

A Fall Detection Study on the Sensors Placement Location and a Rule-Based Multi-Thresholds Algorithm Using Both Accelerometer and Gyroscopes

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Abstract -- Falls are dangerous among the elderly population and are a major health concern. Many investigators have reported the use of accelerometers for fall detection. In addition, the use of miniature gyroscopes has also been reported to be able to detect falls, but the effects of sensor placement on the back of a person have not been studied thoroughly. In this paper we present a simple solution for effective fall detection using both an accelerometer and two gyroscopes placed, as a single unit, on three different positions along the thoracic vertebrae (i.e., T-4, T-7, and T-10). Results indicated that T-10 was not a good location for the gyroscope placement for fall detection. However, both T-4 and T-7 were suitable, with the results for T-4 being slightly better. Using a simple rule-based multi-thresholds algorithm that utilizes the recorded resultant gravitational acceleration, angular change, angular velocity, and angular acceleration, we were able to successfully detect all 60 falls and differentiate between falls and activities of daily living (ADL) with no false positives on young volunteers. More testing data is needed, especially for backward falls, to test the robustness of our simple algorithm and to improve the sensor portability for future trial studies on geriatric populations.

Keywords: accelerometer, activities of daily living (ADL), fall detection, gyroscope, T-4, sensor.

I. INTRODUCTION

Unfortunately, falls are very common among the elderly population, which can lead to high health care costs and mortality [1-3]. After a serious fall has occurred, the fear of future falling can also tax a heavy psychological toll on the patient, leading to functional declines and even eventually limit the person to be placed in an institution for the elderly [4]. Numerous researchers have performed fall detection using body-worn accelerometers [5-7]. Several accelerometer-based fall detection reports use simple threshold values to differentiate between falls and activities of daily living (ADL) for patients. These systems mostly rely on a single threshold value to detect whether an activity is considered as a fall or simply an ADL, therefore are prone to false positives. In addition, an accelerometer-only system cannot measure

movements with constant velocities and is limited in its use for serious gait analysis for potential fall *prevention* for any individual patient. Similarly, research has been conducted where gyroscopes were used to detect falls [8-9]. This kind of system has been able to clearly distinguish between falls and ADL using simple threshold-based algorithms, as well as providing more info on gaits. Therefore, we have used both an accelerometer and a gyroscope and placed them together at the same location of a person's back for robust fall detection. Most of the reported accelerometers have been placed near the trunk or the thigh region [5-7] and gyroscopes have usually been placed on the anterior aspect of the trunk [8-9]. Since our interest lies on fall detection of the elderly, it is expected that they would rather have a device on their backs than on the front on their chests [10]. Commercially available systems are available (e.g., SwayStar™ [11]) and are rather effective for gait analysis and with very high resolution (<0.01 degree/sec). However, this system is expensive and not FDA-approved. We hope the devices and algorithms we developed can be used eventually as a low-cost alternative to gait and risk of fall analysis.

II. SENSORS BASICS

Finding a suitable location for the placement of both an accelerometer and gyroscopes as an integrated unit is important, as a single fall-detection sensor can be more wearable and the readings can cross-check each other to better distinguish falls vs. ADL. During our testing three places were considered as regions of interests: T-4, T-7 and T-10 in the thoracic vertebrae as shown in Fig. 1. The sensors were built with commercially available components. The accelerometer used is Freescale semiconductor's MMA7341LC, which has a selectable range of $\pm 3g$ or $\pm 11g$. In this work the accelerometer is set to $\pm 11g$. The gyroscopes used are the LPR530AL dual axis gyroscope (pitch and roll) and the LY530ALH single axis gyroscope (yaw); both have a sensitivity of ± 300 °/sec and are from the ST Microelectronics.

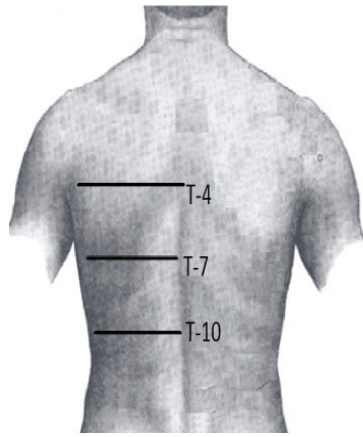


Figure 1: A view of the human thoracic vertebral column, showing regions of interest for sensor placement [12]

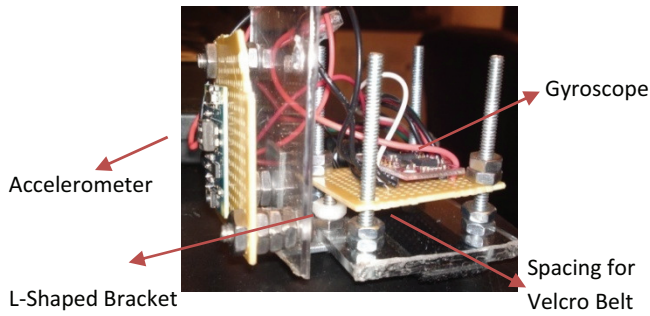


Figure 2: The device that contains the gyroscope and accelerometer sensors with a fixture used in this study. The entire device is 11 cm x 10 cm x 13 cm and weighs 0.4 lb, and it can be easily mounted on a person's back.

III. METHODOLOGY

Team members volunteered to perform the fall trials. They were asked to fall certain ways (e.g., face first, left side, right side) multiple times per condition to improve the statistical power. The same team members also performed ADL wearing the same sensors shown in Fig. 2. The falls were conducted using three team members falling onto two large stacked 4" thick therapy mats. The team members ranged from 22 to 28 years of age. Each test was repeated five times. Both the gyroscope data and the accelerometer data were collected from the sensors using the National Instruments NI-DAQ™ USB 6009. Matlab™ was used as the main program for both gathering the data as well as data processing. To conduct the fall tests, data was continuously read with the NI-DAQ™ at a sampling rate of 1 kHz. Similarly, ADL were also recorded using the sensors shown in Fig. 2. Since the main idea was to select an optimal location for the placement of the sensors for fall detection, all tests were conducted for all three regions where the sensors are placed (i.e., T-4, T-7 and T-10) and then analyzed. The tests conducted were similar to those reported by Bourke (6,9). In this prototype study, sensors are not tested on any geriatric cohort.

IV. RESULTS

Using the data recorded from the accelerometer and the gyroscopes, a simple rule-based multi-thresholds algorithm was developed to calculate the gravitational acceleration, the angular velocity and the angular acceleration (i.e., the derivative of angular velocity) recorded by the sensors. All these three parameters were calculated for all fall and ADL as shown in Fig. 3. Note that during falls and ADL only the peak values are plotted here. The use of the peak values is important because sometimes the peak value may not always happen during the exact time of the fall but may be occurring slightly afterwards. For example, the accelerometer might record a high value when the subject is about to sit down but the gyroscope will record a high value when the subject is fully upright on the chair. We have, therefore, allowed a freedom of 300ms across the peaks of the accelerometer and gyroscope data. For example if we detect a peak in the accelerometer data at 3.4 s, we will check the gyroscope data between 3.1 to 3.7 seconds to detect a peak in the gyroscope data and vice-versa.

The results from the falls and ADL are shown in Figure 3. We have recorded data from several different falls: falling forward (FF), falling sideways (FS), falling forward knee flexion (FF KF), falling sideways to the right (FSR), and falling sideways to the left (FSL). For ADL we have recorded when the subject is sitting down in a chair, when standing up, and when walking with a norm speed. Looking at the data we can clearly see that T-10 is the worst location for the sensors placement, since there is a large overlap between the highest recorded values for ADL and the lowest recorded values for falls. T-7 and T-4 regions can be used since from the recorded data we can distinguish falls from ADL; however, when we examine the highest recorded values of ADL vs. the lowest recorded values of falls, T-4 sensors data generally exhibits a slightly larger separation with better distinction. For example, the lowest recorded value of falls by the gyroscope was 2.74 rad/sec and of the highest recorded ADL was 2.5 rad/sec when sensors are placed at the T-4 region, while for the T-7 region the highest recorded value of the ADL was 2.34 rad/sec and the lowest value of falls was 2.38 rad/sec. Therefore, T-4 should be close to the optimal location when we place both the integrated 3D gyroscope with the 3D accelerometer at the back for fall detection.

From the data collected, the minimum threshold values for falls were determined for the case of T-4 placement. The equations used to calculate the resultant gravitational acceleration, angular velocity, angular acceleration and total angular change are given below.

$$\text{Resultant Gravitational Acc.} = \sqrt{A_x^2 + A_y^2 + A_z^2}$$

$$\text{Resultant Angular Velocity} = \sqrt{x^2 + y^2 + z^2}$$

$$\text{Resultant Angular Acc.} = \sqrt{\left(\frac{d}{dt}x\right)^2 + \left(\frac{d}{dt}y\right)^2 + \left(\frac{d}{dt}z\right)^2}$$

$$\text{Total Angular Change} = \sum \sqrt{x^2 + y^2 + z^2}$$

The threshold values are set as 2.73g for the accelerometer, 2.74 rad/sec for the resultant angular velocity and 0.04 rad/sec² for the resultant angular acceleration. Using these threshold

values we were able to distinguish between falls and ADL successfully. From Fig.4, one can see that the data of ADL(i) did not exceed any threshold values (red dashed lines), so it cannot be classified as a fall. For ADL(ii) and Fall(i) shown in Fig. 4, one can see that their angular acceleration are close to each other. Since we also calculate the thresholds of the resultant gravitational acceleration and the resultant angular velocity, and that ADL(ii) only has its angular acceleration close to its threshold, it can not be classified as a fall.

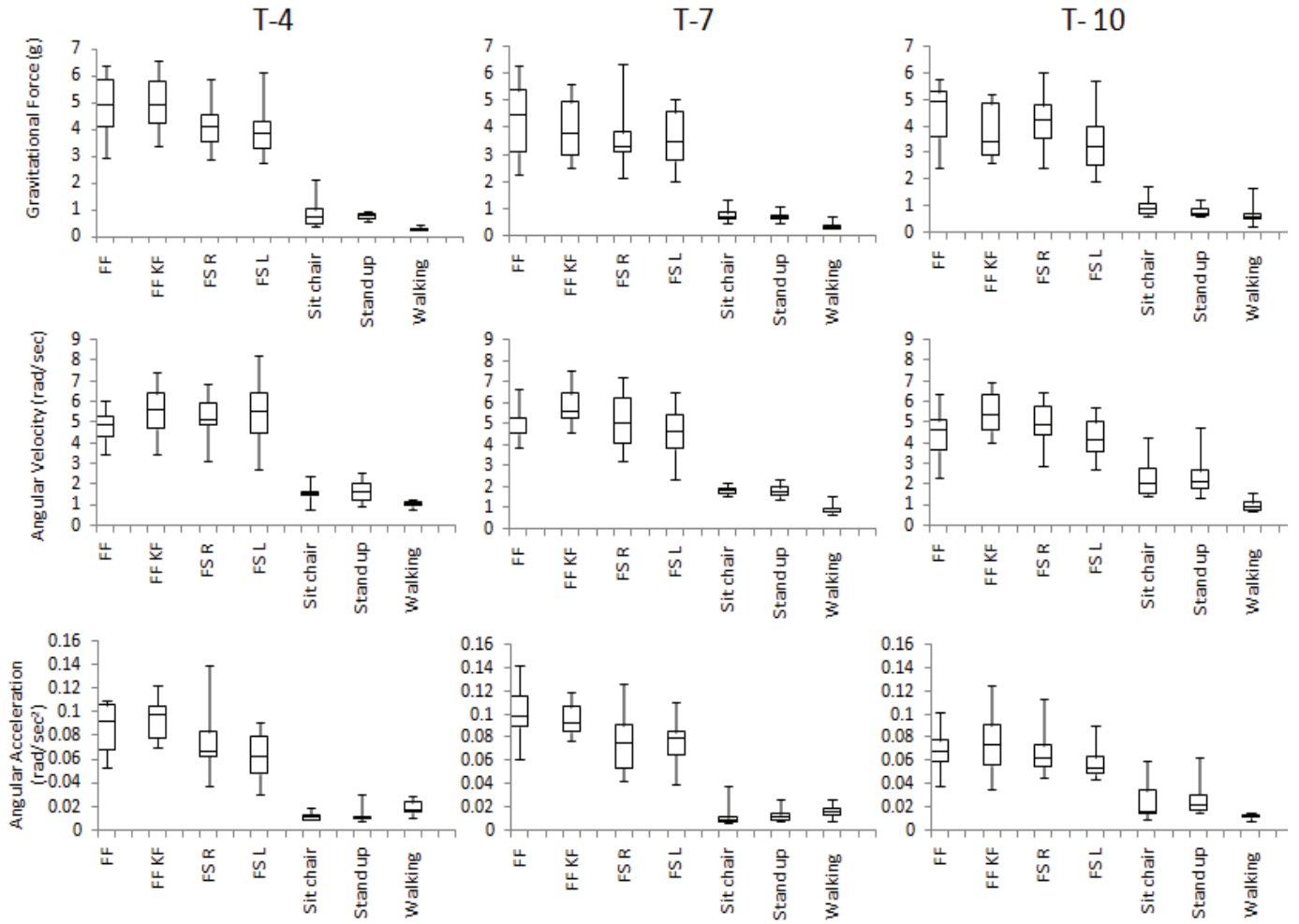


Figure 3: Box plots showing the peak values of measured acceleration, angular velocity and angular acceleration at T-4, T-7 and T-10 for different falls and ADL. FF: Falling Forward, FS: Falling Sideways, KF: Knee Flexion, R: Right, L: Left. The upper edge of each box indicates the 75th percentile of the data value and the lower edge of the box plot indicates the 25th percentile of the data value. The line inside each box indicates the median. The ends of the vertical lines indicate the maximum and the minimum values of each dataset (i.e., the data range).

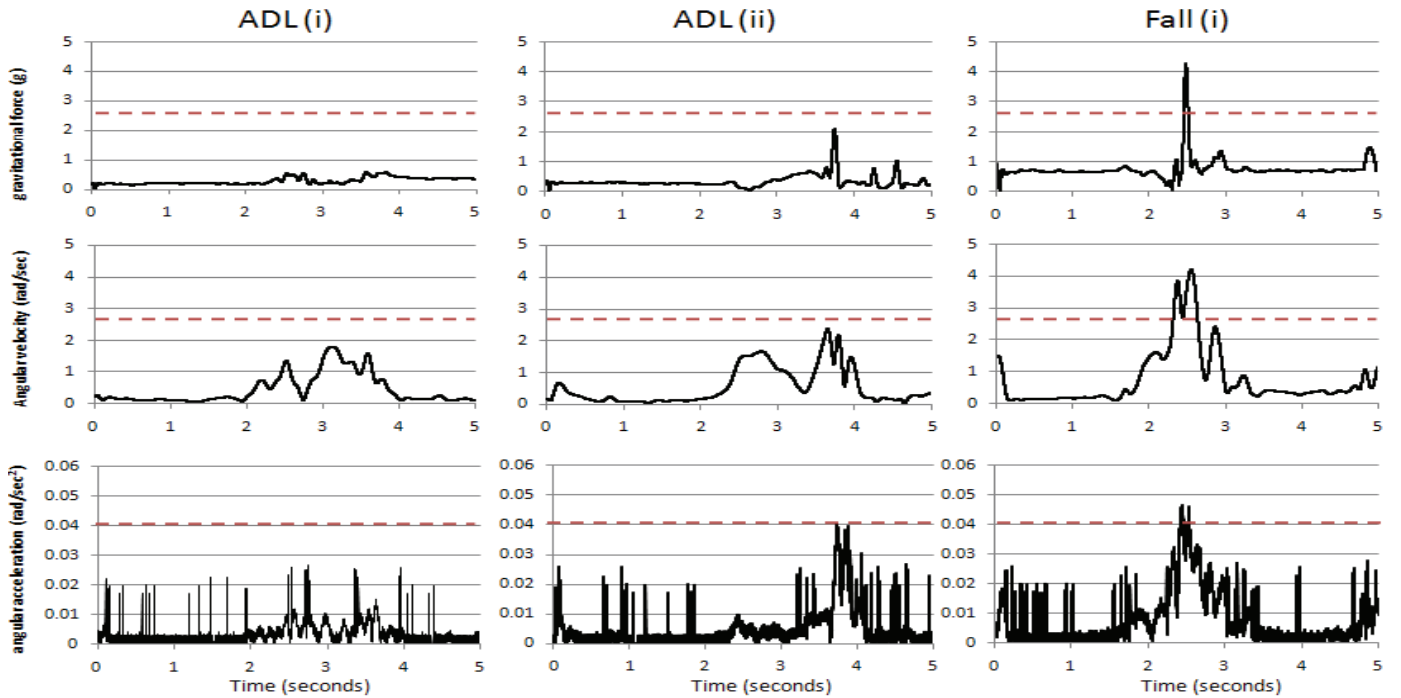


Figure 4: The resultant gravitational acceleration, angular velocity and angular acceleration from several ADL cases. (Left): ADL(i), an ADL that did not exceed any thresholds; (MIDDLE): ADL(ii): an ADL that has only the angular acceleration close to the threshold; and (RIGHT): Fall (i). Note if the sensor data exceeds all three threshold values, it will automatically be classified as a fall.

Note in our initial algorithm, if *all three thresholds* are exceeded, it will automatically be classified as a fall. However, after considering an actual fall case where the sensed data only exceed two threshold value but not three thresholds, we have improved our algorithm by using additional thresholds from the angular changes from the gyroscope data. Fig. 5 shows a flowchart of our simple but effective thresholds-based fall detection algorithm. Note here we also used the total angular change threshold and the thresholds of each axial angular orientation (i.e., the 3 angular changes in the individual axes) in our fall detection algorithm. Here the threshold value for the resultant total angular change was set to be 31° (i.e., “Th4” in Fig. 5). To detect a person falling, a threshold value of -21° in the y-axis is used (i.e., “Th6” in Fig. 5). Similarly, after taking the absolute value of the data from the X-axis, a threshold value of 25° was set (i.e., “Th5” in Fig. 5) and the threshold for angular change in the Z-axis was 21° (i.e., “Th7” in Fig. 5). In this manner, we were able to successfully detect all falls. It needs to be noted that angular change should be used along with other thresholds from the angular acceleration and gravitational force experienced by the sensors. For example, there was one fall case where angular change did not go above any of the threshold values; however, using the entire set of the 4 threshold values, all 60 falls were successfully detected within 2 seconds with no false positives, as will be explained next.

Let us look at these realistic scenarios we encountered: there is one measured fall data that has a peak value of 2.7g, below the gravitational acceleration threshold value of (2.73g);

and there is a 2nd fall data that has a peak value of 2.7rad/sec, below the angular velocity threshold of 2.74rad/sec. If we consider a total of 60 falls, and calculate the fall detection sensitivity for this 1st case (Table I, 1st row), we can see that if we use the accelerometer threshold only we will miss detecting this 1st fall and achieve 98.33% sensitivity. Similarly if we use the angular velocity as the only threshold we will miss detecting the 2nd fall and achieve 98.33% sensitivity. Now if we use both the gravitational acceleration and the angular velocity thresholds, the fall detection sensitivity will drop even further because now two falls are not detected since they do not pass both of the two threshold values (i.e., sensitivity of 96.33% in Table I). However, if we take into accounts of the gravitational acceleration, angular velocity, angular acceleration and total angular change as the threshold values (i.e., Th1, Th2, Th3, Th4), and if we consider an event as a fall where as long as three out of the four thresholds have been exceeded, we are able to achieve 100 percent sensitivity as shown in Table 1. Similarly, if we use four out of seven threshold values, we can achieve 100 percent sensitivity as well. Using this simple algorithm that considers all 7 thresholds as shown in Fig. 5, 100 percent specificity is obtained for these 60 falls. More fall data is needed to improve the robustness of the threshold values selection and specificity.

V. CONCLUSION AND FUTURE WORK

Placing both the 3-D accelerometer and 3-D gyroscope sensors in different locations on a person's back, we were able to find a suitable location for the concurrent placement of our sensors close to the T-4 region. We also developed a simple thresholds-based algorithm by calculating the gravitational force, the resultant angular velocity, the resultant angular acceleration, etc. In this manner, all 60 falls were successfully detected and with no false positives. In our fall detection algorithm we use the threshold values from the gravitational force, angular velocity and angular acceleration along with the resultant angular change and the angular change of each individual axis. If an event exceeds 4 or more threshold values, then the event will be classified as a fall. Using this simple algorithm we have accomplished a sensitivity of 100 percent with no false positives on young volunteers. Table II shows the summary of our prototype system's preliminary test results on young volunteers compared with other fall detection systems reported.

Presently, the system collects 5 seconds of data and the analysis is later done in MatLab™. This data analysis can be further improved by using real-time software like LABVIEW™ and with wireless transmission and smaller fixture size. It can also be improved by creating an adaptive algorithm along with a height and weight profile to automatically calculate the necessary threshold values for each individual. Therefore, more data needs to be collected, including additional falls (especially backwards falling data that is lacking here in this work) and other activities of daily living. Please note that younger subjects were used in this present work as proxies for older persons as a study limitation. After the data collected on young volunteers demonstrates our sensors and algorithms are effective and robust, we will start conducting testing on a more appropriate cohort using our system.

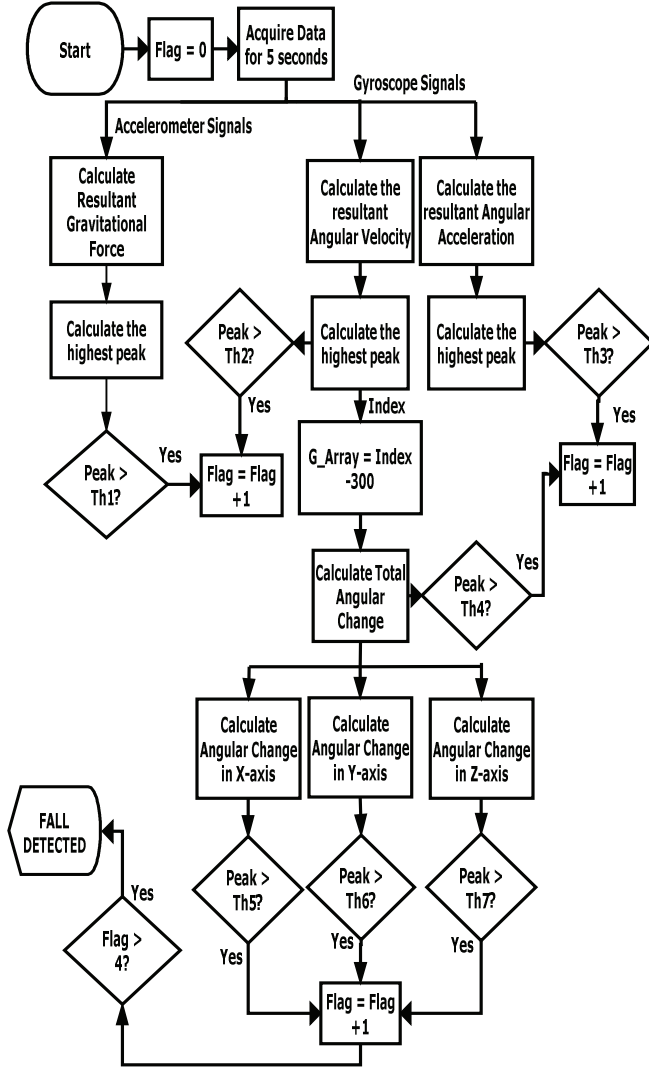


Figure 5: A flowchart of our rule-based multi-thresholds algorithm for fall detection. Th1: accelerometer threshold; Th2: angular velocity threshold; Th3: angular acceleration threshold; Th4: total angular change threshold; Th5: angular change in the X-axis threshold; Th6: angular change in the Y-axis threshold; Th7: Angular change in the Z-axis threshold.

Table I: Fall detection sensitivity percentage obtained using our simple rule-based multi-thresholds algorithm from sensors mounted at T-4.

Different Thresholds to Classify Falls	Sensitivity (%)
Accelerometer (Th1) only	98.33
Angular velocity threshold (Th2) only	98.33
Angular acceleration threshold (Th3) only	100
Two thresholds together (Th1, Th2)	96.66
Two thresholds together (Th2, Th3)	98.33
Three thresholds out of four (Th1, Th2, Th3, Th4)	100
Four thresholds out of seven (Th1, Th2, Th3, Th4, Th5, Th6, Th7)	100

Table II: Summary and comparison of our system with other fall detection systems.

Paper	Accelerometer	Gyroscope	Specificity (%)	Fall Dataset	Placement of sensors
[6]	2	0	100	240	Trunk and Thigh
[8]	2	2	92	70	Chest and Thigh
[9]	0	1	100	240	Sternum
[13]	1	1	96.7	60	Chest
This Work	1	2	100	60	Both on T-4 at back

ACKNOWLEDGMENT

The authors thank our team members for their kind support of performing falls and other tasks. The authors are indebted to the funding support and guidance from Texas Instruments (TI).

REFERENCES

- [1] M. E. Tinetti, M. Speechley, and S. F. Ginter, "Risk factors for falls among elderly persons living in the community," *N. Eng. J. Med.*, vol. 319, pp. 1701-1707, 1988
- [2] J. Askham, E. Glucksman, P. Owens, C. Swift, A. Tinker, and G. Yu, "Home and leisure accident research: A review of research on falls among elderly people," *International Journal of Geriatric Psychiatry*, Vol.6, Issue 11, Pg 825, 1990
- [3] Centers for Disease Control and Prevention, National Center for Injury Prevention and Control. Web-based Injury Statistics Query and Reporting System (WISQARS) [online]. Accessed December 30, 2010
- [4] B.J. Vellas, S.J. Wayne, L.J. Romero, R.N. Baumgartner, and P.J. Garry, "Fear of falling and restriction of mobility in elderly fallers", *Age and Ageing* 1997;26:189-193
- [5] N. Noury, P. Barralon, G. Virone, P. Boissy, M. Hamel, and P. Rumeau , "A smart sensor based on rules and its evaluation in daily routines," *Proc. 25th Annual Int'l Conf. of IEEE EMBS*, Cancun, Mexico, pp. 3286-3289, Sept 2003
- [6] A.K. Bourke, J.V. O'Brien, G.M. Lyons, "Evaluation of a threshold-based tri-axial accelerometer fall detection algorithm. *Gait and Posture*", 26:194-199, 2007
- [7] B. Najafi *et al.* "Ambulatory system for human motion analysis using a kinematic sensor: monitoring of daily physical activity in the elderly", *IEEE Trans Biomed Eng* 2003; 50: 711-23
- [8] Q. Li , J.A. Stankovic, M.A. Hanson, A.T. Barth, J. Lach, and G. Zhou, "Accurate, Fast Fall Detection Using Gyroscopes and Accelerometer-Derived Posture Information", *Proc. Sixth Int'l Workshop on Wearable and Implantable Body Sensor Networks*, p.138-143, June 03-05, 2009
- [9] A.K. Bourke and G.M. Lyons, "A threshold-based fall-detection algorithm using a bi-axial gyroscope sensor" *Med. Eng. Phys.*, 30:84-90, 2008
- [10] G. Wu. "Distinguishing fall activities from normal activities by velocity characteristics", *J Biomech* 2000;33(11):1497-500
- [11] Balance International Innovations "SwayStar™", 15th Sept. 2010. <http://www.b2i.info/web/index.htm>
- [12] Henry, Gray. *Surface anatomy of the back*. 1918. *Gray's Anatomy of the Human Body*, Pg.1303. Lea & Febiger Philadelphia.
- [13] Hwang, J.Y. *et al.* "Development of Novel Algorithm and Real-time monitoring Ambulatory system using Bluetooth module for fall detection in the elderly", *Proc. 26th Annual Int'l Conf. of the IEEE-EMBS*. San Francisco, CA, USA. September 1-5, 2004