Smartphone-Based System for Sensorimotor Control Assessment, Monitoring, Improving and Training at Home

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Abstract. This article proposes an innovative Smartphone-based architecture designed to assess, monitor, improve and train sensorimotor abilities at home. This system comprises inertial sensors to measure orientations, calculation units to analyze sensorimotor control abilities, visual, auditory and somatosensory systems to provide biofeedback to the user, screen display and headphones to provide test and/or training exercises instructions, and wireless connection to transmit data. We present two mobile applications, namely “iBalance” and “iProprio”, to illustrate concrete realization of such architecture in the case of at-home autonomous assessment and rehabilitation programs for balance and proprioceptive abilities. Our findings suggest that the present architecture system, which does not involve dedicated and specialized equipment, but which is entirely embedded on a Smartphone, could be a suitable solution for Ambient Assisted Living technologies.

Keywords: Smartphone · Inertial Motion Unit · Biofeedback · Home-based solution

1 Introduction

Smartphones has become a widely used device in developed countries. Its evolutions and innovations over time have turned it into one of the most outstanding device for pervasive computing [1]. Indeed, there are more than a billion of Smartphones sold worldwide in 2013, and the shipments has increased with 20.3% in the third quarter of 2014 [2]. The sharp decline in prices of mobile equipment now allows the growth of emerging markets. Although mobile phones are becoming more and more affordable, they remain powerful tools composed of a processor, a graphics chip, an advanced connectivity, and an inertial motion unit (IMU) featured with 3D-accelerometer,

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magnetometer, and gyroscope as standard. Albeit first used for game and user interfaces, built-in sensors can also be used for healthcare and activity monitoring.

With these features, Smartphones are quickly becoming an interesting tool for scientific research applied to medicine and, even more interesting for physical activity monitoring. First, they are embedded with telephony and short message services (SMS), which offers valuable opportunities to improve health by providing regular care and informational support [3]. Then, strategies were widely explored for tracking health interventions, for involving the healthcare team, for leveraging social influence, for increasing the accessibility of health information, and for entertainments [4]. Furthermore, new Smartphone models are now emerging to improve traditional healthcare with new services like health social networks, consumer personalized medicine and quantified self-tracking [5]. Additionally, Smartphones can be directly used to detect and classify daily physical activities such as walking, jogging, sitting, standing, walking upstairs and walking downstairs [6]. However, monitoring these free-living physical activities requires precise measurements that are generally provided by dedicated and specialized inertial motion unit(s) or external device(s). These measurements can be processed and interpreted on system board or on a more advanced computational system, for example, when processing more consistent data and calculations such as the use of Discrete Wavelet Transform and SVM-based approach for the classifications of sporting activities [7]. The use and interpretation of sensor data depend on different parameters, such as the reliability of the sensor, its positioning on the body, the algorithm used for interpretation, and possible data fusion with signals from other sensors. A typical health example is fall detection and prevention. Fall detection and prevention system can be designed in three phases which are 1) sense, to measure physical quantities 2) analysis, to use algorithms which can take decisions and 3) communication, to spread the interpretation of the results [8]. To measure human activity, the accelerometer is certainly the most used sensor nowadays. An accurate and reliable fall detection system will rely on the quality of the accelerometer signal and its range of measurement [8].

Other health applications use Smartphone to measure human body orientations and movements to assess balance and gait control [9] or proprioceptive abilities [10]. These health applications aim to provide clear and precise range of motion. They mainly use fusion algorithms provided by manufacturers, which use a combination measurement of the three sensors; the accelerometer, the gyroscope and the magnetometer. These sensors are used for measuring range of motion, and are already validated in several studies with dedicated IMU systems [11]. It is important to mention that such Smartphone-based solutions are only used to sense human movements and do not offer biofeedback. However, and very interestingly, Smartphones do also contain additional standard technologies such as a screen display, an audio system or a somatosensory feedback system that allows interaction with the user of the device. In this context, this more and more affordable, popular and powerful tool could be advantageously used independently (and/or complementarily) by citizen or patients to perform self-measurements/assessments and to execute improve their sensorimotor, cognitive and functional abilities thanks to home-based training or rehabilitation programs.

The aim of this paper is to propose an innovative "all-inclusive" architecture, only based on the Smartphone, with the following three main components: (i) the sensory input unit, (ii) the processing unit, and (iii) the sensory output unit (allowing biofeedback provision). This Smartphone-based solution is designed to be used for the objective and automatic measurement and monitoring of body or body segments orientations and movements with training / rehabilitation exercises using sensory biofeedback, performed in complete autonomy at home with the only usage of the Smartphone.

The remaining structure of this paper is as follows. Section 2 describes related previous works, since the arrival of IMU to Smartphone use, with their advantages and inconveniences. Section 3 presents the architecture and applications that could be used on Smartphone or wearable devices for motor control assessment, monitoring, improving and training at home. Conclusion and perspectives are finally drawn in Section 4.

2 Related Works

2.1 Dedicated Devices

Whether due to aging, accident, injury or trauma, loss of joint mobility can cause the increase of disability in daily life. There are already devices and methods supposed to help a user recover a body function at home. For example, Philips Research has developed solutions to increase the efficiency and effectiveness of rehabilitation with the Stroke Rehabilitation Exerciser [12]. Physiotherapist could prescribe neurological motor exercises with this device that can be done unaccompanied at home. Stroke patients are equipped with a motion sensor system that includes inertial sensors in a small matchbox. Each body segment could be tracked by this way during exercises. Feedback to the user is provided by a dedicated user interface on a computer. The screen provides instructions to put sensors, there are videos to explain exercises and, finally, feedback during exercises is provided by a 3D animated figure that mimics patient movements.

Another example is the MyHeart's Neurological Rehabilitation Concept [13] which proposes motion recognition based on strain sensors placed directly on the clothes. A motor therapy module, which is a touch-screen workstation, provides real-time feedback on the progress and accuracy of movements performed. This workstation is specifically made to provide real-time feedback to all patients, including wheelchair, blind or cognitive impaired users. It has speech recognition and touch screen to allow interaction from the user. Feedback provided by the screen is intended to avoid distraction for cognitive impaired users, it just contains a bar, and metaphor pedestrian lights to indicate exercises time and a simplified smiling (or frowning) face. During the test, a therapist is present to monitor the training session.

Taken together, the above-mentioned systems have provided proof-of-concept that home rehabilitation using sensors and feedback can be realized. The actual lack of those systems is that the installation of the devices is still laborious. In addition, they use dedicated equipment that can clutter the patient's home. This complexity of use of the system can prevent the patient to use the system. Moreover, users are generally not familiar with such specialized systems.

A more recent example is the Valedo system builds by Hocoma AG [14]. It is presented as a medical back therapy device with two motion devices. Each sensor is composed with a 3D gyroscope, a 3D accelerometer, a 3D magnetometer and Bluetooth connectivity. Motion devices should be placed in the lower back, at the level of L5 vertebra, and on the chest, at the high level of the sternum. Then, Valedo provides 45 therapeutic exercises including a set of 17 movements. Exercises and real-time feedback are provided by a tablet. However, this system is also too expensive to purchase for patients themselves, because they have to buy the dedicated system with its sensors network and a tablet or a Smartphone. Moreover, its exercises interface is not specifically adapted for elderly or people with disabilities.

2.2 Smartphone-Based Solution

Assessing body or body segment orientation and movement for postural and gait control or for joint goniometry could be done with the use of Smartphone. Due to the motion sensors (9D IMU), and the autonomous computation units, Smartphones can evaluate and measure angles, in quaternion or Euler space. Clinometer is one of these general applications that were used in clinical studies. It has been validated on healthy and traumatic populations for measuring shoulder and cervical ranges of motion [15-16]. The Angle application can calculate angles, using accelerometers, with respect to gravity, for all planes. It has been used in two surgery studies in which its reproducibility was evaluated against navigation surgery systems [17]. Even standard compass applications, provided by Smartphone manufacturer, were used for cervical range of motion [18]. Other applications such as Simple Goniometer [19] or Knee Goniometer [20] mimics goniometer to measure joint angulations during static range of motion. They were specifically designed for medical use and their validations were made compared to a standard goniometer. Scoligauge [21] or Hallux Valgus App [22] were specifically developed for, respectively, measure trunk angle while patient is performing the Adams forward bend test and measure hallux valgus angle. The only app validated for angle measurement with the Smartphone camera is DrGoniometer [23-24], applied to elbow and knee joint angle measurements.

In their recent review, Milani et al. describe all mobile Smartphone applications for body position measurement in rehabilitation [25]. Twelve mobile applications are presented, including those employing inertial sensors and/or camera to produce angle measurement. However, their conclusion underlines that these tools are validated for the moment within the framework of static protocol: "*A need exists, however, for validation studies on available or new apps focused on goniometric measurement in dynamic conditions, such as during gait or during performance of therapeutic exercises*" [Milani et al., 2014, page 1042].

Unlike the tools presented in the previous section, actual Smartphone application used for measuring joint angles simply imitates existing tools. Their use has been validated in the scientific and medical fields but only by the direct use of professionals in those fields, not by end users. Moreover, feedback was only provided to physiotherapist or clinicians and not to the patients themselves, preventing them from self training. In this context, the following section proposes an innovative architecture to build an all-in-one affordable tool for measurement of body and/or body segments orientations and movement, analysis, storage, and improvement thanks to biofeedback-based training and/or rehabilitation exercises designed to be performed in complete autonomy at home.

3 Rehabilitation at Home, an Actual Ideal Smartphone-Based Architecture

3.1 General Architecture

In order to keep all advantages from previous described solutions and without inconveniences, the present paper aims to describe an actual ideal architecture to objectively and automatically measure body and/or body segment's orientation and position and proposed adaptive training and/rehabilitation biofeedback-based exercises at home. The Smartphone application implements methods specifically developed for motor control assessment, monitoring, improving and training at home [26].

The principle of functioning of our Smartphone-based solution can be composed of the 6 following steps, illustrated in figure 1.

1. Measurement and processing to detect the current movement (or posture) achieved by the user,
2. Comparison of current movement (or position respectively) to a theoretical motion (respectively to a theoretical position),
3. Biological feedback that could allow the user to correct its current movement (respectively its current posture) so that it (respectively) to better match the theoretical movement (to the theoretical position, respectively),
4. Performing automatic or non-automatic update of a level of difficulty of the exercise or of the set of exercises.
5. Calculation of an index based on the result of this comparison, and store it,
6. Possible transmission of this index to a third party to enable it to monitor the user's performance.

Interestingly, following this architecture, Smartphone application is not only used for sensorimotor assessment and monitoring, but also for its improvement and training by the means of the provision of sensory biofeedback and the implementation of adapted training and/or rehabilitation exercises. This allows the patients to practice exercises at home without the help of any physiotherapists, medical doctor or trainer. The nature and the level of difficulty of these training exercises can further be automatically managed by the device, via a real-time analysis of the results during the tests, or managed remotely by the therapist. Biofeedback may consist of the issuance of a type of sensory stimuli (e.g., visual, auditory, tactile) and may vary depending on the sensitivity, capacity and / or user preferences accordingly. Different combinations of sensory outputs could be proposed. Likewise, the principle of the biofeedback provision can be either 'continuous' and/or 'intermittent'. For this last case, in for instance, the user receives real-time information about the difference (or error in direction and / or amplitude) between the current position of the joint and one that should be obtained in respect of the proposed exercise. In other words, in this case, if there is no error, there is no feedback. Two biological feedback variants, at least, could be proposed: 1) The attractive cuing, where user has to mobilize the joint in the direction of the feedback, and 2) the repulsive cuing, where the user has to mobilize the joint in the opposite direction of the feedback.

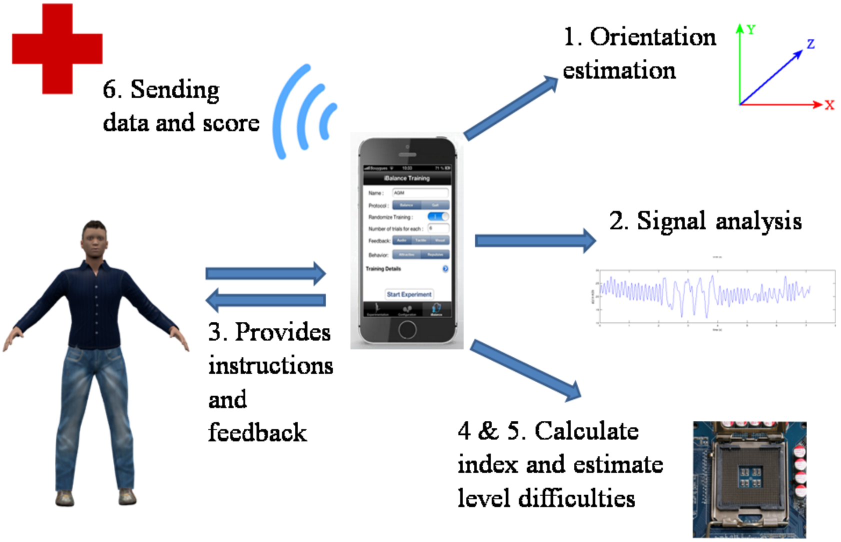


Fig. 1. Overall architecture of the Smartphone-based system

Ultimately, this application is intended to provide an all-in-one, gathering measurement functionality, analysis, storage, correction, feedback and adaptation. This device, by its communicative character, can be used to share information with a third party (e.g. a medical team) to check the results achieved for the exercises, and eventually adapt the sessions proposed to the user. Another feature of the solution resides in the secure transmission of the measured and analyzed data and their comparison to a database. Finally, the user interface must also take into account the user's profile and preferences in order to be easily usable (and effectively used!) by all.

3.2 Orientation Estimation

With the Smartphone built-in sensors, orientation measurement could be obtained from accelerometer, magnetometer and gyroscope 3D raw measurements. But none of these sensors bring noiseless information. In order to provide the most accurate angle estimation, orientation filters have to be used, such as the Kalman filter. Thus, the Earth gravitational and magnetic fields, respectively measured by accelerometer and magnetometer, will be merged with angular velocity from gyroscope to compute a single and complete estimate of orientation angles (Figure 2).

3.3 Use Cases

In this section, we will describe two Smartphone-based solutions developed with the goal to measure, assess, monitor, improve and train balance and proprioceptive abilities, called “iBalance” and “iProprio”, respectively (Figure 3). Each application can provide visual, auditory and/or tactile biofeedback. Thereafter “iBalance” is illustrated in the case of its auditory biofeedback version and “iProprio” in the case of its vibrotactile biofeedback version.

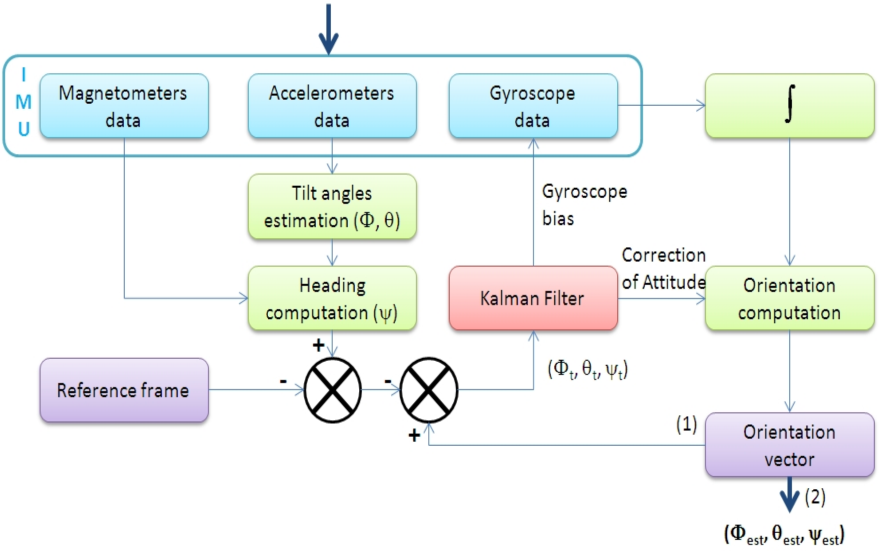
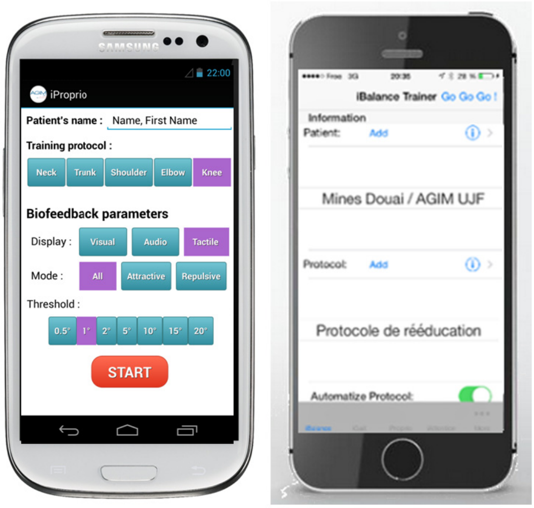


Fig. 2. Orientation estimation from the raw sensor measurement



Patient's name : Name, First Name
Training protocol :
Biofeedback parameters
Display :
Mode :
Threshold :

Information
Patient:
Mines Douai / AGIM UJF
Protocol:
Protocole de rééducation
Automatize Protocol:

Fig. 3. Screenshots of the iProprio (left) and iBalance (right) main screen

“iBalance” is a Smartphone application which monitors the trunk orientation and movement during different postural and locomotor tasks and helps the user to improve and train their balance capacities through the provision of adapted and adaptive exercises and a configurable visual, auditory and/ or tactile biofeedback [27-28]. The instructions can be automatically vocally supplied by the system. The Smartphone, placed at the level of L5 vertebra, records trunk orientations and movement. “iBalance” could provide multiple different combination of sensory feedback (e.g. tactile trough a number of vibrotactors placed on the used hips or shoulder, for instance , or auditory through a pair of earphones). This can be done continuously or in distinct situations, when user leaves the predetermined adjustable “dead zone” for example (Figure 4). The so-called “dead zone” can be set to 1° around the mean of the participant’s trunk position in the medio-lateral direction for instance. Note that the “iBalance” software was implemented to allow the algorithm of biofeedback generation and the “dead zone” size to be easily and quickly modified according to the specific use of the ”iBalance” system (e.g., user’s balance ability, needs, and preferences). For instance, in the case of the generation of auditory biofeedback, when the user goes out of this “dead zone”, the “iBalance” system provides a sound either to the left or the right earphone depending on whether the actual trunk orientation was exceeding the “dead zone” in either the left or right direction, respectively. A first proof-of-concept study recently has been conducted on young [27] and older [28] healthy populations. Results suggest that the “iBalance” application allows users to significantly decrease trunk sway (that is, to improve balance control) during standing exercises with real-time auditory biofeedback. Authors encourage more research to be done to confirm these data and to promote the use of this application for balance training and rehabilitation in targeted populations with impaired-balance capacities.

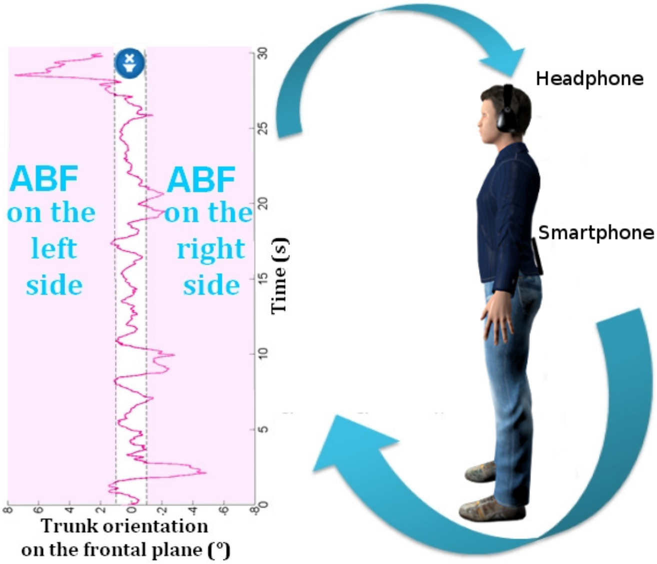


Fig. 4. iBalance principle of functioning which consists of (1) the measurements of trunk orientations and movements and (2) the provision of auditory biofeedback to the user during home rehabilitation exercises

"iProprio" is a Smartphone application developed to measure, monitor, improve and train proprioceptive function of different joints. This application uses inertial sensors included in a Smartphone to allow joint position sense measurement in an autonomous way and to provide a configurable visual, auditory and/or tactile biofeedback, with cheap external wireless devices for end-users at home (Figure 5). The instructions can be automatically vocally supplied by the system. For instance, in the case of knee joint proprioception management, the Smartphone is disposed distally of the tibia. Biofeedback is provided in the same way as described in Section 3.1: attractive cuing and/or repulsive cuing are provided when user leaves (or enters) the predetermined adjustable "dead zone". In the case of knee proprioception measurement and improvement, exercises used to assess knee joint position sense come from a standardized protocol named "active ipsilateral matching". This is commonly used and accepted in clinical routine [29-30]. Vocal instructions are provided by the Smartphone itself always with the aim of making the exercises in an autonomous way. It uses the same architecture as "iBalance" and the same assessment of its efficiency in improving knee joint position sense in young and older adults is in progress.

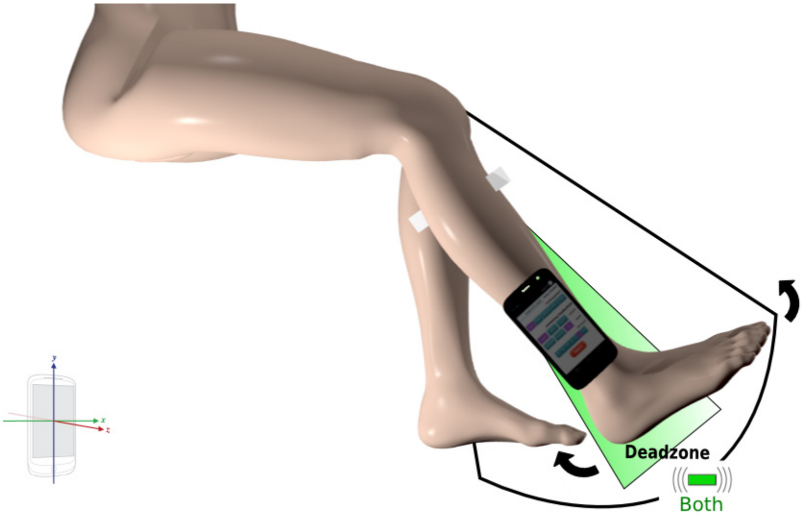


Fig. 5. Overall scheme of the iProprio solution (vibrotactile version)

4 Conclusion

This article proposes an innovative architecture designed to assess, monitor, improve and train motor control by means of exercises program using a sensory biofeedback system to perform at-home autonomous assessment and rehabilitation with an all-in-one tool: the Smartphone. Our solution keeps the advantages from previous proposed solutions, such as precise measurement of orientation with integrated 3D accelerometer, magnetometer and gyroscope and an adequate fusion algorithm.

Interestingly, this solution goes further than the current tools, which are only dedicated to angle and posture measurement, by further supplying biofeedback for rehabilitation purposes in an autonomous way. Smartphones have become a daily-used tool and are much more affordable and portable than dedicated devices. Presented use-cases, “iBalance” and “iProprio”, illustrate the use of this architecture and the first results in the context of rehabilitation exercises and programs that are commonly used. In order to confirm the described architecture, clinical studies have to be performed with patients with balance and/or proprioceptive impairment, for other joints, other postural tasks and with others types of sensory biofeedback. Along these lines, “iBalance” and “iProprio” solutions are currently evaluated with targeted population in terms of effectiveness, efficiency, satisfaction, usability and acceptance with a specific designed model called TEMSED for “Technology, Ergonomics, Medicine, Society, Economics, Deontology” [31].

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