A Secured Smartphone-Based Architecture for Prolonged Monitoring of Neurological Gait

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Abstract. Gait monitoring is one of the most demanding areas in the rapidly growing mobile health field. We developed a smartphone-based architecture (called "NeuroSENS") to improve patient-clinician interaction and to promote the prolonged monitoring of neurological gait by the patients themselves. A particular attention was paid to the security and privacy issues in patient's data transfer, that are assured at three levels in an in-depth defense strategy (data storage, mobile and web apps and data transmission). Although of very wide application, our architecture offers a first application to detect intermittent claudication and gait asymmetry by estimating duty cycle and ratio between odd and even peaks of autocorrelation from vertical accelerometer signal and rotation of the trunk by the fusion of accelerometer, gyroscope and magnetometer signals in 3D. During exercices on volunteers, sensor data were recorded through the presented architecture with different speeds, durations and constrains. Estimated duty cycles, autocorrelation peaks ratios and trunk rotations showed statistically significant difference ($p < 0.05$) with knee brace compared to free walk. In conclusion, the NeuroSENS architecture can be used to detect walking irregularities using a readily available mobile platform that addresses security and privacy issues.

Keywords: Smartphone-based system · Privacy · Security
Mobile health · Inertial sensors · Data collection
Software architecture · Gait analysis

1 Introduction

Neurological disorders are a common cause of gait and balance impairment. Recovery of gait is one of the most desired goals for neurological patients undergoing rehabilitation [1]. Therefore, it is important to have a method to assess the gait of a patient in order to follow its improvement over time. Different methods have been used to analyze gait and balance, including kinematic analysis using

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motion cameras [2], endurance using specialized treadmills [3], or walkways with different types of sensors [4]. However, these approaches require highly specialized and costly equipment in a specific location. An alternative rely on the use of common walking tests – e.g. Dynamic Gait Index (DGI) and Functional Gait Assessment (FGA) – that were developed to capture walking problems in maintaining stability during gait activities and determine falls risk. These tests are conducted in a visual manner by physical therapists, so they provide qualitative results and may be subject to some errors compared to tests that collect data. Recently, mobile health has proven to be a useful tool in health monitoring [5] and has spurred the development of mobile systems capable of collecting quantitative data on gait [6–10].

Most of the existing mobile systems collect and transmit sensor data to a remote site such as a hospital server for clinical analysis. Data transmission is done over the Internet, where mobile telecommunication standards such as 4G allow continuous monitoring even when the patient is outside the home. However, what is often forgotten is that these data are related to a person and are vulnerable when transmitted over the Internet. They can be used to model and even digitally clone the person. In this context, one important issue is how to effectively collect and manage personal data with sufficient security protection [11]. Currently, very few works addresses the issue of privacy and security of the personal data. In this work, we developed a smartphone-based architecture for prolonged monitoring and proposed some preliminary routes in terms of privacy and security of the personal data. Although of very wide application,

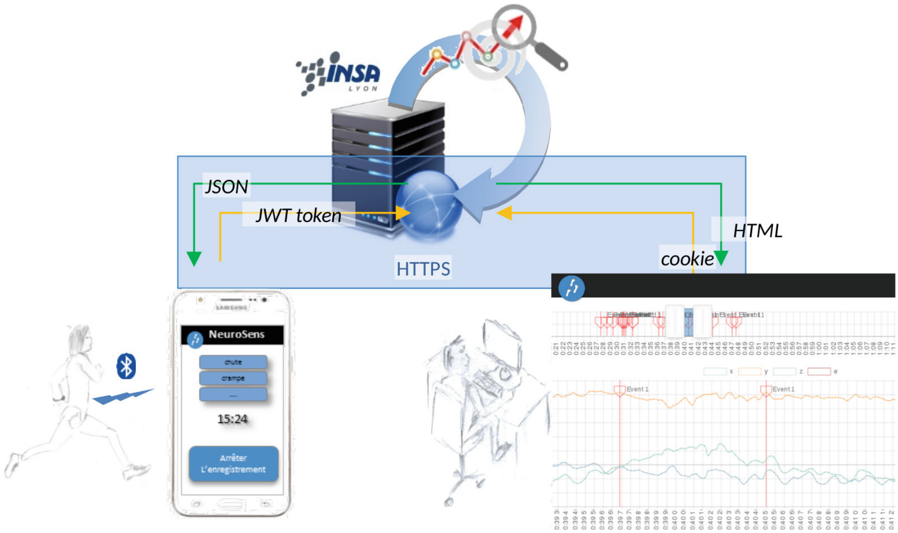

Fig. 1. Overall system architecture and communication. Communication protocols and formats are displayed in green and authentication security tools in orange. (Color figure online)

NeuroSENS offers a first application to evaluate patient's gait and detect intermittent claudication and gait asymmetry. This detection is performed from the duty cycle and autocorrelation peaks ratios of the vertical accelerometer signal and from the patient's trunk rotation estimated by the fusion of accelerometer, gyroscope and magnetometer signals in 3D.

2 Motivation and Objectives

Our work focuses on patient-centered design to develop a technology that is accessible, ergonomic and secured. Building the system around its users helps to provide a sustainable structure accepted by the patients and simplicity to the end-users. NeuroSENS is a smartphone-based architecture that utilizes the sensors of the smartphone to collect data on gait, and utilize computing performance and storage of a server to monitor gait evolution in time. Figure 1 displays the overall system architecture and data flow. The system consists in three parts. The first part (see Fig. 1-left) is a mobile app for sensor data collection on patient's gait and interaction with the patient. The second part (see Fig. 1-middle) consists in a server and associated services to process the sensor data and stores the results on a database. And the third part (see Fig. 1-right) is a client service for viewing data by the patient and the clinician. The mobile and web apps respectively communicate with the server using the HTTP protocol and the JSON format to transmit the data.

3 Architecture

To ensure a good level of privacy and security to the end-users, we decided to set up an in-depth defense system, which consists in using at each layer of our system (see Fig. 2) specific security techniques to limit the damages of a possible attack.

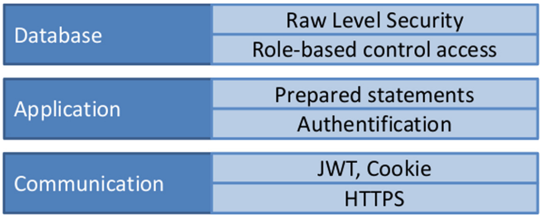

Fig. 2. Defence-in-depth strategy of the architecture

3.1 Mobile App

The goal of the mobile app is to enable the patient to configure a deployment (choice of sensors and tests) and capture data. The mobile app generates its own triggers to transfer the sensor data. Two criteria are taken into account: Wi-Fi needs to be available and battery level has to be greater than 20%. If these two criteria are satisfied, the time-stamped raw data are temporarily stored until they reach a desired data packet size and then are transferred to the server and the database. A default mode was conceived to ensure that the data will be sent at least once a day (even if there is no generated trigger). Data are securely transmitted between mobile app and server using JSON Web Token (JWT) and HyperText Transfer Protocol Secure (HTTPS). This information can be verified and trusted because it is digitally signed. In our case, JWTs are signed using a keyed-hash message authentication code (HMAC) and allow to identify a device hence a user.

3.2 Server and Associated Services

The server accepts packet transfer of patient data from the mobile app. The data are stored into a relational database, where they are separated into two databases: a research database that consists of all the sensor data, saved as they were received and a key database that consists of the identifiers for mobile and web apps (see cookies and JWT in the following). To enforce data security, the database has a role-based access control (RBAC) policy where the access decisions are based on the roles that users have. Clinicians and patients will not have the same rights in the database. For example, a clinician can insert a patient but cannot insert data whereas a patient can only insert data. Below this layer, we added a row-level security, that enables to control access to rows of the database table based on the characteristics of the user executing a query (e.g., patient has only access to his data). The server also acts as a data analysis agent that supplies gait parameters.

3.3 Client Service

The web application allows the patients to see their different data-sets and the clinicians to see the different data-sets from their patients. Access to raw and processed data by the patients is important to encourage them to become active participants. A visualization tool is therefore provided in an easy to manipulate graphical representations together with playback capabilities: (i) for all the measurements taken by the patient (appearing in the form of a dated list) the visualization is carried out in relation to the events specified by the user during the acquisition or detected automatically by the signal processing, (ii) the user can then decide to focus on an event to visualize the raw signals and the indicators given by the signal processing. Data are securely transmitted between web app and server using secure cookies and HTTPS. Session cookies allow the web app to identify and memorize a user and hence to browse the pages of the web app without having to re-identify each time. The user automatically connects to the database from this point on. So individuals who do not have login/password cannot do/see anything because they cannot authenticate themselves to connect to the database. Above this layer, we developed prepared statements to avoid SQL injections into the database when accessing user data.

4 Implementation

Our mobile app was developed for devices running Android 5.0 as a minimum. It uses the Android Sensor API to communicate with the sensors of the mobile phone and the Volley library to transmit network data. The server uses Node.js – a software platform in JavaScript oriented to network applications – and hosts a PostgreSQL relational database for storing sensor data and runs Java algorithms for processing and analyzing data stored in the database. The web application is mainly developed in Javascript. Jade, CSS and various Jade-Boostrap models are used respectively for the application interface, style and visual application. Finally, the Chart.js library allows us to create animated graphics in our web application.

5 Signal Processing and Evaluation

For this study, the patient's smartphone has been fixed at the waist by a fastening system for the sport. Data from the accelerometer, gyroscope and magnetometer sensors are merged and processed. Autocorrelation of the accelerometer signal along the vertical axis is used to detect the steps and segment them automatically. The ratio between odd and even peaks of autocorrelation are computed to quantify the symmetry of the gait. An adaptative threshold on the signal of the accelerometer along the vertical axis is applied to binarize the signal between support phase (0) and oscillating phase (1) and then computing the corresponding duty cycle to quantify fatigue in walking [12]. The fusion of data from the accelerometer, gyroscope and magnetometer (Android API Rotation Vector) enables to detect the rotation of the trunk around the vertical axis which makes it possible to know the orientation of the step in the horizontal plane and therefore to detect a deviation (mean and cumulative, in cm) with respect to the straight path and differentiating left step (positive angle) and right step (negative angle).

The system was tested and evaluated by recruiting volunteers to use this system. The study instructions were given to volunteers and explained by the principal investigator. We recruited 40 volunteers for exercises on a treadmill involving different speeds (1, 2 and 4 km/h), durations (2, 4 and 10 min) and constrains (free walk or use of knee brace). All the sensor data were collected through the presented mobile app. We validated duty cycles, autocorrelation peaks ratio extracted from the sensor data by comparing them with the acquisition of images made laterally to the patient with a high frame rate video camera (Gige Vision). Estimated duty cycles, autocorrelation peaks ratios and trunk rotations showed statistically significant difference ($p < 0.05$) with knee brace compared to free walk. This is more pronounced as the duration and the speed during acquisition are high: $p = 0.04$ with speed = 1 km/h and duration = 2 min versus $p = 0.009$ with speed = 4 km/h and duration = 10 min.

6 Conclusion

There is a rapid increase in health-related applications. This is why research on these applications is important. To conduct it effectively, the system architecture must protect privacy, provide security measures and improve accessibility for all actors, including researchers. In this study, we designed a secured smartphone-based system, NeuroSENS, for prolonged monitoring of neurological gait. It is made accessible online at http://neurosens.creatis.insa-lyon.fr. This work proposes some preliminary routes in terms of privacy and security for the personal data by a three levels defense-in-depth strategy: at the data storage level, the mobile and web apps level and the data transmission level. This system could be extended to assessment of other walking irregularities.

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