SensorShoe: Mobile Gait Analysis for Parkinson's Disease Patients

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Abstract We present the design and initial evaluation of a mobile gait analysis system, SensorShoe. The target user group is represented by Parkinson's Disease patients, which need continuous assistance with the physical therapy in their home environment. SensorShoe analyses the gait by using a low-power sensor node equipped with movement sensors. In addition, SensorShoe gives real-time feedback and therapy assistance to the patient, and provides the caregivers an effective remote monitoring and control tool.

Keywords Sensorshoe · ubiquitous computing · parkinson's disease · user interface design

1 Introduction

In recent years, the advances in ubiquitous computing and wireless sensor technology proved to have a significant impact in wellness and healthcare. In this paper, we propose a mobile gait analysis and real-time feedback system (SensorShoe), for assisting Parkinson's Disease (PD) patients in their everyday life.

PD is a degenerative disorder of the central nervous system and affects nearly one million people only in the USA [11]. PD dramatically affects movement abilities and causes tremors, stiffness of muscles, walking problems and instability [11]. Physical therapy is an important part of the treatment, as it maintains the strength and mobility of the muscles. However, the physical therapy needs to be adapted to the situation of the patient and according to his/her progress. One solution is the clinical gait analysis (i.e. the analysis of the walking pattern) in a motion laboratory, where the movement properties of the patients can be observed in detail by the physical therapists. Through gait analysis, the medical specialists can determine whether or not the motor abilities improved, and adapt the therapy program accordingly. While the laboratory setups provide highly accurate results, they require complex and cumbersome equipment, and cannot give an overview of the progress over a continuous timeframe. We see therefore a strong motivation for a mobile gait analysis and feedback system for home use, which is beneficial both for the patient and the caregiver. This implies the design of a compact system able to perform the analysis in real-time, in order to give the patients corrective feedback. The main objectives are therefore as follows:

1. To provide the PD patients a non-intrusive and non-stigmatizing mobile device that extracts the gait characteristics.
2. To provide the PD patients an easy to use interfacing and feedback system that can help them to improve their daily life.
3. To provide the caregivers an effective remote monitoring and control tool, through which they investigate the success of the physical therapy and adapt it with minimal effort.

In this work, we focus on the first two points of the above mentioned objectives, more specifically the interaction of the patient with the system.

We first propose a solution for the mobile gait analysis device that benefits from the latest advances in MEMS sensor technology and Wireless Sensor Networks. The device is a sensor node capable to sense the movement through accelerometers and gyroscopes, and to extract the gait parameters in real-time. The advantages of this technology include the small dimensions of the device, the low-power operation and the wireless communication capabilities. Second, we focus on the concept design and the interactions between the PD patient and the system.

For this purpose, we use mobile devices such as PDAs or Smartphones because they are widely available and can implement multiple functions, such as graphical user interface, advanced processing for an extensive movement analysis, long-distance connection with the caregiver.

As a general approach, we split the design in three phases (detailed in the following sections):

1. Concept Development, where we gather the ideas for the product, based on user characteristics, scenario and the derived requirements.
2. System Architecture, in which we describe the main functional modules of the system.
3. **Detailed Design and Evaluation**, where we specify all the interactions between the system modules and evaluate the designed concept according to a series of guidelines.

2 **Related Work**

Gait analysis is used as an objective and quantitative method to record the effectiveness of physical therapy. The analysis typically follows three types of parameters: the temporal (e.g. cadence and velocity.), kinetic (e.g. ground forces) and kinematic (e.g. linear and angular displacements) aspects of the gait [3]. Morris [7] showed the feasibility of a multi sensor-based device that can measure these parameters. The device was embedded in the shoe of the patient and connected wirelessly to a computer for processing and examining the data. One important result of this study was that inertial movement sensors (accelerometers and gyroscopes) can be used for an effective gait analysis. Consequently, for our prototype we are using a low-power, low-cost inertial measurement unit (IMU) with five degrees of freedom (see Sec. 4).

Based on the movement analysis, feedback cues help patients with improving their gait [4, 8]. For example, Lewis [5] found that the stride length of PD patients can be increased by using visual cues perpendicular to the walking path. Likewise, audio [7] and tactile [10] (or somatosensory) feedback can be used with nearly similar effectiveness compared to visual cues. For a discussion concerning several design alternatives of feedback, see Sec. 4.

3 **Concept Development**

The concept development phase starts by defining the target user groups and their characteristics. In our case, there are two user groups: the PD patients (mostly elderly people with limited motor abilities, decreasing sight and hearing due to aging, and little computer experience) and the caregivers (personnel with medical background, supervising a large number of patients, and with a reasonable experience in daily computer usage). As a second step, a scenario [3] including the two user groups is described. The scenario leads to the following set of functional requirements:

1. **Gait Analysis** - The main function is to measure and analyse the gait of a PD patient. The raw data consists of 3D acceleration and 2D gyroscopic information acquired from the sensor node. After a processing phase, the following parameters are derived: the walking speed, cadence, stride length and vertical displacement of the foot.

2. **Real-time Feedback** - While walking with SensorShoe, the user receives real time feedback on his gait, in order to improve the cadence and stride length, and also to prevent slipping or falling.

3. **Assistance with the Physical Therapy** - The system reminds the patient about the daily exercises and assists him during the physical therapy, by indicating the type and amount of movements to be done, and giving feedback about the correct execution of the exercises.

4. **Patient Feedback on the Physical Therapy** - It is important for the caregiver to know how the patient experiences the physical therapy. Based on the patient feedback, the caregiver can alter the exercises.

5. **Patient Progress** - The system connects to the healthcare centre and transmits the daily log with the exercises performed by the patient, so that the caregiver can estimate the progress through physical therapy.

6. **Remote Adjustment of the Physical Therapy** - Based on the daily observation received, the caregiver adapts the physical therapy and sends the new settings to the SensorShoe system.

In addition to the functional requirements, a list of usability requirements can also be derived from the scenario, for example:

1. Screen output should be readable for the PD patients.

2. Audio output should be receivable for the PD patients.

3. The prototype should be lightweight and rechargeable.

The complete list of usability requirements can be found in our technical report [3].

4 **System Architecture**

Based on the requirements from the previous section, we can define the system architecture, illustrated in Fig. 1. The system is divided in three main functional modules:

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Fig. 1 System architecture

Fig. 2 Sensor node with IMU
the sensor node, the interfacing (PDA) module and the feedback module.

Sensor Node - The main task of the sensor node integrated in the shoe is to measure the gait parameters by sampling the movement data. For our prototype, we are using the Ambient μNode 2.0 platform [1], which is a low-power, general purpose sensor node. We connect to the μNode a miniature IMU with five degrees of freedom, composed of a 3D accelerometer [2] and a 2D gyroscope [4] (see Fig. 2).

The typical power consumption of the IMU is 30mW, which allows for more than 100 hours of continuous operation on AA batteries. The total price of the prototype components (μNode and IMU) amounts to approximately 150 USD. Besides sampling the movement data, the μNode can filter and integrate them to obtain the required gait parameters (speed, stride length, etc.). These parameters are used to detect walking problems (e.g. the μNode detects a falling danger and signals it immediately to the feedback unit) and are transmitted wirelessly to the PDA module, which has the processing power to perform an extensive analysis (e.g. the PDA establishes that an exercise was not correctly executed).

PDA module - The PDA module is a major component, as it provides the user interface. We decide to use mobile devices, such as PDAs or SmartPhones, because they are widely available and relatively affordable. Furthermore, the PDA is able to communicate with other the sensor node and the feedback module, as well as with the remote caregivers. For our prototype we use the HP iPAQ hx2490, which has both Bluetooth and WiFi communication capabilities.

Feedback Module – An important usability requirement is that the patient can receive feedback in a non-intrusive and non-stigmatizing way. On the one hand, the visual feedback methods [5] do not fulfill this requirement, as they affects the entire environment of the patient. On the other hand, audio cues [8] through earphones are more discreet, but prevent the user from interacting with the environment. Therefore, we consider tactile feedback as an appropriate solution for our prototype (see Sec. 5 for more details on the tactile feedback module).

The detailed description of modules and interactions are specified in [3] as a data-flow diagram of the entire system.

5 Detailed Design

In this section, we describe two types of interactions; (1) between the user and the PDA and (2) between the user and the feedback module. We explicitly focus on the design and evaluation of the graphical user interface (GUI) on the PDA, as it provides a rich set of functions (both feedback and control of the SensorShoe).
GUI Concepts - The design of the 'look and feel' of the GUI starts by determining the required functionality of the interface. Based on the functional requirements, the patient should be able to:
1. Enable the real-time gait analysis
2. Start a physical therapy session
3. View the progress of the gait
4. Check the system status
These functions lead to a decision diagram, which define the structure of the GUI in terms of user options (see [3] for the decision diagram). Next, several GUI concepts with different layouts can be defined. In Fig. 3-7 we present a total of five GUI concepts, which all implement the functions previously listed.

GUI Evaluation - We perform a heuristic evaluation of the GUI concepts, following several guidelines for interface and interaction design [12]: GUI guidelines, website guidelines and disability guidelines. Some examples are:

- Buttons should be large so that users with physical and mobility disabilities can select them easily from the screen (Disability guideline).
- To identify primary windows, start by looking at the main task objects in the conceptual design (GUI guideline).
- Keep the language simple and avoid jargon (Website guideline).

The evaluation proceeds in two steps. Firstly, we indicated the guideline compliance, ranging from 0 points (does not conform to the guideline) to 2 points (fully conforms to the guideline). Secondly, we estimate the potential of improvement for the aspects that do not conform completely to the guidelines (also ranging from 0 to 2 points).

Fig. 6 shows the final score table of our heuristic evaluation (see [3] for detailed score tables and guidelines). The results indicate the GUI concept shown in Fig. 5 as the best candidate. This concept is further developed, as can be seen in the screenshots from Fig. 9-12.

Final GUI Design – The final GUI consists of a start screen containing access buttons for the four important functions: real-time gait analysis, physical therapy exercises, progress overview and system status.

1. The real-time gait support is provided by showing footsteps, and allowing the user to set parameters, such as the desired speed. The user can stop the visual or tactile feedback at any time, and resume afterwards (see fig. 9).

2. The physical therapy screen shows the user the exercises to be done according to the prescriptions of the caregiver. An animation of the exercise is shown as example (see fig. 10).

3. The progress overview screen allows the patient to check his/her evolution over a period of a week or month. The progress is objectively determined by the caregiver through the remote analysis function (see fig. 11).

4. The system status screen informs about the sensor node, battery and communication status. A simple self-test for the sensor and battery is also implemented (see fig. 12).

The functional prototype of this GUI concept can be used for further testing and evaluation, as proposed in Sec. 6.

Tactile Feedback – We analyse several possible technical implementations of tactile feedback, such as rhythmic taps, electronic pulses, vibration, movement on skin and pinching/squeezing.
Based on their specific advantages and drawbacks [3], we decide to use electromagnetic motors. One of the major advantages of electromagnetic motors consists of their small dimensions, which allow for simple integration into everyday, wearable objects, and therefore prevent any stigmatising effect of the SensorShoe. An evaluation of several such objects (e.g. glasses, clothing, caps, bracelets) shows that a bracelet is an appropriate choice for tactile feedback. A bracelet is small enough to be worn under clothes and can be designed for different users (for example male/female or old/young). Another important reason is that a bracelet is worn on a sensitive part of the skin and thus improves the quality of the feedback.

6 Conclusion and Future Work

This paper described the concept design and evaluation of a mobile gait analysis system. We started by selecting the target user groups (PD patients and caregivers) and defining the application scenario. This led to a set of requirements, based on which we developed a modular system composed of three main units: sensing, interfacing and feedback. Finally, we presented the detailed design and evaluation of the user interface. The future work follows two directions. First, we are experimenting with computing accurately the gait parameters from sensor data and discriminating reliably between different types of movement. Second, we plan to conduct a comprehensive usability test that will indicate the level of understanding and acceptance of the system.

References