WRIST-WORN FALL DETECTION DEVICE
Development and Preliminary Evaluation

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Abstract: Falls are the most important cause of accidents for elderly people and often result in serious physical and psychological consequences. The rapid growth of the elderly population increases the magnitude of the problem as well as the generated costs. In order to take care of old people living by themselves or in care centres and to reduce the consequences of a fall, various technological solutions have been studied, however none led to a commercial product fulfilling user requirements. In this work we present an automatic fall detector in the form of a wrist watch which could lead to better life conditions for the elderly. Our device implements functionalities such as wireless communication, automatic fall detection, manual alarm triggering, data storage, and simple user interface. Even though the wrist is probably the most difficult measurement location on the body to discern a fall event, the proposed detection algorithm shows encouraging results (90% sensitivity, 97% specificity) with the signals of our database.

1 INTRODUCTION

Falls are the most widespread domestic accidents among the elderly. Their consequences often give rise to impairments to the health and lifestyle of the victims (Pérolle et al., 2004). In many cases, physical after-effects and other injuries are direct consequences of these accidents and result in significant medical costs.

Furthermore, it frequently happens that elderly people who have previously experienced a fall fear a new fall and sink gradually into inactivity and social isolation. The reduction in their mobility leads progressively to an increase in the risk of a fall (Doughty et al., 2000). Hence, given the growing part of the elderly people in our modern societies, the socio-economic impact that this self-imposed isolation may have should not be neglected.

The most widespread solution for limiting the apprehension of a fall is provided by social alarms consisting of portable devices. These are generally equipped with an alarm triggering button and endowed with telecommunication means suitable for alerting the care centre. Nevertheless, because of the fall, the person may not be able to actuate the button and to trigger the alarm (unconsciousness, state of shock, broken arm, etc.).

To alleviate this drawback, autonomous fall detectors have been developed and are capable of triggering an alarm automatically without any intervention of the victim and transferring this information to a remote site (Doughty et al., 2000). These autonomous detectors operate essentially on two principles. The detector is either sensitive to the person's appearance or impact on its environment and is based on video (CCD or IR camera) or vibratory type sensors (acoustic or piezoelectric layers on the ground) placed in the usual surroundings of the subject. The benefit of these devices is that they do not have to be worn. Instead, they are fixed and integrated in a given spot and cannot be moved easily when the person changes location. Moreover, in the case of a video sensor the person will have the impression of being supervised and feel inconvenienced. The major drawback of acoustic based sensors is that they are surface dependent, while those based on vibration are fragile and expensive. The detector can also be worn by the person and thus detect a fall directly as soon as it occurs, triggering an immediate alarm. In this case, the information provided by inclinometers, gyroscopes or accelerometers is exploited. These devices are generally compact, inexpensive, fairly non-obtrusive, easy to use, and can be worn at various body locations.

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Devices worn close to the centre of gravity (Depeursinge et al., 2001) are the most reliable ones, but also the least convenient to wear on a daily basis, in particular while performing common daily activities. A device having the form of a wristwatch would be well tolerated in all situations, despite the challenge to detect a fall due to changes of position and accelerations that the wrist experiences during everyday actions (Degen et al., 2003). Furthermore, the inclination measurement of the forearm cannot give reliable information about the person's position. Generally, fall detectors placed on the wrist give rise to a large number of false alerts, and this would generate significant and unnecessary costs.

Our goal is to develop a small, comfortable, and user friendly device, as well as an automatic fall detection algorithm that will help elderly people to handle this problem.

2 METHOD AND MATERIALS

The fall detector that we have developed is a device capable of automatically detecting various body falls and sending an alarm to a remote terminal. The user can manually generate the alarm signal in case of necessity or, inversely, he can cancel an automatically generated alarm in case of a false fall detection.

2.1 Fall Detection System

The detection system is integrated in the case of a wrist watch. A picture of our prototype is depicted in Figure 1.

Figure 1: Wrist fall detection system.

The core of the wrist-located device consists of a microprocessor (MSP430) and two MEMS sensors arranged perpendicularly to allow the measurement of acceleration along three axes with a range equal to ±18g (ADXL321). The user interface is simple and comprises a small LCD screen (Nokia 3310), a vibrator which advises the user that a fall has been detected and an alarm will soon be sent, and a push button on the front panel to manually trigger the alarm signal. Data can be transmitted from fixed and/or mobile devices over short distances utilizing a short-range communication technology (Bluetooth protocol).

For experimental purposes, the acceleration signals can also be stored in a flash memory card. The serial RS232 port as well as three additional buttons are also available for debugging and test.

The device is powered by a 3.7 volts rechargeable Lithium-Cobalt-Polymer battery. The battery life of the device varies from about 15 days to one month, depending on the sampling frequency and the details of the implemented data handling and storage functionalities.

2.2 Fall Detection Algorithm

The three-axes acceleration signals are recorded and stored in the flash memory, with a sampling frequency of 910 Hz and 12-bit resolution. Although the algorithm has not been implemented yet in real-time, it has been tested offline using Matlab.

Initially, the device is slowly rotated a few times in order to project the gravity vector on the three axes in various configurations. The resulting acceleration signals roughly define the surface of a sphere in a three dimensional space and are used to calibrate the sensors. We define the time-dependent acceleration vector $\mathbf{A} = (\tilde{a}_x, \tilde{a}_y, \tilde{a}_z)^T$ whose entries are defined as $\tilde{a}_i = a_i - c_i$, for $i = x, y, z$, where a_i represents the acceleration in the *i*-direction while c_i is the *i*-coordinate of the centre of the sphere corresponding to a zero acceleration. Therefore, the equation of the sphere is defined using Cartesian coordinates as:

$$\|\mathbf{A}\|_2^2 - r^2 = 0 \qquad (1)$$

where the radius r corresponds to the gravity acceleration and defines the sensor gain while the centre (c_x, c_y, c_z) defines the accelerometer offset. Notice that one can use the Gauss-Newton method to estimate (c_x, c_y, c_z, r) by minimizing the left-hand part of equation (1) and use those parameters to calibrate the acceleration signals (see Figure 2).

The three-axes acceleration experienced at the wrist of the person wearing the device can not be directly linked to the specific posture of the body. However, it has been observed that the distribution of the acceleration norm $\|\mathbf{A}\|_2$ experienced at the wrist over a time window ΔT provides a particularly reliable signature, allowing the identification of a given event happening to the person wearing the device.

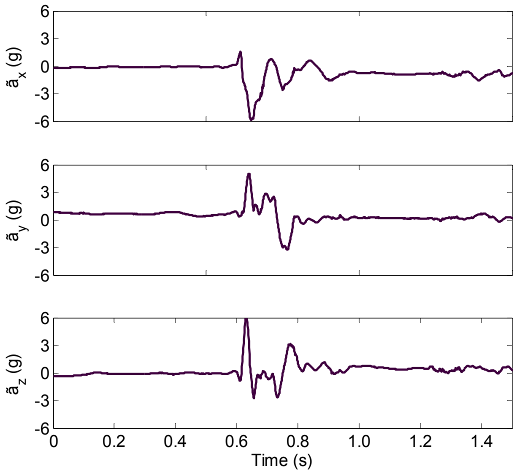

Figure 2: Typical recording of a fall event. Each signal corresponds to the acceleration in the x, y, or z direction.

We define S_t as the signature at instant t that represents the distribution of the acceleration norm $\|\mathbf{A}\|_2$ over a time window ΔT. The signature S_t can be extracted via a simple amplitude threshold and compared to a reference signature S_{ref}. To obtain S_{ref}, a subset of all the fall signatures recorded in the database is used to obtain statistics in the form of means and variances. Specifically, a particular value of each signature in the subset is identified so as to carry out an alignment, for example on the maximum. This particular value is used to align the signatures, so as to obtain a group of aligned fall signatures. On the basis of the various aligned signatures, the reference signature S_{ref} is obtained by averaging the values of the aligned signatures.

In order to construct a similarity measure d between S_t and S_{ref}, the squared value of the acceleration due to gravity is subtracted to remove its influence. For this application, d is calculated according to the Mahalanobis distance definition. The variances of the aligned signatures are placed on the diagonal of a matrix θ that is used together with S_{ref} to estimate if the instantaneous signature S_t arises from a fall:

$$d(S_t, S_{ref}) = e^{-(S_t - S_{ref})^T \theta^{-1} (S_t - S_{ref})} \tag{2}$$

The influence of the least reliable samples is reduced due to the use of the variances. One can see that the value of d is in the interval [0,1] and therefore can be considered to be a fall probability. A threshold was used to discriminate between the two classes: “fall” and “no fall”.

2.3 Experimental Setup

A preliminary validation has been performed with three adult healthy adult volunteers to assess the reliability of our system for fall detection tasks. The study consists in recording the three-axial accelerometer signals (wrist-located) during controlled fall events and daily life activities. Each case was repeated three times and stored in a separate file. In our database we have documented 180 situations by recording acceleration signals and video sequences. The latter are particularly useful to understand the dynamics of the wrist movement.

To evaluate the sensitivity of the fall detection a first subset consisting of six kinds of falls is created. The kind of falls selected for this subset are: front, back, left, right, falling backwards while sitting down, and falling forward while standing up. Each fall was intentional and a mattress was used to protect volunteers from injuries.

A second subset was used to estimate the specificity of the fall detector. It includes 14 common situations representing challenges for the detection algorithm (slow/fast walking, walking upstairs/downstairs, hit on a table with the fist, sitting down, lying down, applauding…).

3 RESULTS

To generate the reference signature of a fall event we have taken 8 recordings representing fall events randomly selected from the 54 falls of the database and we have computed the mean and the standard deviation for each event. Figure 3 shows a typical reference signature that we obtain with the signals of our database. The mean and standard deviation values of the reference signature are then used to compute a normalized similarity measurement for each recording of the database and a binary classifier is used to separate falls from other events.

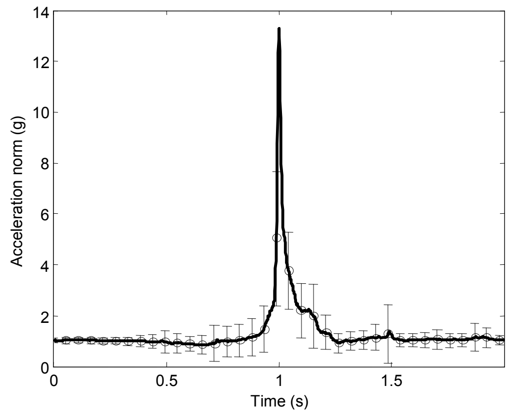

Figure 3: Reference signature in terms of mean and standard deviation.

A binary classifier system is generally assessed in terms of sensitivity and specificity. A useful graphical tool to represent the sensitivity versus (1-specificity) for a binary classifier system as its discrimination threshold is varied is the receiving operating characteristic (ROC). Figure 4 shows the ROC curve obtained with the signals of the database.

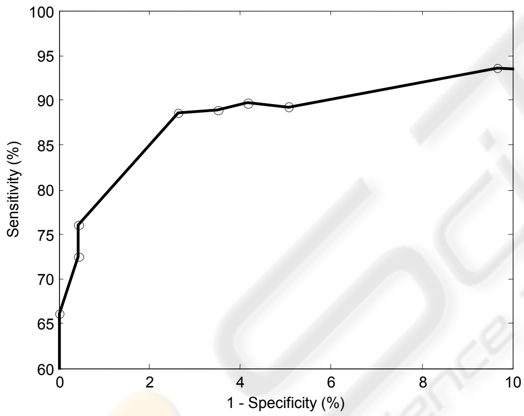

Figure 4: The receiver operating characteristic shows the relationship between the sensitivity and (1-specificity).

In order to become independent from the recordings used to generate the reference signal, we repeated the same procedure ten times: random selection of 8 fall events, estimation of the mean and the standard deviation, classification of the 172 recordings, and estimation of the ROC curve. The circles in the plot of Figure 4 are thus a mean value of the ten simulated results.

One can see that there is a tradeoff between sensitivity and specificity: the larger the sensitivity, the smaller the specificity. We can decide to favour one characteristic over the other, but a good balance is normally to privilege the upper-left corner of the ROC curve. In the present case, this particular point allows us to detect about 90% of the falls while keeping the false alarm rate below 3%.

4 CONCLUSIONS

We have developed a small, light, and comfortable fall detector device which is worn at the wrist like an ordinary watch, removing the social stigma of wearing a medical device. The real advantage of fixing the fall detector at the wrist is the possibility of wearing the device at night, when falls can also occur. The device is thus easy to wear continuously without any specific constraints. The major drawback is the signal processing challenge of estimating a fall from wrist acceleration data, due to the strong accelerations experienced by the forearm during daily-life activities.

The proposed algorithm to detect falls is based on accelerometric signals and has the advantage to be simple and robust showing promising results with our present database. Results demonstrate high sensitivity (90%) as well as high specificity (97%) for the detection of intentional falls.

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