A Multimodal Human Sensory System to support Mobile Gait Rehabilitation

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Abstract

In a dynamic operational environment of human-robot interaction, awareness of the interacting human state and activity is essential to the decision making of the robotic system. We present our approach by illustrating its application in a particularly challenging context of human-robot co-working supported by our Human Sensory System, for measuring physiological data during robot-assisted gait rehabilitation, which provides sensors and infrastructure to measure the physiological data. This data is used by a Situation Assessment Architecture in the monitoring the human state, activity and performance to aid the process of gait rehabilitation. Both the Human Sensory System and the Situation Assessment Architecture have been developed as part of the CORBYS project, in which a mobile robotic gait rehabilitation system demonstrator has been developed. The Human Sensory System consists of three sensor module types; **i)** a Chest Unit collecting one-lead ECG, heart rate and skin temperature measurements, **ii)** an IsenseU unit equipped to measure humidity and inertial movements and **iii)** an EMG measurement unit. Synchronised sensor readings are transmitted wirelessly formatted as standardised Robot Operating System (ROS) data from the Human Sensory System controller. This enables a seamless sharing of physiological data with the Situation Assessment Architecture, robotics control and end-user graphical interfaces.

1 Introduction

The use of robotic systems in gait rehabilitation can help provide safe, intensive and task-oriented rehabilitation to people with mild to severe motor impairments after neurologic injury [1]. Robotic training in principle can allow more precise and controllable training sessions; it offers objective measures for therapy evaluation and patient training motivation, and it can reduce the need for human intervention and assistance during the therapeutic sessions. Gait recovery robotic systems vary from simple electromechanical walking aids such as a treadmill with body weight support [2] to electromechanical exoskeletons [5].

Gait rehabilitation robotic systems have to be in truly symbiotic relationships with human users. While biomechanical effort can be quantified by torque and force sensors integrated in the robotic system, it is also of high interest to measure the corresponding physiological effort of the subject of the rehabilitation process; for example by measuring parameters such as ECG or heart rate, breathing rate, and muscular activation (EMG, Electromyography). In addition, the user's mental engagement is also of interest, since an active mental engagement has been shown to be a key success factor in rehabilitation [3]. Koenig and co-workers [4] have reported on work to estimate psychological states from physiological recordings during robot-assisted gait rehabilitation, and found that the parameters heart rate, skin conductance responses, and skin temperature could be used as markers for psychological states in these applications. Ultimately, for robotic systems supporting walking, it is also desirable for the robot to sense human intention, thereby making smooth and fluent interaction possible.

The work reported here is part of the CORBYS project where a gait rehabilitation robotic system has been developed [5]. This system consists of a mobile platform and a powered orthosis attached to the platform. The mobile platform provides mobility for a patient, and the powered orthosis assists with their leg movements. Our work on the design and development of a Human Sensory System (HSS) focuses on the premise that such a sensory system needs to act as a facilitating device within an overall robotic system such as CORBYS to allow physiological understanding of the interacting subject. In this case, the subject is a patient undergoing gait rehabilitation. This information is crucial for the CORBYS project gait rehabilitation demonstrator and is in general significant for cognitive robot control architectures with man-machine interaction. In addition, sensor components must be compact, easy to attach and remove, not disrupting or discomforting for the patient, and must be designed to coexist with the robotic system. Finally, data must be adapted to standardised robotics software interfaces.

2 Methods

A physiological sensor system has been designed to be applied to the CORBYS gait rehabilitation system shown in Figure 1. Whereas this is a highly specialised application, the physiological sensor system is however designed to be useful outside the given application scenario. Sensor interfaces to the user, as well as interfaces to the robotics system employ standards based data transmission formats; hence the system has potential as a general physiological sensory system for robotics.

A typical training session for the CORBYS gait rehabilitation system is estimated to last approximately thirty minutes. Patient and therapist need to be focused on the rehabilitation process; hence the preparation time for mounting sensors should be kept to a minimum by keeping the number of sensor units low. Also, sensors should not be invasive or obstructive during gait rehabilitation. The physiological sensors should provide data to build an understanding of the patient state and to check muscle activation pattern in gait cycles against patterns found in normal and healthy locomotion. Low level control of the gait rehabilitation system will not use the physiological sensor data directly, however training sessions will be adapted based on analysis of the readings. Patients will be fastened to an orthosis with cuffs and straps, hence physiological sensor units should be wireless to avoid cables influencing leg/orthosis movement.

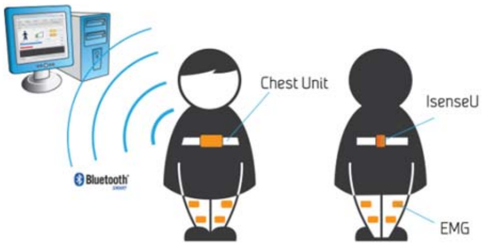

Figure 1 CORBYS HSS sensor units

Figure 2 (a) Chest Unit with elastomer electrodes (b) Dual channel EMG unit. (c) IsenseU sensor unit

Based on these requirements the three types of sensor modules shown in Figure 1 were developed:

1) The ***Chest Unit*** includes multiple sensors. Heart rate and heart rate variability, extracted from ECG measurement, indicates physical activity and stress level. Additionally, skin temperature, activity level, and a tri-axial accelerometer and gyroscope data are provided. This vital signs-and-activity-monitoring unit is shown in Figure 2 (a) [6]. The device is strapped to the chest by an elastic belt with elastomer electrodes for one-lead ECG. Data can be immediately transferred via Bluetooth or stored on the unit.

2) ***IsenseU***, another multi-sensor device shown in Figure 2 (c), is located on the user's back attached to the same belt as the chest unit. A second IsenseU device is fixed to the gait rehabilitation robotic system providing environment temperature and robot IMU data. Internally the IMU includes a Motion Processing Unit, providing wide bandwidth motion data. An external humidity sensor is connected via an I2C port. All sensor data are transmitted on Bluetooth Smart as an attribute indication operation to minimise the transmission overhead [7].

3) The ***Surface EMG*** sensor modules are placed on the thigh and calf of both legs for measuring muscle activities [8]. In the CORBYS gait rehabilitation setting, the sequence and amount of activity at the thigh front and back and calf front and back muscles are measured, requiring eight separate surface EMG channels. To reduce the number of separate units for the user and the number of Bluetooth links, a dual channel EMG unit was developed, as shown in Figure 2 (b). A software framework, the ***Human Sensory System Controller*** (HSS controller), was devised to gather data from all the HSS sensors and integrate such data as input to support the gait rehabilitation cognitive controllers through standard Robot Operating System (ROS) topics.

The ***Situation Assessment Architecture*** interprets the state and effort of the human (patient) undergoing gait rehabilitation therapy, including their physical and psychological state. This interpretation is used to create appropriate inputs for control adaptation of the mobile robotic gait rehabilitation system. In particular, the Situation Assessment Architecture processes EMG data from the Human Sensory System to assess the in-session performance of the patient undergoing gait rehabilitation therapy by monitoring their muscular activity. Gait analysis entails muscle activation pattern detection and tracking against expected activation per previously reported studies [9]. The EMG signal enables the detection of muscle activity orchestration per gait cycle which enables the determination of the expected muscle activation pattern (via a confidence measure) as exhibited in normal locomotion. The muscle activity analysis verifies that the muscle groups are activated consistent with gait motion; this is of interest to the therapist from the rehabilitation point of view. Furthermore, the architecture also processes inertial measurements from the Human Sensory System to recognise activities including standing, walking and turning.

3 Results

We present the results and observations as collected from the initial validation of the HSS supporting the CORBYS project gait rehabilitation demonstrator. Thus the results as reported here include the inertial measurement based activity recognition and EMG-based muscle activation analysis. Both modules have been implemented and tested individually with datasets from the Human Sensory System. The results are based on the integrated conformance testing and the first stage of planned trials and performance evaluations of these two modules of the Situation Assessment Architecture; a second phase of larger scale evaluations is ongoing as planned. This includes user evaluation trials which will involve the Human Sensory System in facilitating the situation, state and performance assessment process undertaken by the cognitive architecture to decide the next best assistive-remedial actions for gait support.

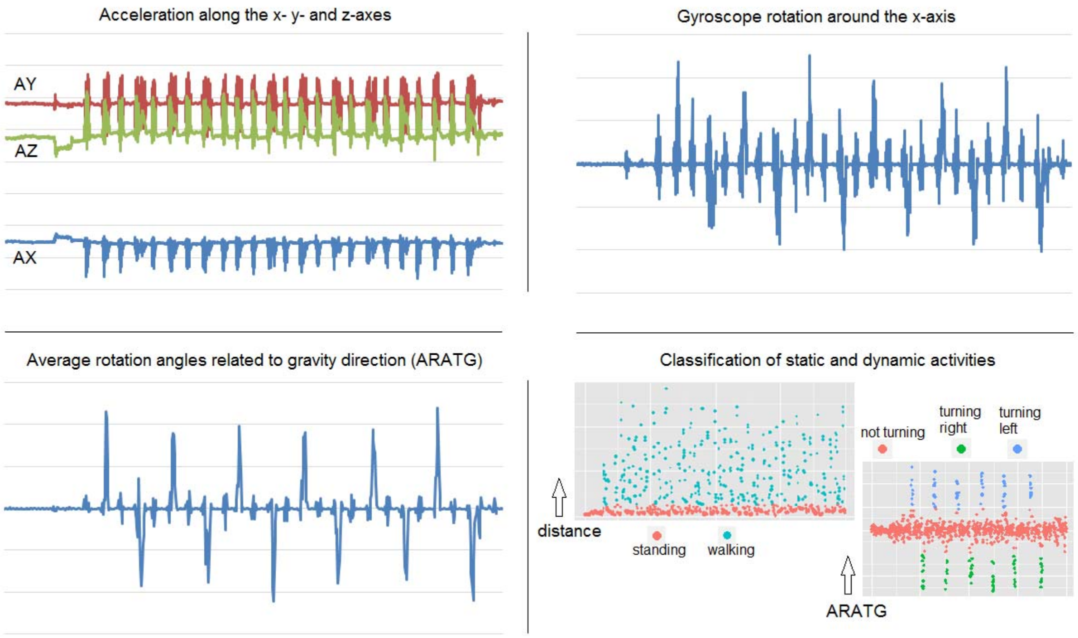

Figure 3 Classification of static (standing) and dynamic (walking, turning) activities as supported by the HSS IsenseU unit (IMU): **a)** Raw acceleration tri-axial signal (forward progression along the z-axis, all three axes are highly correlated), **b)** raw x-axis rotational signal from gyroscope, **c)** ARATG feature extracted from gyroscope signal – turning activities can be distinguished from other activities (turning direction left for upward peaks and right for downward peaks, **d)** Expectation-Maximisation clustering shows linearly separable data suited to multi-class SVM (w/o kernel)

Acceleration and rotation from the IMU in the back unit of HSS are used to detect static and dynamic activities including standing, walking, turning left and right. Activity classification is carried out using a multi-class support vector machine with features including the Euclidean distance for walking and standing activities and the Average Rotation Angles related to Gravity direction [10] – also known as ARATG – which simplifies the identification of left and right turns (see Fig.3). A classification accuracy of 88.73% with an average detection latency of 34µs is achieved in a 10-fold cross validation. Through this processing of the inertial measurements, the robotic system using the CORBYS framework is thus supported with dynamic situation assessment information regarding the acceleration and orientation of the human with whom the robotic system is interacting. In the robotic gait rehabilitation system, this information enables suitable adaptations in the gait trajectories depending on the activity (for instance, starting and stopping).

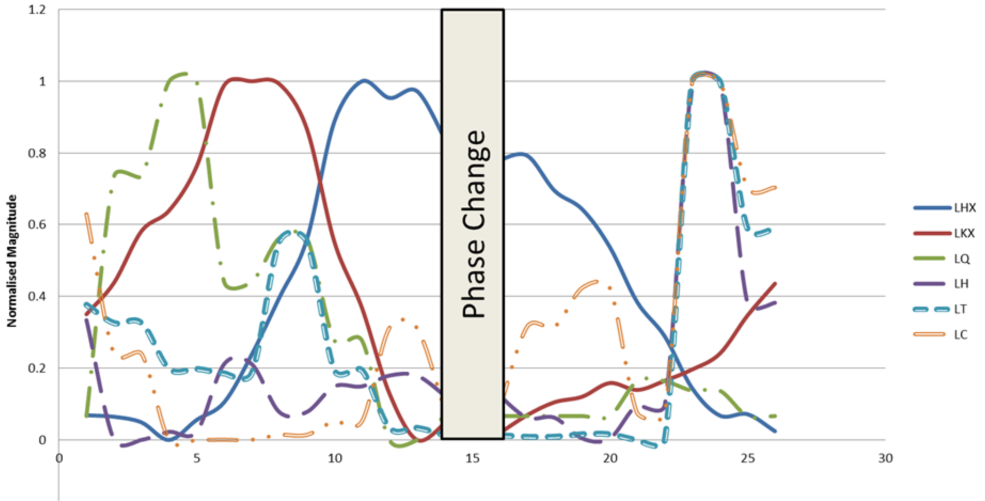

Figure 4 EMG activation in the left quadriceps, hamstring, tibialis and gastrocnemius, in relation to the gait trajectories in the left hip and knee joints along the sagittal axis

Regarding the EMG-based muscle activity analysis, Figure 4 illustrates the data received from HSS for one gait cycle that is segmented at the transition in the gait cycle phases (stance and swing). The EMG sensory data from HSS is essential input to the Situation Assessment Architecture in supporting peak extraction from the signal in order to count the number of activations.
The expected numbers of activations determined by clinical experts in CORBYS are twice for the quadriceps in the stance phase (once in swing phase), once each for the hamstring in both gait phases, once

for the tibialis in the stance phase (four times during swing phase – the tibialis is active through the swing phase) and finally thrice for gastrocnemius in the stance phase (this muscle is not active in swing phase). Muscle scores are calculated for each muscle based on the Euclidian distance between a calculated number of activations and expected number of activations for each muscle during a gait cycle. These scores are used in order to evaluate the performance of the gait therapy patient using the CORBYS demonstrator. Initial evaluations with healthy persons in the CORBYS system showed that the EMG activity analysis reflected the activation in the muscle groups accurately.

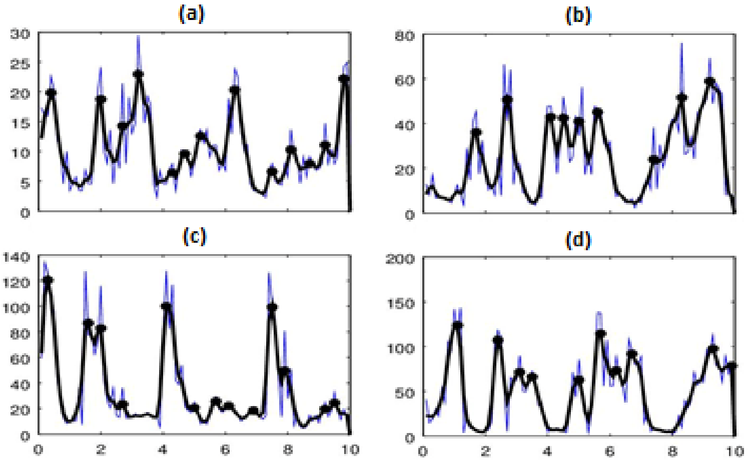

Figure 5 Peak and trough detection of the EMG signal for the four muscle groups of the left leg as part of the muscle activation analysis, a) quadriceps, b) hamstring, c) tibialis, d) gastrocnemius

4 Conclusion

The Human Sensory System and the Situation Assessment Architecture as developed in the CORBYS project have been presented in this paper. The sensory units facilitate a compact, easy to use physiological measurement system that can be deployed for unconstrained recording of physiological data in a robotic environment. While the CORBYS Human Sensory System has been demonstrated in its application for a gait rehabilitation system, the system can easily be integrated in other robotic (or other medical or performance) systems given its ROS-based interface and configuration capability. The sensory system has been shown to facilitate the process of building situational awareness in robotic systems by the cognitive architecture in CORBYS, which assesses current states of the system and environment (including humans). This provides essential information for dynamic situation update to support decision-making regarding potential interaction possibilities with the environment.

Acknowledgments

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