DESIGN AND TEST OF A LONG-TERM FALL DETECTION SYSTEM INCORPORATED INTO A CUSTOM VEST FOR THE ELDERLY.

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***Abstract*— Falls in the elderly are a major problem for society. A serious consequence of falling is the "long-lie". A fall detection system and algorithm, incorporated into a custom designed garment has been developed which will automatically detect falls and potentially reduce the incidence of the "long-lie".**

The developed fall detection system consists of a tri-axial accelerometer, microcontroller, battery and Bluetooth module. This sensor is attached to a custom designed vest, designed to be worn by the elderly person under clothing. The fall detection algorithm was developed and incorporates both impact and posture detection capability. The vest was developed using feedback from elderly subjects donning, wearing and doffing a prototype vests and subsequently filling in a questionnaire. The re-designed vest and fall algorithm was tested in two clinical trials. Trial 1: young healthy subjects performing normal activities of daily living (ADL) and falls onto crash mats, while wearing the vest and sensor. Trial 2: The system was subsequently tested using 10 elderly subjects wearing the system over the course of 4 weeks, for 8 hours a day. Two teams of 5 elderly subjects wore the sensor system in turn for 2 week each.

Results from trial 1, show that falls can be distinguished from normal activities with a sensitivity >90% and a specificity of >99%, from a total data set of 264 falls and 165 normal ADL. In trial 2, over 833 hours of monitoring was performed over the course of the four weeks from the elderly subjects, during normal daily activity. In this time no actual falls were recorded, however the system registered a total of the 42 fall-alerts.

Further development of the system will include a more accurate fall-detection algorithm, more comfortable sensor attachment method, lighter and smaller sensor as well as, mobility monitoring and energy expenditure measurement.

A fall detection system incorporated into a custom designed garment has been developed which will help reduce the incidence of the long-lie, when falls occur in the elderly population.

***Keywords* –long-term fall-detection, accelerometer, Bluetooth, elderly.**

I INTRODUCTION

Recent technological advances in wireless telecommunication combined with sensor miniaturization and an overall reduction in technology cost, have facilitated the development of more affordable and wearable health-monitoring systems. With the percentage of Europe's population set to increase dramatically over the next 40 years, a severe burden will be put on the health services in each country in Europe. In order to reduce this load, greater emphasis will be put on technology to monitor the health of elderly people when it begins to deteriorate, thus allowing them to remain at home and carry on with life safely and as normal.

One of the major problems that occur in the elderly population is falls. On average, one in every three adults, 65 years old or older, falls each year [1].

A serious consequence of falling is the "long-lie", this is remaining on the ground or floor for more than an hour following a fall [2]. The long-lie is a marker of weakness, illness and social isolation and is associated with high mortality rates among the elderly [1].

A number of accurate accelerometer-based fall-detection algorithms and methods do currently exist [3-6], however to date a limited number of long term fall detection systems have been developed as rigorously tested [7, 8].

The system developed by tunstallgroup is one of the most common commercially available fall-detection systems. In promotional material the system boasts a fall-detection accuracy of 90% however fall testing was performed using a wooden mannequin and the system has not been tested on elderly people just surveyed [6].

The system develop by Karantoins [7] is a waist worn fall and mobility monitoring system. A tri-axial accelerometer is used to detect periods of activity and rest, postural orientation and detect events such as walking and falls to a reasonable degree of accuracy (fall accuracy 95.6%) and provides an estimation of metabolic energy expenditure. Even though the system was developed as a long-term monitoring device, no long-term trials testing of the accuracy of its algorithms were performed using the device.

The aim was thus to develop a long-term fall-detection monitoring system which was suitable to be worn by the elderly on a daily basis which would provide high fall-detection accuracy under long-term monitoring conditions

II SYSTEM DESIGN

a) Sensor Design

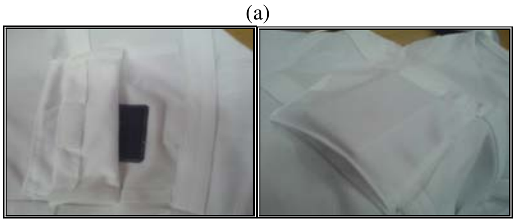
The fall-detection sensor was developed and consists of a tri-axial accelerometer (Freescale MMA7261QT), microprocessor (Texas instruments MSP430F1611), battery (PowerStream Li-ion Battery HO83448), mirco SD card and Bluetooth module (Roving networks RN-24) Figure 1. When attached to a subject, the sensor measures lateral, sagittal and vertical accelerations relative to the trunk.

Figure 1: The fall-detection sensor.

b) Vest Design

The fall-detection sensor is attached to a custom designed vest. The vest is a light-weight (320g) garment made from 100% polyester mesh, Figure 2(a). The vest can be opened and closed using a zipper at the front off the vest. The sensor is held in place using Velcro, supported using a wide elastic strap running horizontally around the trunk and covered using a novel pocket/flap Figure 2(b).

(a)



(b)

Figure 2: The (a) vest, and the (b) sensor pocket.

c) Fall detection algorithm

The fall detection algorithm which operates on the fall-detection sensor, Figure 3.

The algorithm was developed using research carries out by Bourke et al. [3]. The fall-impact threshold was thus set at 3.3g, mid way between the largest upper peak ADL value (3.16g) and the smallest upper peak fall value (3.52g). Following detection of a suitable large impact, the subject's orientation is then monitored to determine if a fall (fall-event) followed by a "long-lie" had occurred (fall-alert). A person was assumed to be in a lying position if the vertical accelerometer signal value was between 0.5g and -0.5g, this was considered to be a lying posture, suggested by Culhane et al. [9].

III TRIALS

Two separate trials were completed for system test:

1) A simulated fall-event and ADL study - used to evaluate and improve the vest and fall-detection algorithm. This study was performed by young healthy subjects
2) A long-term Activities of Daily Living, study, to determine the extent of miss-detection of normal activities as fall events.

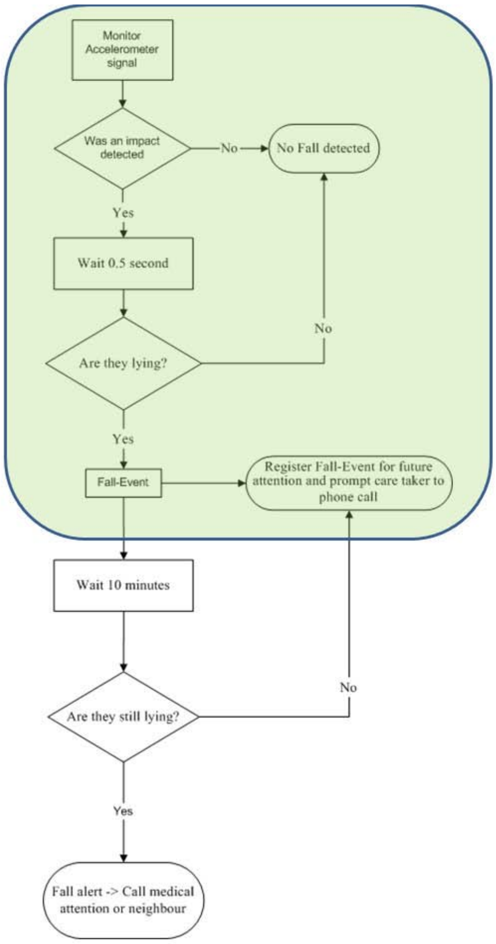


Figure 3: The fall-detection algorithm flow-chart. The shaded section was tested in trial 1(The simulated fall and ADL trial).

IIII THE SIMULATED FALL-EVENT AND ADL STUDY

a) Introduction

This study involved young healthy males performing simulated falls onto large foam crash-matts and normal ADL using normal house hold furniture. Each subject was fitted with the vest and the fall-sensor was fitted to both the chest (CH) and left under arm (LU) locations in turn. The trials took place over the course of 5 days, All subjects, from this study, gave written informed consent and the University of Limerick Research Ethics Committee approved the protocol.

b) Method

At the beginning of the trial, each of the three axes of the TA was calibrated statically against gravity. This involved orientating the fall-sensor into 6 different positions and the tri-axial accelerometer signals were recorded, allowing for offset and calibration-sensitivity values to be determined later. Following this another calibration was performed, this time to determine the offset and calibration-sensitivity values for the fall-sensor, which would be used in conjunction with the real-time fall-detection algorithm.

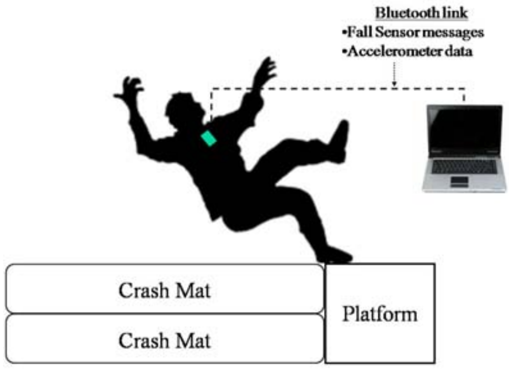


Figure 4: The recording set-up for the simulated fall-event and ADL study. Raw accelerometer signals as well as "fall-impact" and "fall-event" messages were transmitted.

Longitudinal, sagittal and medial-lateral accelerations as well as algorithm result messages of the real-time fall-detection algorithm were recorded via Bluetooth from the trunk during each simulated fall-event, Figure 4.

A total of eight different fall types were completed with each fall-type being repeated three times, by each subject. Falls in al direction were performed, forward backward, left and right, with both legs straight and relaxed, with the knees allowed to flex.

Subjects also performed a number of normal ADL. A total of 5 different ADL were performed three times by each subject.

The normal ADL performed were:

- Lying on a bed
- Sitting on a kitchen chair type 1
- Sitting on a kitchen chair type 2
- Sitting on a bed
- Walking 10m

The subjects were young (<35 years) healthy males. A total of 11 subjects were recruited for the study. The mean±standard deviation age, height and mass of the subjects were 23.4±4.6years, 1.8±0.076m and 80.9±13.28kg respectively.

The fall types were selected in order to best simulate the type of fall that may occur and cause injury to an elderly person. Thus, each fall was performed with the subject initially in a standing position. All the falls were performed onto large crash mats with a combined thickness of 0.76m.

c) Data Analysis

Using the recorded results of the real-time fall-detection algorithm and the recorded accelerometer signals, analysis was performed using

MATLAB[1] to determine the sensitivity, specificity and accuracy of the algorithm. These parameters were determined for both the real-time implemented algorithm and also by simulating the algorithm using MATLAB. Analysis of the results from the performed falls and normal ADL were used to update and adjust the thresholds for the fall-detection algorithm. In order determine the most appropriate threshold for the long-term ADL study, the accuracy (1), for a range of threshold values was determined using the recorded fall and ADL upper peak values.

$$Accuracy = \frac{TP + TN}{P + N} \qquad (1)$$

TN- True Negative, number of ADL correctly detected.
TP- True Positives, number of falls correctly detected.
P- Positives, number of falls performed.
N- Negatives, number of ADL performed.

d) Results

A total data set of 264 falls and 165 normal ADL, from both chest and left-under arm, were recorded. The results of implementing the shaded portion of the fall-detection algorithm in Figure 3 were recorded for both a real-time and simulated implementation of the algorithm. Sensitivities, specificities and accuracy values are displayed in, Table 1.

Chest	*Algorithm*	*Sensitivity*	*Specificity*	*Accuracy*
Impact	real-time	65.5%	75.7%	69.4%
	simulated	98.8%	98.1%	98.6%
Event	real-time	41.2%	86.0%	58.5%
	simulated	90.5%	99.4%	93.9%

(a)

LU Arm	*Algorithm*	*Sensitivity*	*Specificity*	*Accuracy*
Impact	real-time	76.9%	51.5%	67.1%
	simulated	98.9%	94.5%	97.2%
Event	real-time	43.2%	93.9%	62.7%
	simulated	97.0%	99.4%	97.9%

(b)

Table 1 – Sensitivities (proportion of falls correctly detected as falls), specificity (proportion of ADL correctly detected as non-falls) and Accuracy (proportion of true results (both true positives and true negatives) in the population) for both the Chest (a) and Left Under (LU) Arm (b) fall detection algorithm both simulated and real-time implementation.

Results show that the simulated implementation of the algorithm achieved higher sensitivity, specificity and accuracy values that the read-time implementation, this was due to an in-accurate calibration of the fall-detection sensor at the start of the trial.

From examining the recorded accelerometer signals and the simulated implementation of the algorithm, results show that falls can be distinguished from normal activities with a minimum sensitivity of 98.9% and a minimum specificity of 94.5% for "fall-impact" detection, and with a minimum sensitivity of 90.5% and a minimum specificity of 99.4% for "fall-event" detection when the fall-sensor is attached to either the chest or left underarm.

From an examination of the impact values recorded for both falls and normal ADL, peak-accelerations associated with sitting activities were frequently miss-detected as fall-impacts, however these were distinguished from a fall using the posture detection thresholds. However one lying activity did however raise a fall-event on both the chest and LU Arm, Poorer fall-event sensitivities were achieved for the chest, 90.5% and LU Arm, 97% however much high specificity values, 99.4% for both, were achieved than the fall-impact thresholds, Table 1, as the subject were not correctly categorised a lying following the impact from a fall.

The fall-impact threshold which produces the maximum accuracy was determined for both the chest and LU Arm locations this was done by varying the threshold between maximum recorded fall value and minimum recorded ADL value, with the Accuracy being determined for each threshold increment. By locating the fall-impact threshold at 3.09g for the chest sensor and 3.35g for the LU Arm, fall-impact detection accuracies of; 99.1% and 97.9% can be achieved, Table 2.

e) Algorithm update

Since repositioning of the fall-impact threshold would have achieved only marginal improvements in the fall-impact detection sensitivity, specificity and Accuracy, Table 2, the threshold remained at 3.3g as it could be positioned at either the chest and LU Arm and still achieve high test parameter values.

Chest

Threshold	*Sensitivity*	*Specificity*	*Accuracy*
3.3g	98.8%	98.1%	98.6%
3.09g	99.6%	98.2%	99.1%
Improvement	0.8%	0.1%	0.5%

(a)

Left-under Arm

Threshold	*Sensitivity*	*Specificity*	*Accuracy*
3.3g	98.9%	94.5%	97.2%
3.35g	98.8%	96.4%	97.9%
Improvement	-0.1%	1.9%	0.7%

(b)

Table 2 – Fall-impact-sensitivities specificity and accuracy values for the original and improved fall-impact threshold for both the Chest (a) and Left Under (LU) Arm (b).

[1] The MathWorks Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, U.S.A.

V A LONG-TERM ACTIVITIES OF DAILY LIVING, STUDY

a) Introduction

The vest, fall-sensor and fall-detection algorithm was subsequently tested on a group of 10 elderly subjects wearing the system over the course of 4 weeks, for approximately 8 hours a day from Monday to Saturday. The trials took place in the nursing home "Benincasa" in the city of Ancona, Italy and were coordinated by COOSS Marche Onlus who recruited the subjects for the trials and obtained the relevant ethical approval. During the trial, messages from the fall-sensor were relayed to a care-centre as described in Figure 5. The care-staff could thus take the appropriate action depending on which message type was received; the care-taker site was created by the Research and Development department TID-Telefónica Investigación y Desarrollo, at Telefonica in spain and was located at the offices of COOSS Marche Onlus, Ancona, Italy.

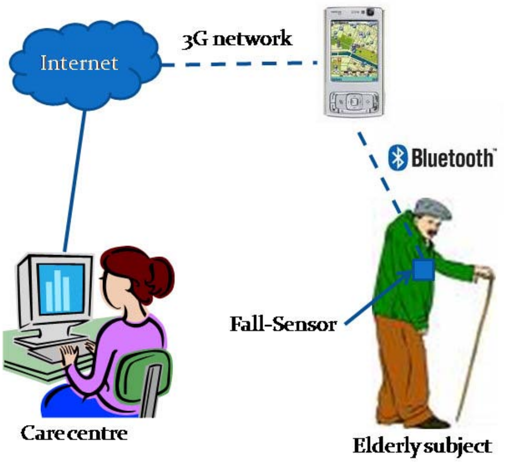


Figure 5: Messages from the fall-sensor were relayed to the care-centre via Bluetooth to the Nokia N95 which was attached to the subject in the vest; they were then relayed further via the 3G network and the internet.

b) Method

Two teams of 5 elderly subjects wore the sensor system in turn for 2 week each with the fall-sensor located at the chest for week 1 and 2 and the LU Arm for week 3 and 4, Figure 6.

Week	*Team*	*Sensor Location*
1	A	Chest
2	B	Chest
3	A	LU Arm
4	B	LU Arm

Figure 6: Trial recording set-up for the 4 week trial.

A the beginning of each day the subject donned the vest and the fall-sensor and Nokia N95 mobile phone were attached to the vest. The subject then carried out their normal daily activity which included: sitting, lying on a bed, walking, using the bathroom, travelling on a bus, using the stairs, using an elevator and dining. At the end of the day the subject doffed the vest and the phone and fall-sensor were charged over-night for the following days monitoring. A nurse assisted the elderly subjects in donning and doffing the vest, fall-sensor and phone.

The fall-sensor transmits a number of messages to the care-taker site: "fall-event", "fall-alert" and "fall-recovery". These would appear at the care-taker terminal and the relevant steps would then be taken by the care-taker staff to ensure the elderly subjects safety. As well as transmitting messages the fall-sensor also logs the raw accelerometer data and the event messages to an SD card for later analysis. After 2 weeks of the trials, the SD cards were replaced and the sensors were re-calibrated.

c) Results

In total 833 hours of monitoring was recorded over the course of the four weeks from the elderly subjects during normal daily activity. During the trial at total of 115 fall-events and 42 fall-alerts were detected by the fall-sensor,

Table 3. During the four weeks at least 230 fall-messages were forwarded for transmission to the care centre.

Sensor location	Chest	LU Arm	Total
Fall-impacts	175	248	423
Fall-events	41	74	115
Fall-alerts	21	21	42
Fall-recovery	20	53	73
Total messages sent	82	148	230

Table 3 – Totals of impacts, fall-events, fall-alerts and fall-recoveries detected by the fall-sensor. The SD card on fall-sensor 5 malfunctioned thus 1 week of data for 2 subjects is unavailable. Fall-impact messages were not transmitted to the care centre.

At the care-centre a total of 740 fall-messages were received. However only 9 fall-alerts were received and 532 fall-events were received. The large number of fall-events was due to a malfunction of the sensor on one day in which 550 fall-messages, which include fall-event, fall-alert, fall-recovery and help messages, were sent, Figure 7.

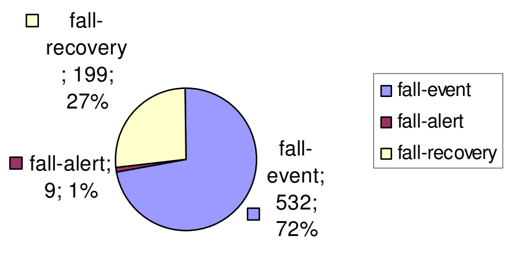


Figure 7: Totals of fall-messages received by the care-taker site

During weeks 1 and 2 of the trials, 140 fall-messages were received by the care centre and 701 fall-messages were received by the care-centre in weeks

3 and 4 with 550 of these fall messages occurring in one day.

Feedback from the elderly subject and the nursing staff indicated that the vests were not appreciated. The elderly subjects felt the vest was uncomfortable and they disliked wearing them for eight hours each day.

The nursing staff also felt that the vests were somewhat uncomfortable for the subjects and that the vest was too bulky and too intrusive as it was to be worn under clothes, as well as the fall-sensor. A number of improvements were suggested:

- The vest should be made larger but shorter so that the subjects have no difficulty in wearing and move about especially when using the toilet.
- During the summer vest would not be appropriate for the high temperatures.
- The vest should be made from more elastic material

d) Discussion

From analysis of the fall-message results above it is clear that some of the fall-alert messages did not arrive at the care-centre, this may be attributed to the fact that transmission from the fall-sensor to the phone via Bluetooth was not successful as often the phone was powered off at the end of the days recording. Also the extra fall-event and fall-recovery messages were most likely due to the malfunction of the device on day 18 of the trials in week 3.

In general the system operated well, many fall-events and fall-alerts were detected by the fall-sensor and received by the care-centre. The care-taker staff described that when a fall-event or fall-alert was received the care-staff contacted the nurse in the nursing home. When the nurse verified the event, provided help or just verifying that nothing was happened, the care-taker manage the alert, defining it as “false” or “correct”. The false alarms that did occur were attributed to the subjects who were sitting into a car, lying down on the bed and sitting down rapidly on the bus.

Both the elderly subject and the nursing staff suggested that a more comfortable method of wearing the sensor would be appreciated, for example incorporating the fall-sensor into a bracelet or a belt. The subjects also appreciated the idea of being monitored for fall-detection, with subjects commenting that it would be useful at time when they are completely alone or when out walking. Thus the elderly participants clearly see the value and necessity for such a system.

VI DISCUSSION

Through incorporating the fall-sensor into a vest that can be worn by the elderly, it is considered that greater compliance with wearing and using a fall detection system will be achieved. During the long term trial (4 weeks) involving the 10 elderly subject’s, 42 fall-alerts were detected (however only 9 were received) However since no actual falls followed by a period of lying were reported then clearly further development of the fall-detection algorithms is required.

VII FUTURE WORK

Further development of the system will include a more accurate fall-detection algorithm, more suitable attachment method, lighter and smaller sensor as well as, mobility monitoring and energy expenditure measurements.

VIII CONCLUSION

A fall detection system incorporated into a custom designed garment has been developed which has the potential to reduce the incidence of the long-lie, when falls occur in the elderly population.

REFERENCES

[1] S. R. Lord, C. Sherrington, and H. B. Menz, *Falls in Older People: Risk Factors and Strategies for Prevention*. Cambridge: Cambridge University Press, 2001.

[2] D. Wild, U. S. Nayak, and B. Isaacs, "How dangerous are falls in old people at home?," *Br Med J (Clin Res Ed)*, vol. 282, pp. 266-8, 1981.

[3] A. K. Bourke, J. V. O'Brien, and G. M. Lyons, "Evaluation of a threshold-based tri-axial accelerometer fall detection algorithm," *Gait Posture*, vol. 26, pp. 194-9, 2007.

[4] M. Kangas, A. Konttila, P. Lindgren, I. Winblad, and T. Jamsa, "Comparison of low-complexity fall detection algorithms for body attached accelerometers," *Gait Posture*, 2008.

[5] N. Noury, "A smart sensor for the remote follow up of activity and fall detection of the elderly," presented at 2nd Ann. Int. Conf. IEEE Eng. Med. Biol. Society, Madison, Wisconsin, 2002.

[6] K. Doughty, R. Lewis, and A. McIntosh, "The design of a practical and reliable fall detector for community and institutional telecare.," *J Telemed Telecare*, vol. 6 Suppl 1, pp. S150-154), 2000.

[7] D. M. Karantonis, M. R. Narayanan, M. Mathie, N. H. Lovell, and B. G. Celler, "Implementation of a real-time human movement classifier using a triaxial accelerometer for ambulatory monitoring," *IEEE Trans Inf Technol Biomed*, vol. 10, pp. 156-67, 2006.

[8] "www.tunstallgroup.com ".

[9] K. M. Culhane, G. M. Lyons, D. Hilton, P. A. Grace, and D. Lyons, "Long-term mobility monitoring of older adults using accelerometers in a clinical environment," *Clin Rehabil*, vol. 18, pp. 335-43, 2004.