Smartphone-Based Applications for Investigating Falls and Mobility

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Abstract—**The aim of this study is to develop a system for investigating human falls and mobility based on a Smartphone platform. We have designed and tested a set of software applications building on the inertial data captured from the tri-axial accelerometer sensor embedded in the Smartphone. We will describe here two applications: a fall detection and management application, and an application for the administration of a popular and standardized test in the field of human mobility assessment, namely the Timed-Up-and-Go test.**

Keywords: fall detection; fall risk assessment; Smartphone application; Android; elderly oriented application; Timed-Up-and-Go test;

I. INTRODUCTION

Falls in older persons have multiple causes. Risk factors can be intrinsic and extrinsic. Intrinsic factors include a history of falls, high age, impaired mobility and gait, medical diseases, medication, sedentary behavior, fear of falling, visual impairments, foot problems, nutritional deficiencies and impaired cognition. Extrinsic factors include environmental hazards (like poor lighting, slippery floors, uneven surface), footwear and clothing and inappropriate walking aids or assistive devices. Meta-regression analysis of the predisposing risk factors has shown that gait difficulties, muscular weakness and an impaired standing balance are the most prevalent risk factors for falls [1].

A variety of methods and tools have been proposed for fall risk assessment, most of which have discriminated poorly between fallers and non-fallers [2], and none of which is universally accepted. Methods and tools for assessing fall risk in home-dwelling older persons with minor functional problems are several: Functional balance and mobility assessment, by use of the Berg Balance Scale, the Tinetti Mobility Scale, the Functional Gait Assessment (FGA) the Balance Evaluation Systems Test (BESTest) or the Timed Up-and-Go[3]; Physiological fall risk assessment, by use of the Physiological Profile Assessment (PPA); Posturography to measure quiet standing by use of force plates; and Assessment of psychological aspects of falls by the Falls Efficacy Scale International[4]. Other methods are based on assessment of gait characteristics like gait speed [5], step width [6], gait variability during simple and dual task conditions [7].

Recent developments of feasible body worn accelerometer- and gyroscope-based sensor systems have made it possible to develop algorithms for calculation of gait characteristics over longer distances in natural settings and physical activity throughout the day. However, as yet, no standardized tests for predicting fall risk have been developed based on these or similar sensor-based assessments. Most of this work has been carried out during controlled trials or within observational studies. Other findings have been gathered during interviews with fallers. These rely on incomplete and sometimes controversial oral reports by the subjects themselves, witnesses and by informal or formal caregivers. For example, falling to the ground without an injury might not be interpreted as a fall by every person. There is evidence that up to 80% of all falls without injury are not reported spontaneously by older persons.

In overview *there is a paucity of evidence about older people's and other stakeholders views, beliefs and attitudes towards the use of technologies in the detection and prevention of falls, and more generally in the promotion of active and independent living.* What we do know is that older people are likely to embrace such technologies if they are congruent with their own beliefs, attitudes, lifestyle and aspirations and are designed in such a way as to be accessible to them. What we do not know is the nature of those beliefs, attitudes, lifestyles and aspirations that will specifically result in high uptake and adherence to any assistive technology, nor what the optimum design parameters of the technologies are for them to be acceptable and usable by older people.

We believe that the need to have a user-friendly device able to perform an ubiquitous sensing with a full connectivity (e.g. WiFi, 3G/4G, Bluetooth, etc.) makes the sensorized **Smartphones** able to revolutionize many sectors of our economy, including *business, healthcare, social networks, environmental monitoring, and transportation.* We choose to design our applications on a Smartphone platform to keep all the advantages in terms of usability, accessibility, low cost, high-performance computation capabilities for real-time data processing, complete inertial sensing unit, and the availability of an open platform (such as **Android**). We believe that Android-based Smartphone solutions can meet the needs and requirements of older users to help them improve their mobility and quality of life. The first application we describe in this paper is aimed at the real-time detection of a fall event and its subsequent management. The second one is in the field of fall-risk assessment by collecting and analyzing the data of an instrumented Timed-Up-and-Go test (iTUG). In section II we will provide our arguments in favour of the choice of the

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Smartphone platform; in section III we will describe the "Fall detection" application and in section IV we will describe the "iTUG" application. Conclusion and Future Works will be discussed in section V.

II. SMARTPHONE PLATFORM

Today's Smartphone not only serves as the key computing and communication mobile device of choice, but it also comes *with a rich set of embedded sensors*, such as an *accelerometer*, *digital compass*, *gyroscope*, *GPS*, *microphone*, and *camera*. Collectively, these sensors are enabling new applications across a wide variety of domains, such as *healthcare*, *social networks*, *safety*, *environmental monitoring*, and *transportation*, and give rise to the new area of research called *mobile phone sensing* [8]. Until recently mobile sensing research such as activity recognition, where people's activity (e.g. walking, driving, sitting, talking) is classified and monitored, required specialized mobile devices to be fabricated. Mobile sensing applications had to be manually downloaded, installed, and tuned for each device. User studies conducted to evaluate new ***mobile sensing applications and algorithms were small-scale because of the cost and complexity of doing experiments at large-scale***. As a result, the research, though innovative, gained little momentum outside a small group of dedicated researchers. *Although the potential of using mobile phones as a platform for sensing research has been discussed for a number of years now, in both industrial and research communities, there has been little or no advancement in the field until recently.*

In the fall-detection domain the *iFall* [9] application has been developed to detect fall events: data from the accelerometer is evaluated with several threshold-based algorithms and position data to determine a fall. If a fall is suspected a notification is raised requiring the user's response. If the user does not respond, the system sends alerts message via SMS. The fall-detection algorithm needs lots of threshold calibrations without any assurance about its performance.

The *Mover* [10] application has been developed to monitor human activity level and to detect falls. In order to measure activity levels, Mover reads data from the phone accelerometer and sums it out throughout the day. People's average level of activity is then translated into a simplistic categorization of users: Sleeper, Sitter, Lagger, Walker, Mover or Hyper. Mover can also detect user falls and send alerts to user's emergency contacts (through SMS or email). Before calling for help, Mover will play a sound to make sure the user is unconscious. This feature is still experimental as the algorithm is still being tested.

The *PerFallD* [15] is a pervasive fall detection system tailored for mobile phones. It has been designed with two different detection algorithms based on the mobile phone platforms for scenarios with and without simple accessories. They implement a prototype system on the Android G1 phone.

The Smartphone Platform we chose for our design is **Android** because it is an open platform which allow the full programmability of all the relevant software components: sensor management (e.g. sampling frequency, sensor accuracy), power management, data storage management, connectivity management (Internet connection, SMS), and a complete design of the elderly-oriented user interface. In addition, with the Android framework we can select the best device in terms of computational performance, sensing capabilities and device size.

III. "FALL DETECTION" APPLICATION

We have designed and developed a Smartphone application able to analyze in real-time fall data in an elderly population. Data are captured from the inertial sensor (tri-axial accelerometer). An *elderly-oriented* user interface has been designed to make as easier as possible the interaction between the elderly subject and the device.

A. System Architecture

The Smartphone is at the core of the system architecture since it embeds a sensing unit, a computation unit, and the network connection. The device we choose for our design is the HTC Desire, carrying a Bosch BMA150 accelerometer (range +/- 2g, resolution 4mg, digital output resolution 10bit).

The user wears the Smartphone on a waist belt: this allow to get accelerometer data near the center of body mass providing reliable information on body movements, minimally affected by sudden limb motion artifacts. Furthermore, the use of a waist belt is generally perceived by elderly persons as non invasive [16].

The application collects data and runs the real-time fall detection algorithm and provide a secure connection with a remote server, typically connected with a secure protocol (SSL, Secure Sockets Layer), to provide access to caregivers, relatives or the user itself. When a fall is detected, an audio notification is generated for 30 seconds to verify the subject response. During this time the subject can press a "Stop Alert" button to stop the notification and to disable the external alarm procedure. If the subject does not react to the audio notification, and is hence supposedly unconscious, an alarm is automatically sent to the caregivers (by e-mail and/or SMS) to start the assistance procedures.

After each fall is detected, accelerometer data related to subject movement patterns immediately before and after the fall event are sent to a remote server on a VPN (Virtual Private Network). In this way, the clinician can analyze the data received to get more fall related information.

The application user interface has been designed to be as easier as possible because of elderly users. It only includes the possibility to set up some useful parameters (sampling frequency, telephone number or e-mail to be used for the alarm procedure, subject information, etc.) and give the user the possibility to run it in background allowing a normal use of the Smartphone.

By default, the application run in background and it is automatically started when the Smartphone is turned on. *With this choice the* ***user is not asked to interact with the application****: the only interaction is required when a fall is detected.* The clinician can use the application interface just to set up some parameters before leaving the system to the user.

Data collected during all the monitoring time has been stored on the Smartphone SD-card. In this way activities of daily life of the monitored subject can be efficiently analyzed .

Continuous monitoring can last no more than 11 hour because of battery draining. This time can be increased by the use of a more powerful battery or can be increased with the use of newer less-consuming Smartphones.

B. Fall Detection Algorithm

Several algorithms have been defined in literature using Sum Vector (SV) (i.e. the accelerometer vector norm [11]). Algorithm performances are defined in terms of impact detection capability and identification of the false positive events. These algorithms make a single or double thresholding or detect the subject speed before the fall occurs.

We chose a simple single-threshold algorithm to implement the fall detection because it requires the lowest computational power and it is the most appropriate for a real-time application. Moreover, we targeted a restricted, yet representative, subset of possible falls, listed in **TABLE I**. After an experimental tuning, the threshold (T) was fixed at 2.3 g for each subject.

The algorithm proposed acquires accelerometer data with a sampling rate of 50 Hz, computes SV and makes a comparison with T. When SV is greater than T an impact is detected. Subsequently, the subject behavior is monitored, checking subject orientation to verify the presence of a possible fall recovery. Subject orientation is evaluated as the mean value on the vertical axis on the time window that starts two seconds before and ends two seconds after the fall event.

The fall is detected when the orientation before the impact is “vertical” and the orientation after the impact is “horizontal” (e.g. falling during walking) or both the orientations, before and after the impact, are “horizontal” (e.g. falling out of bed). Our algorithm cannot detect those falls starting and ending with trunk orientation in both cases “vertical” (e.g. falling against a wall).

Simulated intentional falls were performed by three healthy subjects, age: 25 yrs (range 24-26), height: 171 cm (range 164-175), body mass: 62.6 Kg (range 60-66). Falls have been performed on a 20 cm thick, 800 springs, mattress. We report here the number of different fall typologies used to test the system: forward with subjects starting from an erect position – with mattress (15); forward while walking - with mattress (5); forward with subjects starting from erect position - without mattress (20); backward - with mattress (10); lateral - with mattress (7); falling out the bed (5); falls sliding against a wall ending in vertical position (2); falls sliding against a wall ending in horizontal position (3). Seventeen falls were followed by a recovery.

Preliminary performance evaluation of our algorithm is provided in terms of *sensitivity* and *specificity*. The results of our tests are shown in **TABLE I**: both specificity and sensitivity are 100% , *except the case when fall dynamics is completely in the vertical direction*. This is the only case in fact where falls cannot be recognized by our algorithm, as anticipated. This preliminary result supports the choices made: the combination of the sum vector and subject orientation can be considered effective and usable in an embedded system due to the low computational power required. In addition, the threshold chosen seems to be effective with SV in the limited set of simulated falls. As expected, false negatives are obtained in case the final orientation of the user after the fall is vertical.

TABLE I: Classification results
on 67 simulated fall events

Typology of fall	Recognized	Not recognized
Forward fall	40	0
Lateral fall	7	0
Backward fall	10	0
Fall sliding against a wall final position vertical (**not in the recognition set**)	0	2
Fall sliding against a wall, final position horizontal	3	0
Falling out the bed	5	0
Total	65	2

IV. “iTUG” APPLICATION

The Timed-Up-and-Go (TUG) is one of the most used clinical tests to assess mobility: it measures the time taken by an individual to stand up from a chair, walk 3m, return to the chair and sit down. An instrumented Timed-Up-and-Go (iTUG) makes use of a measurement system (e.g. an accelerometer) to compute a set of parameters able to more subtly investigate balance and gait impairments. iTUG has proven to be sensitive to age-related changes and fall risk prediction [12]. The possibility to perform an instrumented TUG with a low cost device and a usable application can be considered as a key-point to increase the knowledge of balance and gait impairments.

A. Preliminary Study to Test Suitability of a Smartphone Accelerometer to Instrument the Timed Up and Go

Before designing the iTUG application for Smartphone device we tested the suitability of the Smartphone sensing unit (accelerometer). We performed some tests to compare the mass-market accelerometers as those included in modern Smartphones (HTC Desire) with those provided by a commercial measurement system already used in clinical applications (McRoberts Hybrid node).

The reliability of the parameters calculated using the Smartphone has been assessed by means of the Bland-Altman analysis [14]; several parameters are within the limits of agreement, including total duration of the TUG, duration of the sit to stand, cadence mean and standard deviation. For more details about the comparison between the two devices see [13]. After this study we see an evidence that in a near future Smartphones may incorporate suitable solutions for quantitative movement analysis with a clear clinical value, providing a pervasive and low-cost support to eHealth.

B. iTUG application design

Starting from the results of the previous comparison, we designed an iTUG application for Smartphone. The application is designed with an easier interface to increase its usability: the application interface only presents “Start” and “Stop” buttons on the touch-screen. When the start button is pressed the application starts to collect accelerometer data. At the end of the timed up and go test the Stop button have to be pressed to stop the data acquisition and to start the data processing. All the significant parameters and indexes describing the TUG (both in the anteroposterior and the mediolateral plane, when applicable) are calculated and stored in the SD-card (i.e. total duration, sit to stand duration, RMS Acc. Sit to Stand, Max Acc. Stand to Sit, Gait Duration, Mean Cadence, Cadence Standard Deviation, Cadence Coefficient of Variation, etc.).

Also in this case the application has been designed assuming that the user wears the Smartphone on a waist belt.

As an option, there is the possibility to setup the number of iTUG repetitions: automatic algorithms may ask subjects to repeat the iTUG more than once if errors while performing the task are detected (e.g. stopping, not turning, etc.). Finally, the user profile (name, age, gender, additional information) can also be included in the final iTUG report.

After the test is over, raw accelerometer data and calculated parameters can be automatically uploaded by the application on a remote server to be analyzed by the clinician.

The iTUG application is in its early stage of development, we designed it and we are now porting the algorithms for data processing on the Smartphone. Till now the application only collects data and make them available for a Matlab routine processing. We have developed some basic functions for real-time data processing to test if the Smartphone is able to perform the parameters computation in a reasonable time. Our results show that the Smartphone can compute all the relevant parameters and store them in the SD-card in 5 to 10 seconds. Android is simplifying our work because it provides the Native Development Kit: with this kit it is possible to write the processing in C++ code by optimizing the application performance and reuse previously developed library.

V. CONCLUSIONS AND FUTURE WORKS

Falls in older persons have multiple causes. Risk factors can be intrinsic and extrinsic. A variety of methods and tools have been proposed for fall risk assessment, most of which have discriminated poorly between fallers and non fallers, and none of which is universally accepted. The needs to have a user-friendly device able to perform an ubiquitous sensing with a full connectivity (e.g. WiFi, 3G/4G, Bluetooth, etc.) make the sensor-equipped *Smartphones* a device able to revolutionize many sectors of our economy, including healthcare. We designed and tested a fall detection application to detect falls and start alarm procedure to reduce the effect of falls. Raw accelerometer data captured during the fall event (one minute before and one minute after) are stored to allow further analysis and new fall-related features to be extracted. Of course the sample size available in this study and its design make the proposed validation only preliminary. More subjects and more fall types (real falls ideally) need to be tested in order to fully validate and further improve the algorithm.We also designed a preliminary version of an application for the iTUG test with a low cost, accessible and usable Smartphone. As mentioned, future work, will be done to implement all the parameters computation for the iTUG test on the Smartphone to build an independent system able to collect data and perform the first level data processing. Finally, we think it is possible to implement several others mobility-oriented and fall-oriented applications on Smartphone device because of its widespread use in our daily life (according to the *Eurostat* Statistics, nearly 65% of people living in the Europe aged more than 65 owned or used a mobile phone in 2008) facilitating the increase of its usability, computational and sensing capabilities.

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