Simplifying Tele-rehabilitation Devices for Their Practical Use in Non-clinical Environments*

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Abstract. The lack of success of tele-monitoring systems in non-clinical environments is mainly due to the difficulty experienced by common users to deal with them. In particular, for achieving a correct operation, the user is required to take care of a number of annoying details, such as wearing them correctly, putting them in operation, using them in a proper way, and transferring the acquired data to the medical center. In spite of the many technological advances concerning miniaturization, energy consumption reduction, and the availability of mobile devices, many things are still missing to make these technologies simple enough to be really usable by a broad population, and in particular by elderly people. To bridge this gap between users and devices, a smart software layer could automatically manage configuration, calibration, and data transfer without requiring the intervention of a formal caregiver. This paper describes the key features that should be implemented to simplify the needed initial calibration phase of sensing systems and to support the patient with a multimodal feedback throughout the execution of the exercises. A simple mobile application is also presented as a demonstrator of the advantages of the proposed solution.

Keywords: eHealth, patient-centric, sensors, monitoring, bio-feedback.

1 Introduction

The average age of the population is increasing and so is the need for rehabilitation and motor therapy sessions. This increment of prospective patients together with the problem of the decreasing availability of public money for the healthcare sector, is likely to turn into a degradation of the quality of care to the whole population. A tendency of the last years is to enhance the usage of self-care procedures, such as motor therapy sessions and rehabilitation exercises performed outside of "formal" healthcare structures. To monitor the correct execution of the intended exercises, and provide valuable self-correction information, scientists are proposing a broad range of technologies, wearable and not, that promise

* This work has been partially suported by Telecom Italia under the grant agreement POR CRO FSE 20072013, SISTAG, no. 16.

F. Ortuño and I. Rojas (Eds.): IWBBIO 2015, Part II, LNCS 9044, pp. 479–490, 2015.

to be usable in such contexts. Moreover, the cross- contamination among heterogeneous areas, like psychology, medicine, arts and technology is giving birth to new approaches and methodologies, which can be combined to build systems that are more effective in stimulating people's regarding the rehabilitation activities.

In particular e-Health and tele-rehabilitation, represent clear efforts aimed at offloading hospitals and clinics from time consuming and costly services. In fact, several operations related to rehabilitation can be carried out independently by the patient at home or followed by an *informal caregiver*. By informal caregiver we mean a relative or someone paid to assist the patient, who has no specific knowledge on rehabilitation. However, a series of issues arise if patients have to carry out rehabilitation exercises outside hospitals, as no specialized personnel is observing and supporting them directly how to:

- how to *monitor* the exercise execution?
- how to provide a valuable *feedback* to the patient?
- how to *inform the patient / informal caregiver* about the execution performance?

Considering specific tele-rehabilitation sessions, focusing on motor tasks, we propose the adoption of a set of wearable sensors coupled with an application running on a smartphone to directly help the patient or the informal caregiver. In this work, we do not focus on the communication between the system and the physician therapist but rather on the patient side infrastructure.

The rest of the paper is organized as follows: Section 2 describes the components of a wearable tele-rehabilitation system; Section 3 the system requirements; Section 4 presents the proposed system; finally, Section 5 concludes the paper and discusses some future perspectives.

2 Wearable Tele-Rehabilitation System Components

In this paper we refer to tele-rehabilitation systems for patients that have to recover from injuries or rehabilitate after some kind of orthopedic surgery. These systems are generally composed of three main components as schematically shown in Figure 1: (i) a set of wearable sensors, (ii) a system to process sensor data in real-time, integrate the data, present information to the patient, and communicate with the remote physician, and (iii) an interface for the physician to overview the rehabilitation work of the patients.

The wearable sensor nodes, whose number depends on the number of joints that need to be monitored, send data to a central mobile unit that performs sensory integration reconstructing the posture of the monitored limbs and possibly recognizes the performed actions. The central unit can be a mobile system that runs an application under the Android operating system. The mobile application processes the data and provides indications and feedback to the user. This work focuses on the system in charge of monitoring the patient activity, and on providing a guide and feedback for the execution of rehabilitation sessions, while a discussion of other components of the system can be found in [5].

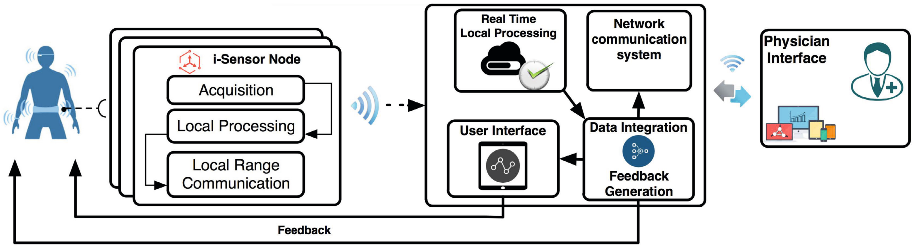


Fig. 1. The tele-rehabilitation reference model

A wide range of wearable devices has been developed for rehabilitation purposes in the last years [12,14]. The introduction of the MEMS (Micro-Electro-Mechanical Systems) enabled the development of motion sensors, like accelerometers, gyroscopes, and magnetometers. These sensors can be combined to create an Inertial Measurement Unit (IMU), that allows the acquisition of the body dynamics without external hardware to instrument the environment [13]. However, these devices suffer from non-negligible measurement errors, that give rise to a drift in the reconstructed signals.

Another possibility is to use vision-based systems [4]. For instance the Vicon [22] uses data captured from a set of cameras to compute 3D positions with a high precision. However they are quite expensive and require to instrument the scene and have a line of sight. On the other hand, low-cost solutions like the Microsoft Kinect [7], are more inaccurate. Another solution is represented by the use of exoskeletons, which are rigid structures mounted on the body where the interconnections are monitored with potentiometers or encoders to monitor the patients joint. These systems provide high precision, but are expensive and intrusive.

The following section briefly analyzes the requirements for the patient-side technological components of the tele-rehabilitation system.

3 System Requirements

When dealing with people that are not specialized in handling technology, devices, interfaces, and procedures have to be designed in such a way that they are unobtrusive, easy to use, and robust. In the next sections we briefly overview the requirements of the patient-side components of the system: the monitoring subsystem, the user interface, and the system for handling exceptions.

3.1 Monitoring Subsystem

Monitoring movements and actions is the primary task that needs to be executed in order to acquire information about how patients are executing motor tasks. This acquisition can be performed using a broad range of devices and technologies. However, data gathered through any kind of equipment needs to be sufficiently precise to enable analysis and to understand whether movements have been performed correctly.

Continuous Monitoring. Several health problems can only be detected by sporadic events that cannot be predicted in advance. For this reason some patients are required to be monitored continuously for 24 or 48 hours. The monitoring is a process composed of several phases and processes: gathering data through sensors, cross-checking the information, data analysis, data storage, and results notice to caregiver [3]. Such processes have to be continuous to provide relevant information about all actions performed by the patient and his/hers psycho-physical status.

Fixation. The setup procedure before the exercise must be simple and able to handle the issues related to the correct placement of sensor nodes. This is crucial to produce meaningful and accurate data for the analysis. The *fixation* of the sensors on the body should be easy to handle even for people with significant loss of functions [10]. The sensors need to be attached to each limb that needs to be monitored, and if interested in monitoring a single joint two sensors are needed, one for each segment starting from the joint. The user interface should guide the patient in such a delicate phase.

Accuracy and Precision. When monitoring limb positions and movements, there are crucial aspects to guarantee valid and useful measurements. For example, in knee tele-rehabilitation applications, the flexion/extension angle must be typically monitored with a precision of 1 degree [9].

Self Calibration and Auto-orientation. If the users operate in a non-controlled environment, it becomes impossible to exactly know in advance whether sensors are worn on the intended limbs. This problem can be solved by assessing the orientation of the sensors with respect to the limbs. Another issue is related to the nature of the used inertial sensors, accelerometers and gyroscopes, which suffer from errors in motion estimation because of measurement noise and fluctuation of offsets, thus requiring a specific *calibration* phase, that should be implemented in an automatic and easy way.

Real-Time Acquisition and Processing. Data acquisition and processing have to be managed by proper real-time kernels, since sensory data must be analyzed as they are produced to enable a prompt feedback generation for the user. A time synchronization is also needed among multiple nodes to know the precise time at which each sample is acquired. In fact, small time differences between samples affect the error in the sensor data integration phase.

Wearability and Comfort. Since the patient must carry several sensor nodes for long periods and during physical activities, the comfort becomes an important design consideration to provide the highest degree of convenience. This requires the development of unobtrusive devices with a small form factor. However, the node size is limited by the battery dimension because the node must have enough autonomy needed to perform the whole rehabilitation exercise without recharge. Also the weight is important because it can modify how the patient performs the exercise thus distorting the information.

Wireless Communication. Wireless communication technology is essential in these types of systems to avoid the encumbrance of wires and leave the user free to move during the execution of exercises.

Local Storage on the Node. is needed to save data in the case of temporary loss of connection in the wireless communication channel.

Energy. Energy consumption is a crucial problem in wireless devices, especially when they are required to be used for several hours (or days) for a continuous monitoring activity. Several solutions can be adopted to reduce energy consumption, as lowering the acquisition rates or turning off specific devices when they are not used. Also, a wireless recharge capability of the nodes is highly desired to simplify the task to non expert users.

Cost. The costs of the monitoring system becomes crucial in the cases in which this technology is adopted in a large scale. The current technology allows reducing the cost by an order of magnitude with respect to some commercial devices available today on the market.

3.2 Interaction Between System and User

The interaction between the system and the user needs to be accurately designed and implemented. In particular the feedback generation and the user interface are crucial, and will be analyzed next.

Feedback Generation for the User. Feedback can be broadly classified into different categories [19], depending on the *modality* and the *point in time* at which is provided. Concerning the modality, it can be *unimodal* (e.g., visual, auditory, haptic) or *multimodal* (a different combination of unimodal feedback). Concerning the time dimension, feedback can be *anticipatory*, if generated to help the user in predicting the correct time at which an action has to be performed (as in the case of a metronome); *contemporary*, if generated to provide a real-time representation or evaluation of the performance of the currently executed action; *posterior*, if generated after the task execution to provide a final evaluation of the exercise performance.

Visual feedback can be provided in the form of a virtual mirror [16], on which a 3D avatar represents a virtual image of the patient performing the same actions reconstructed by sensors; the avatar can also be coupled with a "ghost" avatar, acting as a guideline for the motion that needs to be performed. Rodger et al. [15] use a *auditive* feedback to produce walking sounds to help alleviating gait disturbances in Parkinson's disease. Sound was also used in other contexts to provide a feedback for different motor activities, e.g., to guide swimmers in increasing the degree of symmetry [6] or enhance a rehabilitation system [20]. *Haptic* feedback, in particular in the form of vibrotactile feedback, was used to help users in executing different locomotor performance tasks [18]. *Multimodal* feedback, namely the combination of the aforementioned three methods is thoroughly discussed in [19]. Motor-task learning and motor rehabilitation require different kinds of feedback: in learning, emphasis needs to be put on how the movement has to be performed, whilst in rehabilitation the feedback should provide information about erroneous performance, thus preventing wrong movements and motivating the process of rehabilitation [23].

Providing a feedback during the execution of exercises is important not only to guide the motion and provide immediate information about possible errors, but also to motivate the patient in a given direction of motion.

Easy Interface. Guiding the patient or the informal caregiver is essential if no formal caregiver is present during the rehabilitation session. In this case, to attain clinically relevant improvements [8] the system must be designed to provide a continuous guide for the patient through a graphical user interface. Before each exercise detailed illustrative instructions can help the patient in understanding how it has to be executed, while during the execution, visual and auditive cues can notify the user about possible errors, reached "check points", and progress state of the exercise. Taking into account that during the execution of the exercises sensor nodes are associated with mobile devices (tablets or smartphones), any type of information can be conveniently displayed on the mobile devices' screen. In fact, translating raw data from sensors to visual or auditory information allow to have "messages" that are immediately understood by the user. Once the exercise's execution is complete, the system should provide a short summary on the user performance, to allow him/her to understand the progress made in the rehabilitation process.

3.3 Handling of Errors and Unforeseen Conditions

To simplify the interaction with non expert users, the system should be able to detect at least two anomalous conditions that can derive from an incorrect usage of the system or from the malfunctioning of the system's devices:

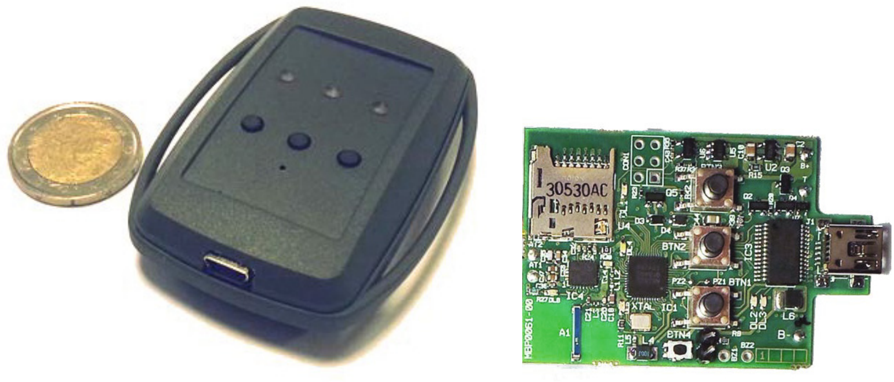
- **Sensor misplacement detection and support**. The system should automatically detect whether the user is wearing the sensors correctly and, in the case or placement or orientation errors, provide indications on how to solve the problem.
- **Automatic detection of malfunctioning of devices**. The system should be able to detect a set of problems related to the wearable devices, such as low energy in the battery, values out of range, missing data, connection errors, etc. Once the problem is detected, the system should support the user to solve it, suggesting for instance to recharge the battery, or contact the help service for technical assistance.

4 Proposed System

The monitoring system described in this paper has been designed taking into account the main concepts and requirements described above. The system is composed of a set of wireless sensor nodes, a mobile application, which incorporates a graphic interface, an auditive feedback, auto-calibration functions for the sensors, and a communication module to send data to a remote server. These components are described below.

4.1 Sensor Nodes

The sensor nodes employed in the system use an inertial measurement unit (IMU) incorporating three accelerometers, three gyroscopes, and three magnetometers [2]. These signals are directly integrated onboard to provide an accurate estimation of the sensor orientation. The device has a very low-power consumption guaranteeing a continuous acquisition operation for at least 3 days at full sampling rate. It also provides a good balance between lifetime, dimensions ($4 * 3 * 0.8$ cm) and weight (30 g). The node and its internal circuitry are shown in Figures 2(a) and 2(b).



(a) Closed node (b) Node's interior

Fig. 2. Sensor node

The nodes can be easily mounted on limbs using elastic bands, taking into consideration that a good node attachment technique increases the overall accuracy of measurements. Furthermore, the sensor nodes are characterized by an overall easy setup and handling, as they are equipped with a wireless recharging circuitry, an easy to calibrate IMU, and a Bluetooth 4.0 radio, that enables them to seamlessly work with modern Android devices. Figure 3 shows the block diagram of the node internal architecture, composed of an ARM-Cortex M0 processing unit, a Bluetooth 4.0 transceiver, an SD card slot for local storage, a 9-axis

IMU, a power manager with battery charge regulator, a Li-Po battery, and two chargers: one USB and one wireless.

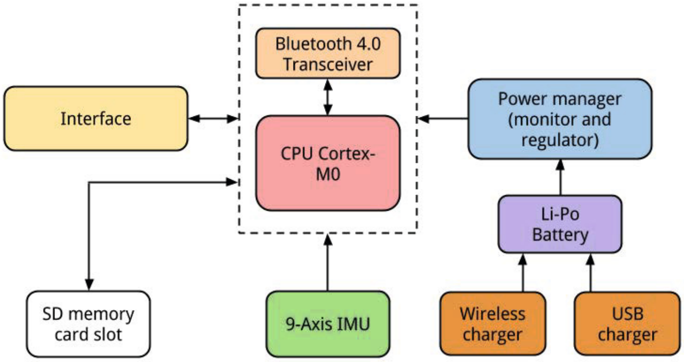


Fig. 3. The sensor node's block diagram.**TBD**

4.2 The Application Running on the Mobile Device

The mobile app running on the Android-based device incorporates a visual interface, an auditive feedback generation module, an auto-calibration unit, and a sensor data integration module. Data arrive to the application through the Bluetooth connection that is automatically established when the application is activated.

Auto-calibration Unit. The auto-calibration unit includes a set of functions, some of which have already been developed, while others are still under development. In particular, "fixed errors" are corrected performing a static calibration procedure of the nodes before being handed by patients, while "random errors", related to electrical noise or thermal drift are managed following the procedure illustrated by Gietzalt et al. [11], and should be further investigated to enable a sensor node to automatically compute the offset and adjust his calibration algorithm. Calibration techniques are paramount for the accuracy of measured data, especially in dynamic conditions. Designing hardware and software auto-calibration techniques is still an open research area. Once the data from each sensor is accurately processed and filtered, it can be integrated into a kinematic model of the body and used to reconstruct the parameters that are relevant for the rehabilitation process.

Processing. The processing activities running on the mobile device are in charge of integrating the various sensory data coming from the sensors, to reconstruct the posture of the monitored limbs, analyzing the reconstructed signals for detecting critical conditions, and evaluating the performance of the actions to generate an instructive feedback for the user. Such an evaluation is done by comparing the actual trajectory with a reference trajectory acquired in the presence of a physician (or physiotherapist), using techniques as Dynamic Time Warping [1] to derive the error signal for the feedback generation module.

The Visual Interface. The visual interface is developed to guide the patients in the execution of the exercises and is depicted in Figure 4. It includes a 3D Avatar (acting as a virtual mirror) and a simple 2D display for a more quantitative signal representation. The 3D Avatar replicates the movements executed by the patient or a set of prerecorded motions to act as a guideline for the what needs to be done. The 2D representation indicates the current angular value of a joint and a target position.

The Auditive Feedback. is embedded into the mobile application and reproduced either over loudspeakers or user worn earphones. Audio is produced by a module based on the PureData library for Android (libpd). The sound provides information about the difference between the target position and the current patient position, underlining and reinforcing the visual information form the simple 2D representation described before.

Communication Module. The communication module exploits the capabilities of the smart-phone to transfer all data about exercise execution to the physician or the official caregiver, according to a more general framework presented in [5].

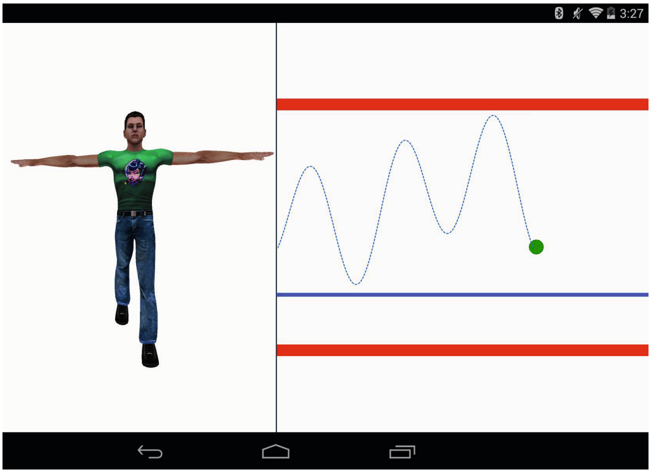


Fig. 4. The mobile application interface

4.3 The Complete System Usage

The proposed rehabilitation cycle that exploits the sensor nodes and the mobile phone is schematically represented in Figure 5. The user is required to wear the sensors, the system setups itself and then the exercise can begin, either carried out independently or with the help of a caregiver that follows instructions provided by the application. At the end of each exercise a quick report, acting as a post-execution, final effect feedback, is generated and provided to the patient and/or the informal caregiver.

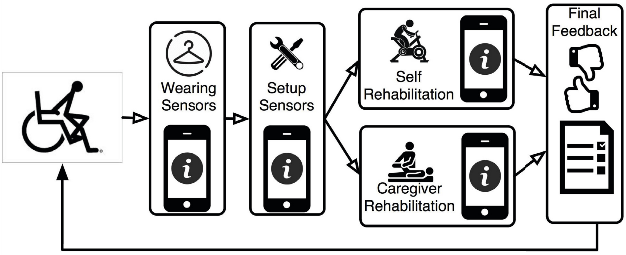


Fig. 5. The proposed rehabilitation cycle

5 Conclusions

This paper presented a mobile wearable monitoring system that can be effectively used during tele-rehabilitation sessions to monitor and evaluate the performance of motor exercises. The system has been designed and implemented according to a set of requirements aimed at simplifying the procedures and helping patients that are not familiar with technology.

Some features include a specific help to select the exercise, measure its execution performance, detect and notify sensor misplacements, and provide a valuable multimodal feedback that, at present, consists of visual and auditive stimuli.

In the future, to further reduce the impact of technology, we aim at incorporating energy-harvesting devices into the sensor nodes to prolong their lifetime and possibly avoid explicit battery recharge cycles. Other issues considered for a future research concern the following problems: (i) reducing the number of wearable sensors with respect to the number of interesting limb segments, by integrating a kinematic model of the body in the posture reconstruction algorithm; (ii) automatic detection of the limb where each sensor is mounted on, following the approach described in [21]; (iii) exploiting kinematic constraints of the human limbs to automatically estimate joints' axes and positions from inertial measurement data, following the approach [17] by T. Seel et al.

We wish to conclude the paper remembering that psychological aspects are of primary importance in a rehabilitation process. In fact, patients are often affected by post event depression and need to be motivated and encouraged to adhere to long term medical therapies. Rehabilitation exercises are usually considered boring for patients because of their repetitive nature. An interesting solution could be to present an exercise as a form of game, incorporating both pedagogical and entertainment elements, with increasingly difficult levels to make the patient feel the challenge and increase its involvement in the rehabilitation process.

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