60	30
Portability	20%	70	50	90
Adaptability	5%	90	90	30
Ease of Analysis	15%	90	40	30
Safety	20%	90	60	90
TOTAL	100%	83	59	64

Figure 3: *Design Matrix Visual*



Due to our results and design observations, Design 1 (the commercially purchased logger system from Medical Research Limited) was chosen to begin prototype construction as our semester project.

Future Work

There is an increasing demand for a gait monitoring device capable of recording/transmission outside a clinical setting. Often times, a patient feels conscious of the actual procedure and may change technique. Thus, it is important to monitor a patient under normal circumstances. An optimal solution to this discrepancy can be defined by a gait detection device reliant enough for home-use. A greater potential for gait instabilities may be detected during the routine activity monitoring. This would allow prevention of life-changing or life-threatening falls in the elderly population with therapeutic intervention. To attain this, more data has to be discerned to determine the best indicators in the analysis of instability. Using this information, only the indicator signals will have to be stored, allowing for a greater testing duration. After the indicators are determined from clinical studies, a specialized data logger can be designed to collect only the signals necessary from the future design using wireless accelerometers (which would eliminate any restrictive wires) located on the patient's heel columns and S2 vertebra.

Below is a small segment of sample data collected from normal gait parameters in figure 4. If the graph was extended, it would be more noticeable that the gait cycle is very repetitious with very little variations.

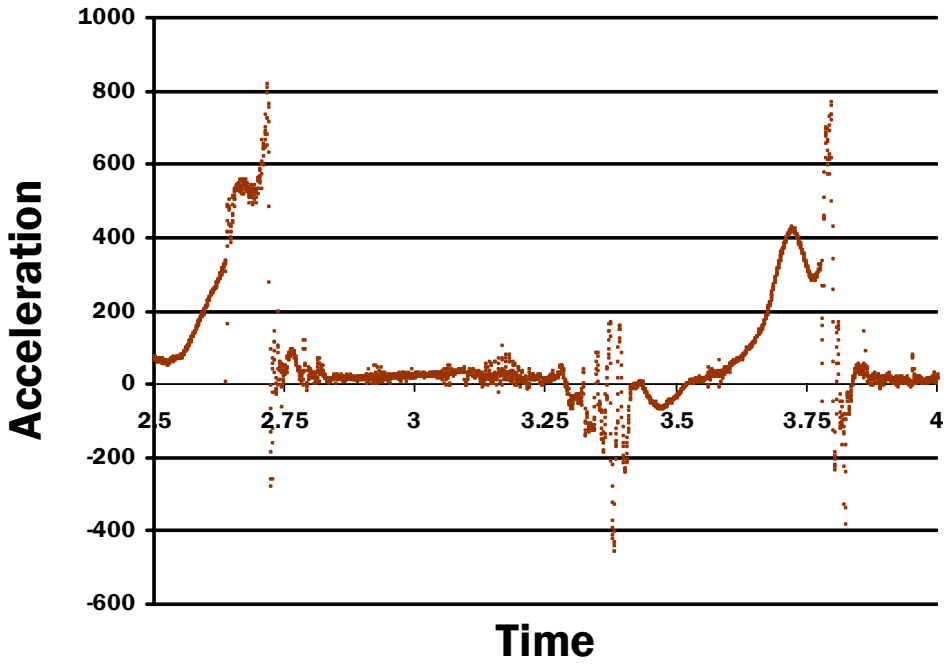


Figure 4: Sample data collected from uni-axial accelerometer placed on right heel column of tennis shoe. Displays normal gait parameters. Notice the repetitious spikes in acceleration (measured in volts).

Contrary to normal gait, shuffling strides are not easily discernable when the accelerometer is placed in the vertical/horizontal position on the heel column of the shoe. As explained earlier, detection of differentiated gait parameters is an essential component to the prediction of frequent fallers. To truly differentiate and understand the kinematics of altered gaits, the data logger and accelerometers must provide the maximum amount of information. The simulated data of a shuffling gait, a common altered gait form, was collected with a uni-axial accelerometer in the vertical/horizontal and anterior/posterior positions. Figure 6 shows the data collected from the horizontal/vertical direction of the accelerometer, in which very little information can be discerned. Figure 5 shows the same altered gait, but measured with an accelerometer in the anterior/posterior position. Notice that this graph is more regular, and easier to discern the heel strikes of the patient. Based on these two graphs, the prototype will consist of two dual-axial accelerometers since seeing both parameters will be an asset in the analysis.

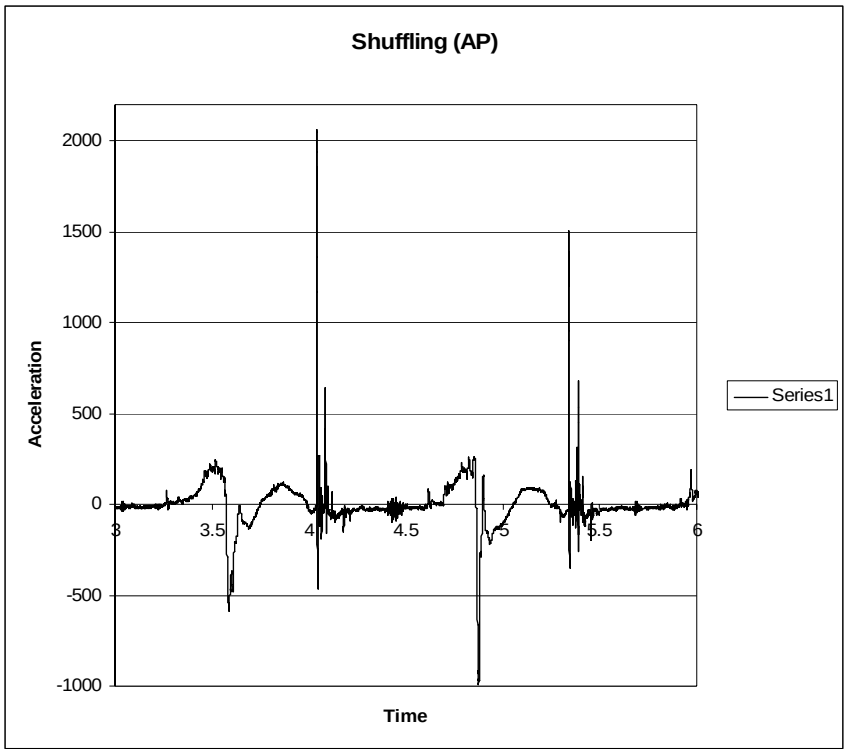


Figure 5: Simulated shuffling gait, measured with uni-axial accelerometer placed in the anterior/posterior position on the patient's heel column of the right shoe. Acceleration measured in volts and time in seconds.

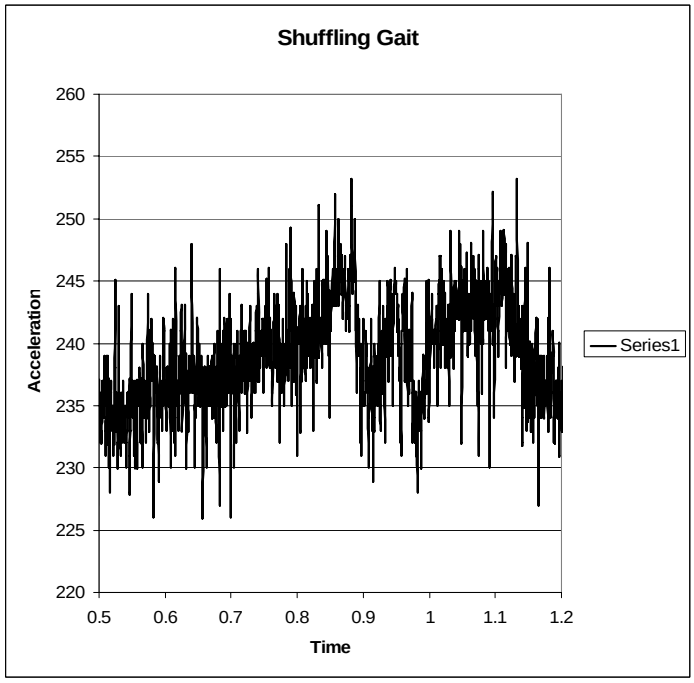


Figure 6: Simulated shuffling gait, measured with uni-axial accelerometer placed in the vertical/horizontal position on the patient's heel column of right shoe. Acceleration measured in volts and time in seconds.

Data from a uni-axial accelerometer attempted to stimulate through changes in positions (anterior/posterior, medial/lateral, and vertical/horizontal) a tri-axial accelerometer. Since this data could not be manipulated to appear as it would from a tri-axial accelerometer, it is omitted. Once the tri-axial accelerometer is obtained, we expect to see very steady accelerations in all three positions. Based on previous papers, the best indicator of altered gait is dependent on the degree of sway referenced to the anterior/posterior position.

Future endeavours for this project include progressively improving and implementing prototypes. The commercially available data logger will provide us with a working prototype that can be utilized in any research study regarding the inquiry of gait monitoring. From the data of the research studies, the specialized data logger will be optimized in its future applications.

Appendix A

References:

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T. Scott Saponas, et. Al. *Devices That Tell On You: The Nike+iPod Sport Kit.* University of Washington: Department of Computer Science and Engineering. Retrieved 28 February 2007. < http://www.cs.washington.edu/research/systems/privacy.html>.

Appendix B

Product Design Specifications for BME 201: Gait Device
(March 12, 2007)

Group Members: *Ann Sagstetter, Karissa Thoma, Timothy Balgemann, Kelvin Ng*

Project Title: *Portable instrumentation to detect gait instabilities*

Statement of Purpose and Function:

Our project seeks to measure various spatio-temporal parameters suitable for accurately detecting gait instability in elderly individuals. We base our design on two important results from recent studies: trunk acceleration and stride/step length/duration. Trunk accelerations are proven to be accurate in the detection of imbalance normal walking habits (Zijlstra & Hof, 2003[7]; Cho et al., 1998[8]). Stride/step length and duration were found to positively correlate with the risk of falling (Hausdorff, 2005[9]; Hausdorff et al., 1995[10]). Combining these two techniques of analysis, we can encompass all known aspects of measurement regarding the probability of elderly gait instability. To achieve such analysis we will develop the necessary software and instrumentation solely using 2- and 3-dimensional accelerometry. We envision a device combining 2 dual-axis accelerometers and 1 tri-axial accelerometer interfaced to a data logger that is user-friendly and suitable to be worn over clothing.

Client Requirements:

- Light Weight
- Reproducible
- Durability/Multiple Use
- Record Remotely for at least 2 minutes
- Placement of accelerometers: 1 on each heel and 1 on the S2- vertebra
- Tri-axial and duel-axis accelerometer

[7] "Assessment of Spatio-Tenporal Gait Parameters from Trunk Accelerations during Human Walking" published by Zijlstra W and Hof Al, on October 18, 2003
[8] "Detecting Balance Deficits in Frequent Fallers Using Clinical and Quantitative Evaluation Tools" published by Chiung-Yu Cho and Gary Kamen, in "JAGS" Volume 46, Number 4, April 1998
[9] "Gait Variability: Methods, Modeling and Meaning" published by Jeffrey M Hausdorff, on July 20, 2005
[10] "Footswitch System for Measurement of the Temporal Parameters of Gait" published by Jeffrey M Hausdorff, Zvi Ladin and Jeanne Y Wei, in "J Biomechanics" Volume 28, Number 3, 1995

- Sampling rate of 60Hz
- High Resolution of +/- 10g
- Data processing at hardware level
- Adaptable for clinical and home settings
- No movement constraints
- Intended prototype use for research in Summer 2007

Design Requirements:

1. **Physical and Operational Characteristics:**
    a. **Performance Requirements:** This device needs to sustain multiple uses and multiple patient models of varying body types. One dual axis accelerometer must be placed on each heel column and one tri-axial accelerometer on the S2 vertebra. The attachment of this device must be adaptable to multiple patient body types.
    b. **Safety:** This device must be user compatible, no loose wires, no radiation, no sharp edges.
    c. **Accuracy and Reliability:** This heel/strike duel axial accelerometers must maintain a sampling rate of 60 Hz. The tri-axial accelerometer located on the S2 vertebra must have a lower range from 0-50Hz.
    d. **Life in Service:** Device recording time must be at least 2 minutes; however this device must sustain multiple uses (as long as possible with changeable battery life-times). Perhaps letting the patient take it home and wear it through normal day activities (Future application).
    e. **Shelf Life:** Normal AA alkaline batteries as power source for data logger; shelf life 10+ years.
    f. **Operating Environment:** Room Temperature (25°C), low humidity, in clinical or home setting.
    g. **Ergonomics:** Interaction with elderly people. Two location placements will be needed: one on each heel and one on the S2-vertebra, roughly 4 inches from the ground and 2.5 feet from the ground. This device must cling to the clothing of the patient, and must withstand the walking process of 2 minutes and the jostling that is associated with such motion.
    The accelerometer attached to the heels of the patient must be a dual axis accelerometer, because elderly persons walk gingerly or with a 'shuffle' instead of a pronounced walking stride. Because the change in acceleration is much more subtle for a 'shuffling' stride, the second axis needs to be incorporated for an accurate stride to be identified.
    h. **Size:** This device must be as small as possible to ensure minimal interference with standard walking motion. Such dimension includes the existing a manufacturing box from Medical Research Limited (Leeds, United Kingdom) of 72 by 55 by 18 mm.
    i. **Weight:** This device must be lightweight, as it has to easily be carried to assess normal walking conditions. The weight of the data logger from Medical Research Limited is 90g which is below the weight limit of 1 Kg.
    j. **Materials:** Heavy materials should not be used. LEMO wires, Data Logger and attaching belt, accelerometer, and accelerometer attachment adhesives.
    k. **Aesthetics, Appearance, and Finish:** Appearance exhibit smooth surface and edges. It also is sleek and discrete while patient is using it.
2. **Production Characteristics**
    a. **Quantity:** One unit will be made as a prototype; however, this device can be easily reproducible if contact with manufacturer is maintained.
    b. **Target Product Cost:** $5000 for the initial customization and purchase of the Medical Research Limited Data Logger, and an additional $1000 for other materials.
3. **Miscellaneous**
    a. **Standards and Specifications:** International and /or national FDA standards must be abided by for patient safety and patent purposes.
    b. **Customer:** Specific information on customer likes, dislikes, preferences, and prejudices should be understood and written down.
    c. **Patient-related concerns:** If appropriate, consider issues which may be specific to patients or research subjects, such as Is there any storage of patient data which must be safeguarded for confidentiality of medical records.
    d. **Competition:** Equivalent devices utilizing accelerometers are available with prices ranging from $20 to $5000.