A System for Monitoring Stroke Patients in a Home Environment

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Abstract: Currently, the changes of functional capacity and performance of stroke patients after returning home from a rehabilitation hospital is unknown for a physician, having no objective information about the intensity and quality of a patient's daily-life activities. Therefore, there is a need to develop and validate an unobtrusive and modular system for objectively monitoring the stroke patient's upper and lower extremity motor function in daily-life activities and in home training. This is the main goal of the European FP7 project named "INTERACTION". A complete sensing system is developed, whereby Inertial Measurement Units (IMU), Knitted Piezoresistive Fabric (KPF) goniometers, KPF strain sensors, EMG electrodes and force sensors are integrated into a modular sensor suit designed for stroke patients. In this paper, we describe the systems architecture. Data from the sensors are captured wirelessly and stored in a remote secure database for later access and processing via portal technology. In collaboration with clinicians and engineers, clinical outcome measures were defined and the question of how to present the data on the web portal was addressed. The first implementation of the complete system includes a basic version of all components and is currently being extended to include all sensors within the INTERACTION system.

1 INTRODUCTION

Currently, the changes of functional capacity and performance of stroke patients after returning home from a rehabilitation hospital is unknown for a physician, having no objective information about the intensity and quality of a patient's daily-life activities. As a consequence, the physician is unable to monitor the prescribed training program for sustaining or increasing the patient's capacity and performance and cannot give advice to the patient outside the hospital setting. Therefore, there is a need to develop and validate an unobtrusive and modular system for objective monitoring of daily-life activities and training of upper and lower extremity motor function in stroke patients. That is the main goal of the European FP7 project named "INTERACTION". A physician will be able to continuously evaluate the patient's performance in a home setting by using the INTERACTION system, allowing the physician to compare the patient's performance at home with the patient's capacity in the rehabilitation hospital. Thereby, the system will support the physician in making decisions to, for example, alter the prescribed training programs.

The INTERACTION sensor system is composed of Inertial Measurement Units (IMUs), Knitted Piezoresistive Fabric (KPF) strain sensors, KPF goniometers, EMG electrodes and force sensors. These sensors are integrated into a custom made modular suit for stroke patients (e-textile), which consists of a shirt, a pair of trousers, shoes and gloves. The iterative design process for the sensor suit includes several usability tests as well as an extensive user requirements analysis with medical and technical experts.

Data are captured wirelessly on a home-gateway, which transmits the data to a secure database. Portal technology can access and process the data. The results can be consulted by a clinician whenever necessary.

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In this paper, we describe the system architecture and the requirements for presenting the outcome measures to clinicians. Specifically, in section 2, the system requirements are given along with an overview of the whole system and a detailed description of each component. In section 3, the data processing aspects of the system will be explored in further detail. In section 4, the design process of the data presentation is elaborated upon. In section 5, the current implementation of the system is presented and finally, in section 6, the conclusions and future work are described.

2 SYSTEM ARCHITECTURE

2.1 System Requirements

Four major requirements were set before the initial system development:

1) The system should compute and display capacity and performance measures to evaluate stroke patients during daily-life activities (for example: grasping an object) in a home setting.
2) The INTERACTION system should be divided into several modules: upper extremity (shirt), lower extremity (trousers), gloves and shoes. This will allow clinicians to assign different modules to different patients according to the clinicians specific interests.
3) Analysis of the sensor data will not be done in real time. The system should be able to store the computed data such that it can be accessed by a clinician when needed.
4) The system should present the performance information of the patient to the clinician, such that it optimally supports monitoring the progress of the patient and decisions about continued therapy. The clinician should be able to inspect the information in progressive detail from global performance parameters to details concerning the quality of specific movement tasks, according to his or her needs.

2.2 System Overview

The INTERACTION system's architecture is based upon a generic architectural approach described by Pawar et al. (2012). Figure 1 shows a general overview of the current system's architecture. The Body Area Network (BAN) is composed of several sensors listed in table 1 and a home gateway. The Xsens wireless Awinda protocol is used to connect and synchronize the sensors to the home gateway, which captures the data and stores it in a European Data Format (EDF). The EDF file protocol was extended for the INTERACTION project by adding additional signal labels to the header of the file. Finally, the EDF file is uploaded to a secure and remote SQL database if an internet connection is detected. A server, installed at the University of Twente, runs a Liferay portal software (Liferay, Inc.) with custom made portlets and Matlab (Mathworks, 2013). The portal obtains the data from the database and sends the results to Matlab for processing. The results are saved and visualized on the web-portal on request. Each component is explained in detail in the following sub-sections.

Figure 1: System Architecture.

2.3 Body Area Network

The Body Area Network (BAN) consists of all body sensor components and a gateway to capture, store and upload sensor data.

2.3.1 Sensors

The INTERACTION sensor system is divided into four modules which comprises of a number of sensors listed in Table 1. Each Xsens MTw sensor box includes 10 primary signals: a 3D accelerometer, a 3D goniometer, a 3D magnetometer and one Pressure channel. Knitted Piezoresistive Fabric (KPF) strain sensors and goniometers are developed by the University of Pisa and are integrated into the textile clothing. The EMG electrodes are integrated into the shirt and the signal is pre-processed by a on body front end into a smooth rectified signal. The KPF strain sensors, KPF goniometers and EMG electrodes are each physically linked to an MTw sensor box by parsing

the data to the MTw's pressure channel. As a result, the wireless capabilities of the MTw's for data transmission from the BAN to the gateway are preserved. Figure 2 provides a global overview of the sensing system for the upper and lower extremity.

Table 1: Sensor overview.

Type	Number			
	Shirt	Trouser	Shoes	Gloves
IMU*	6	4	2	2
KPF Strain**	2			
KPF goniometer**	1	2		6
EMG electrodes	1			
Force			***	6

*Xsens MTw, **Developed by University of Pisa, ***Work in progress

Each MTw outputs 10 primary signals and 4 derived signals (orientation in quaternions), each of which is assigned a unique sensor label within the EDF file. The data collection rate is dependent on the number of sensors. In our case, the collection rate is set to 20 Hertz. This data collection rate has been assessed to be adequate, since 3D kinematics is analyzed at a higher frequency (1800 Hertz) inside the MTw sensor units before transmission to the Awinda station.

This local analysis provides a more accurate estimation of acceleration and angular velocity values and includes 3D estimation of orientation. 20 Hz is an adequate rate for transmission of 3D orientation as well as the other sensed quantities, as specified in table 1.

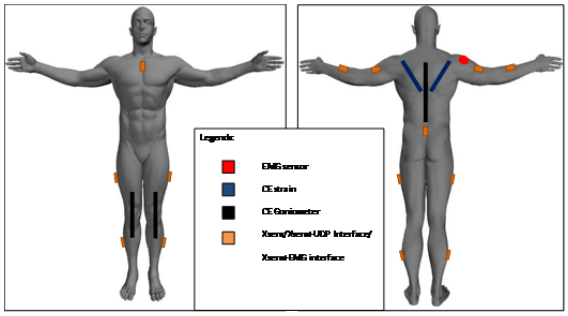

Figure 2: Sensing System overview.

2.3.2 Gateway

The home gateway has three main functions: 1) collecting the data from the sensors, 2) storing the sensor data inside an EDF file every five minutes and 3) uploading the EDF file to the database. The data storage interval of five minutes was determined by considering the available network bandwidth as well as the decreasing overhead of the EDF file with measurement time (Figure 3).

With five minutes of data, the EDF data record has a size of 2.24 MB in total according to equation 1 (also called the "payload") and a header size of 49.25 kB according to equation 2. Therefore, the header occupies only 2.14% of the total EDF file space. The relation between the payload and the header of a file is called the "overhead".

$$\text{Payload size} = M_t * F_s * N_{imu} * N_{signals} * 2 \text{ bytes} \quad (1)$$

$$\text{Header size} = (N_{imu} * N_{labels} + 1) * 256 \text{ bytes} \quad (2)$$

The input for equation 1 and 2 are as follows: N_{imu}: 14 (Number of IMU's), $N_{signals}$: 14 (Number of sensor signals), N_{labels}: 14 (number of sensor labels), M_t: 300 seconds (Measurement time) and F_s: 20 Hertz (data collection rate). The general EDF header is 256 bytes in equation 2.

The data is uploaded to the database with SSL secure data encryption over the network using RESTful web services, and the users of the database are authenticated using a username and password combination. Furthermore, within the EDF file, only a device ID is used to identify each sensor suit, so no patient names are exchanged.

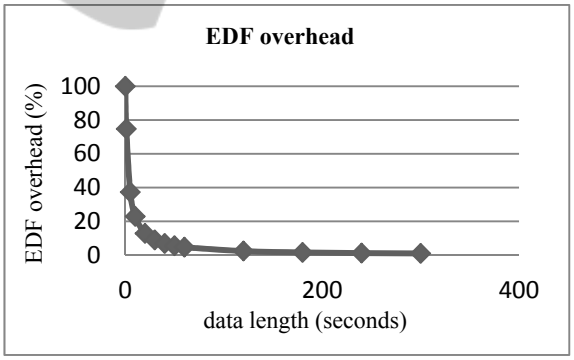

Figure 3: EDF overhead for the complete INTERACTION sensing system.

2.4 Database

An SQL database was configured at the Roessingh Research and Development centre (RRD) by reason of their technical experience in secure databases. Dedicated API's were constructed for communication between the home gateway and portal using SSL. For obtaining the data, a correct combination of username and password is required to authenticate the user, and a separate authorization model is in use which determines the access rights of the user, including his or her reading and writing

rights. A query engine is developed based on RESTful web services to obtain EDF sensor data from the RRD database on receiving a request from the web portal with a start and end time.

2.5 Portal

The web-portal is responsible for controlling and visualizing the data. We chose the Liferay portal framework as it provides a flexible working environment to develop portlets in a Model-View-Controller (MVC) structure using Java, JavaScript, CSS and JSP. Liferay includes a dedicated Content Management System, which allows the portal to be personalized for different users by means of a detailed access-control scheme for assigning different rights to different users.

The View component is responsible for displaying the processed data to the user and includes two visual libraries: the Highchart library (Highcharts Solutions AS) for graphs and the Bootstrap library (http://getbootstrap.com) for a responsive layout and website elements. The Controller component is connected with the View and initiates the Model(s). The Model components obtain the data from the database by use of multiple queries and subsequently send the data to Matlab via a Matlab-Java bridge (Matlabcontrol Java API v4.1.0, http://code.google.com/p/matlabcontrol/). The complete structure is shown in Figure 4.

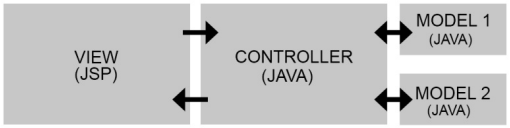

Figure 4: MVC structure.

Users are able to send requests for different types of measurement data in a specific portlet (by pressing, for instance, a button on the web-portal). These requests are directly forwarded to the Controller component associated with that portlet. This Controller initiates several Models accordingly. With this MVC structure, we are able to process and visualize large amounts of data in an organized way. Different portlets are constructed, each having a different function to show different types of data on the same web-page or on different web-pages.

3 DATA PROCESSING

The data processing flow is shown in Figure 5 and represents a Model within the MVC portal structure.

The Model is composed of four steps. The first step involves obtaining the data from the database by use of the RESTful web services and initiating Matlab to read the EDF file and assign each sensor label to each data record. This step is realized by a custom made Java portlet in the Liferay Portal software. The second step is to pre-process the raw sensor data by the use of a biomechanical model within Matlab to derive the angles and positional values of body segments. The results are then fed into activity recognition algorithms in the third step which are able to detect the type of activities shown in Figure 6 with a high specificity. The type of activities is based upon daily-life activities for both upper and lower extremities.

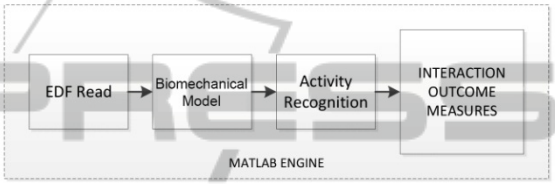

Figure 5: Data Processing flow.

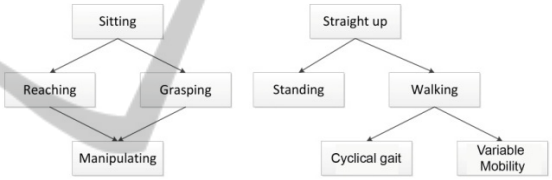

Figure 6: Activity recognition schemes for the upper and lower extremity respectively.

In the final step, the INTERACTION clinical outcome measures are computed. These measures are visualized towards the clinicians and should provide valuable insight into the patient's capacity and performance during daily-life activities. The results are saved for quick access by clinicians and for time comparison of the results by the end of the week or month. A list of basic outcome measures is shown in table 2.

4 USER INTERFACE

Designing a graphical user interface for clinicians to access the web-portal and determining what outcome parameters to present on the portal is one of the major challenges in the INTERACTION project. The INTERACTION system will be collecting data that clinicians are not familiar with in current practice and the data has to be presented in a format that clinicians can understand and evaluate within a

Table 2: Examples of clinical outcome measures in the INTERACTION system.

1	Arm usage of the affected and non-affected arm
2	Maximum reach of the affected and non-affected arm
3	Range of Motion of the elbow and shoulder of the affected and non-affected arm
4	Range of Motion of the trunk
5	Maximum grasping force of the affected and non-affected arm
6	Number of grasps of the affected and non-affected arm
7	Number of steps, step length and step time
8	Weight support by affected and non-affected leg

few minutes. Therefore, in close collaboration with clinicians, we investigated which clinical outcome measures are relevant and how to present the data in such a way that the capacity and performance of a patient can be easily evaluated and compared over time.

After some interviews with clinicians and engineers from Enschede (Roessingh research and development rehabilitation centre, RRD) and Zürich (University hospital in Zürich, USZ), we concluded the following:

Clinicians can have as many as 40 stroke patients in treatment at a given moment, all of whom have to be evaluated within one hour by the end of the week. This amounts to only a few minutes per week to analyze the performance of each patient. Hence, there is a need for a basic overview of all patients on the web-portal with an option to successively drilldown to a particular data set for a particular patient. Based on these preliminarily results, we made a set of mock-ups for the web-portal. An overview mock-up (called a "dashboard") is shown in Figure 7 for three patients.

It includes a patient overview on the top, a general INTERACTION system statistics at the bottom left and a recent blog entry by the patients at the bottom right. The main navigation menu is divided for the upper and lower extremity, each presenting different global statistics of a patient. Furthermore the navigation includes a patient list page, a suit performance page (to check which sensor suits are operational and if no errors are present) and a tech support. For the clinical trials, some modifications will be made in the mock-ups to protect the anonymity of the patient.

A detailed overview mock-up for a particular patient is shown in Figure 8 (for the upper extremity). The selection panel allows for easy scrolling through patients, times of measurement and specific body sections. The clinician can also click on a specific anatomical body part to drill deeper down into the patient's data. The weekly statistics gives an overview of the patient's performance during the selected week, and the INTERACTION score summarizes the patient's overall performance over multiple weeks.

The mock-up for the final tier of the web-portal drilldown into the patient's data is shown in Figure 9. Specific clinical outcome measures are presented over time on the left (for example, elbow angle, trunk flexion and reaching distance), outcome measures like Range of Motion (ROM) can be extracted and can be compared during several weeks of measurements.

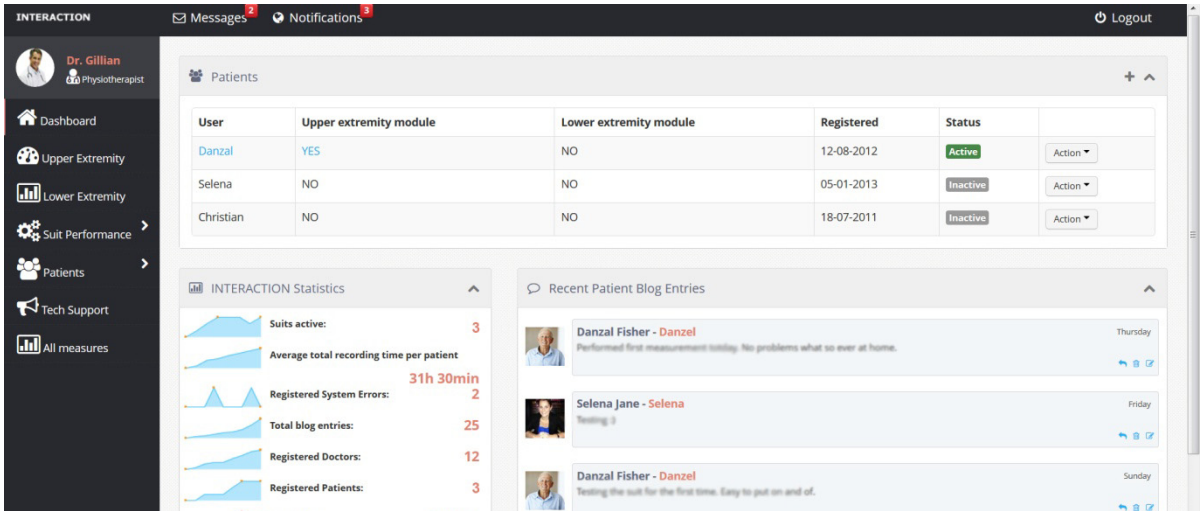

Figure 7: Dashboard page.

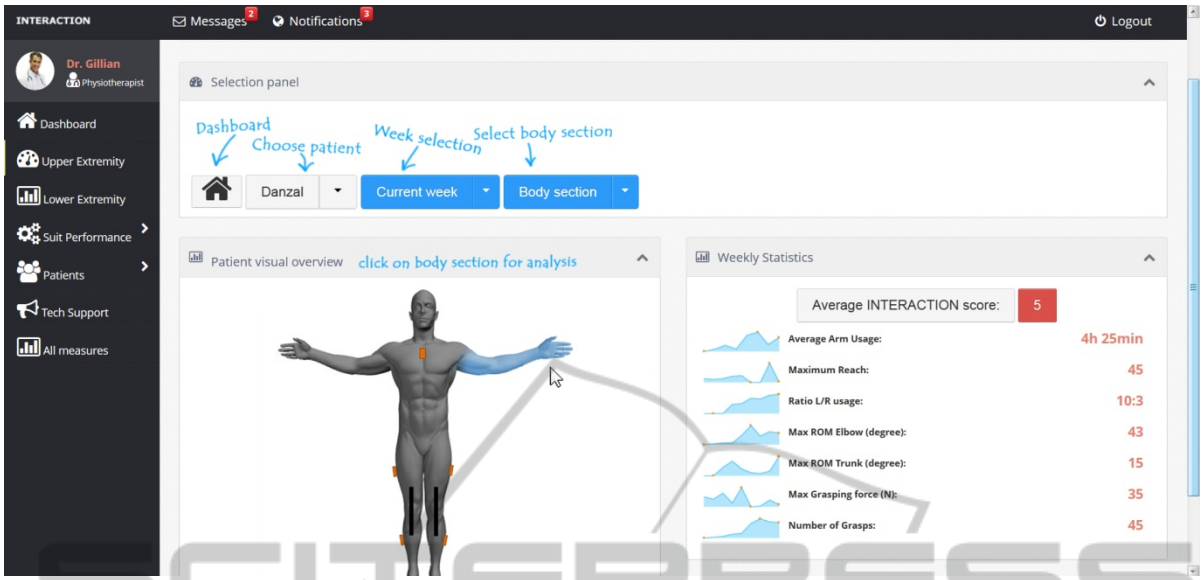

Figure 8: Upper extremity overview page.

Figure 9: Drill down page of the patient data.

5 IMPLEMENTATION

We finished the complete system architecture structure involving all the components discussed in this paper. The first prototype consists of three Xsens MTw sensors, one gateway platform (a laptop with an Xsens Awinda base station), one secure database, one server with Liferay, Matlab and custom-built portlets. Each data processing component described earlier has been implemented, but with a basic setting for processing data from three MTw sensors. A demonstrational setup of the sensors is shown in Figure 10.

Three MTw sensors are placed on the upper arm, lower arm and trunk of the body. For demonstrational purposes of the system, the following measurement was performed. One subject simulated a repetitive reaching motion of a stroke patient's non-affected arm for 10 seconds followed by simulating the motion of the affected arm for 10 seconds. There was a 5 seconds rest period in between.

During the first 10 seconds, the subject stands up straight and does not move the trunk while reaching for an object. During the last 10 seconds, the subject utilizes the trunk to compensate for the decrease in elbow flexion and elbow/shoulder coupling (Dewald, 1995) to reach for an object.

Figure 10: MTw sensor placement.

The home gateway captures the measurement data, stores the data in an EDF file and uploads the file to the database if an internet connection is detected. If an end-user (for example, a clinician) presses the "analyze" button on the web portal (within a portlet), the portlet retrieves the data from the database. Subsequently, the data is processed according to the data processing flow. In this demo, the biomechanical model calculates the following: elbow angle, shoulder abduction, hand-sternum distance and trunk orientation. The activity recognition functions detect the two types of movement (the reaching movements of the non-affected and affected arm) and the results are visualized as graphs on the web-portal. The result of one measurement is shown in Figure 9. During the use of the affected arm, there is a decrease in elbow flexion and an increase in trunk flexion while reaching multiple times for an object.

6 CONCLUSIONS AND FUTURE WORK

The INTERACTION project aims to develop and validate an unobtrusive and modular system for objectively monitoring the daily life activities of upper and lower extremity motor function in stroke patients. The system's complete architecture was developed according to the requirements identified at the beginning of the project. The architecture, including all its components, was validated by using three Xsens MTw sensors in a short measurement, during which we simulated a Stroke patient's reaching motion of the affected and non-affected arm. In the first prototype of the architecture system, we included a biomechanical model in combination with activity recognition functions to compute several clinical outcome measures, which are then shown on a web-portal.

Extension of the architecture to a full on body sensing system is a feasible task, as all components are designed for that purpose. The system will be extended to incorporate the full number of sensors and each component needs to be updated accordingly. The gateway software will be transferred to a Smartphone and the Xsens Awinda base station will be replaced by an Xsens dongle connected to this Smartphone. Furthermore, the portal's MVC structure has been designed for extensions and provides a flexible coding environment for Engineers by the inclusion of a Matlab-Java bridge.

In this project, we have identified an extensive list of potential clinical outcome measures. The list of clinical outcome measures given in this paper is an example of what the INTERACTION system will deliver. We are now in the process, together with clinicians and engineers, to make a final selection of the clinical outcome measures to be implemented by the system. Finally, both the sensing system and web-portal have to be evaluated before starting clinical trials.

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