Towards an Insole Sensor Platform for Auditory Feedback Applications in Gait Rehabilitation

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Abstract

Due to the broad and fast development in embedded sensor and wireless communication technologies, wearable and mobile platforms for gait analysis have emerged in the field of clinical rehabilitation. These systems may also be used for providing feedback and thus assist in motor learning processes during rehabilitation. Feedback in the motor learning context does not only comprise a visual display of a person's walking pattern, but may also highlight critical gait characteristics by means of auditory representation. This approach can be referred to as sonification of movement. Scientific research regarding the sonification of movement and the number of published prototypes are constantly increasing in the last years in the field of sports and partly in the area of rehabilitation. As there is a huge potential for applications in the field of gait rehabilitation as well, the objective of this research is to conclude guidelines for the development of sonification applications to support rehabilitative motor learning and control processes in gait based on the needs of therapists and patients. Based on these guidelines a mobile sonification system was developed, existing of sensor, controller and feedback unit. This paper describes the so far completed tasks for the construction and first technical tests of these units, as well as first considerations on appropriate audio designs.

1 Introduction

One of the major challenges in health treatment is the rehabilitation of gait. Diagnosis and treatment of gait abnormalities are costly and time-consuming tasks. To assess relevant aspects of human gait in a scientific setting, typically complex motion capture systems are used. The relatively high accuracy of such systems is accompanied by large financial outlays and increased needed space. In clinical settings, gait rehabilitation often involves therapy sessions with healthcare experts analyzing gait via visual inspection (cf. Götz-Neumann 2011). This procedure is the most frequent applied, due to the fact that resources for complex technical systems are limited. During rehabilitation of gait, healthcare experts provide necessary feedback to assist motor learning processes.

Feedback can be divided into 'intrinsic' and 'augmented' feedback. Intrinsic feedback describes information physiologically gathered by the sensory system (visual, auditory, proprioceptive, and tactile), whereas augmented feedback comprises supplemental feedback by an outside source to intensify a person's sensory perception of critical or usually not perceivable aspects of movement. This type of feedback is crucial for people after injury or with impaired sensory abilities. Thus, feedback is typically provided to the learner verbally (e.g. instructions), visually (e.g. video recordings or displaying kinematics/kinetics), or by using alternative approaches, such as vibrotactile or auditory representation of performance (cf. Magill & Anderson 2013).

A specific auditory feedback technique, the sonification of movement (cf. Rosati et al. 2013), deals with the transformation of distinct movement aspects to sound. Several approaches in sports and rehabilitation have already shown the effectiveness of sonification in enhancing motor learning and motor control (cf. Effenberg et al. 2011; Godbout & Boyd 2010; Redd & Bamberg 2012). Existing approaches to sonification in gait rehabilitation range from a simple system delivering a ticking sound at every heel contact (cf. Baram & Miller 2007) to more complex applications, e.g. based on an optical system for motion capturing, which sonifies the swing phase of gait (cf. Rodger et al. 2013).

For the integration of assisting technical systems into clinical settings as well as in home training sessions and during everyday activities, there is a need for mobile, low-cost feedback scenarios. Due to the broad and fast development in embedded sensor technologies and wireless communication, wearable and mobile platforms for gait analysis have emerged (cf. Grenez et al. 2013; Noshadi et al. 2013; De Rossi et al. 2011). First approaches to sonification in gait rehabilitation indicate an interesting potential for the application of sonification as a feedback tool in the motor learning context. Therefore the objective of this research is to develop guidelines for the construction of a mobile sonification system, as well as to describe first design and prototyping aspects towards an insole sensor platform and an auditory feedback application in gait rehabilitation.

2 Methods

On the basis of a literature review, we proposed general guidelines for the construction and application of a mobile gait sonification system. In this process electronic databases (PubMed, Google Scholar) were searched using the following keywords: gait, walking, symmetry, asymmetry, disorders, patterns, characteristics, parameters, sonification, auditory inputs, auditory feedback, augmented feedback, osteoarthritis, arthrosis, arthroplasty, neurological, hemiparesis, hemiparetic, parkinson, multiple sclerosis, ataxic, spastic or paraparetic. Keywords were used separately as well as in several combinations. Reference lists were manually checked for additional studies. Criteria for literature search were specified: Literature should be available in full text, published in a peer reviewed journal or conference proceedings, and adding knowledge as the aim of the review.

As a result of the literature review process, existing sonification applications in gait rehabilitation were identified and analyzed, in order to develop guidelines for the construction of a mobile, cost-effecitve sonification system. Based on clinical demands towards an insole sensor platform and auditory feedback applications in gait rehabilitation, design and prototyping aspects were developed, a first prototype was constructed and prime technical tests were completed. Moreover first recommendations for an appropriate audio design were gathered and will be presented in this paper.

3 Results

Besides being low-cost and affordable for a broader population an appropriate auditory feedback system for gait analysis needs to be unobtrusive: The system must ensure natural movement execution without altering movement itself. Therefore a thin and flexible instrumented insole seems to be an good choice. To pursuit the concept of unobtrusiveness a wireless construction as well as the miniaturization and the embedding of sensors and electronics is required. It should present data with a minimum latency in order to provide the user with real-time auditory information and thus enable optimum learning outcomes. In addition to the system's hardware requirements and the latency, attention has to be paid to an appropriate audio design of the movement sonification. As the system is thought to to be employed in therapeutic settings as well as in self-directed home-based training without therapeutic assistance, energy supply should last for a minimum of 30 minutes training sessions. An integrated insole battery should be charged wirelessly, as already employed in recent technologies (e.g. Qi standard[1]), to offer highest user convenience.

Based on the system requirements described above a first prototype of an insole sensor platform with a modular and generalizable approach was chosen. Three basic units are essential for capturing and transmitting gait data to a feedback application:

- Sensor unit: Low-cost, embedded sensors such as pressure sensors and inertial measurement units (IMU) capture pressure levels, acceleration, angular velocity and help estimate derivate parameters like step count and width, foot posture and help determine gait cycle phases.
- Controller unit: Miniaturized, low-powered microcontroller board with radio module for data transmission to the feedback component.
- Feedback unit: One potential and media-rich feedback unit is a standard mobile device for data processing and cleansing and generating real-time auditory feedback for the patient. Furthermore it meets the demands of a low-cost, portable, and locally unrestricted gait rehabilitation device.

With the advance of the Bluetooth Low Energy (BLE) standard, a wireless personal area network with a simple protocol structure and reasonable data rate was identified. The Sparkfun Arduino Fio v3 Board comes with an XBee socket for RF communication. As a feedback unit Google Nexus devices with Android 4.4.2 OS version were used.

With some optimization of firmware and software the total latency of 70 ms splits up into 20 ms for the capturing and transmission and 40–50 ms for the native audio processing on Android OS. The data rate with a modified

1 http://www.wirelesspowerconsortium.com/what-we-do/qi/ <02/06/2014>

BLE Bee firmware could be increased from 1 Byte chunks to 20 Byte chunks at constant 100 Hz with minor modifications. Assessing and sonifying asymmetries in gait on both feet requires multiple connections with constant data rate throughout the system. Our initial test with two simultaneous links did not show any performance loss.

For the second task of sensor placement we have identified seven positions spread over the sole area where pressure levels should be sensed. A commonly used pressure sensor is the FlexiForce A301 sensor with a force range between 0–100 lb. Additionally a Sparkfun IMU combining an ADXL345 accelerometer and an ITG3200 gyroscope is used for data capturing. In future these components should be integrated into the instep of the shoe sole (see Fig. 1).

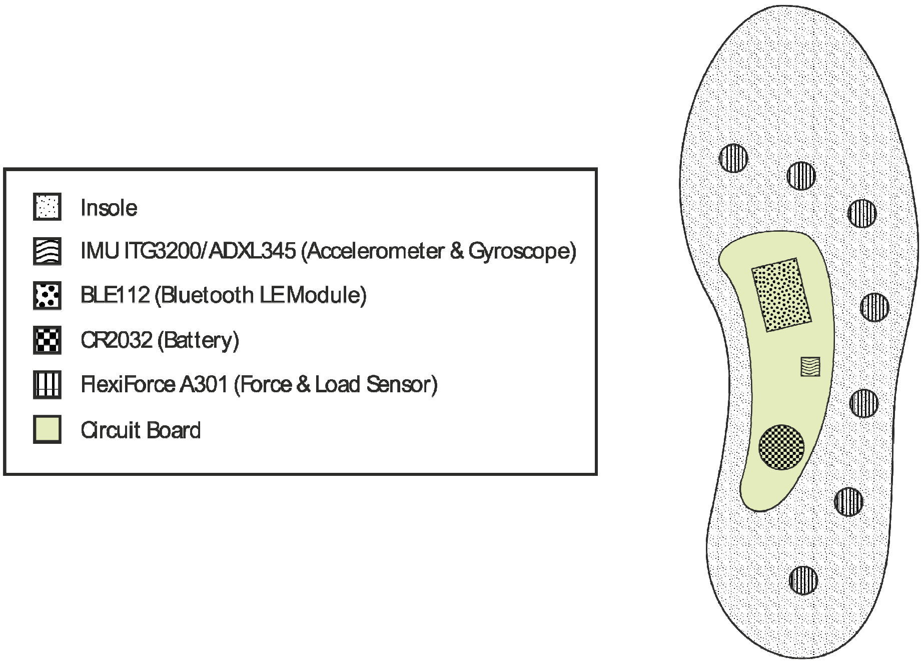

Figure 1
Layout of the instrumented insole with embedded sensors, microcontroller and battery

The third task is the development of the feedback application on the Android OS platform. Besides the promising outlook to announced improvements of the overall audio latency on the Android OS we want to leverage generative audio processing by integrating PureData patches as the main component for audio processing. Thus we could outsource the sound generation and production also to non-coders and provide simulation tools with prerecorded data on gait disorders. We identified a first set of methods based on NASAs documentation of the xSonify project[2] that serve the purpose of data sonification and auditory display design.

- Sensor Onset: This event based approach proposes a direct mapping between the gait cycles initial contact phase and the triggering of a sound. Required latency: low; preferred parameters: loudness, attack
- Pressure Modulation: The constant audio streams parameters are modulated depending on the stance or stride progression. Required latency: mid to high; parameters: pitch (note difference), sharpness, fluctuation strength
- Localization: The idea is to sonify overlapping gait cycle phases by panning sounds of left foot actions to the left earphone and vice versa

4 Discussion

First tests of the prototype of the auditory feedback system showed a stable wireless connection for longterm data transmission. The systems data rate of 100 Hz conforms to the recommendations of sampling rates for medical plantar pressure measurement systems (cf. Giacomozzi et al. 2012). Even when testing with two simultaneous links no performance losses were obvious. The achieved latency time of 70 ms between sensor onset and audio play back lies beneath the threshold for intermodal detection of asynchrony (cf. van Vugt & Tillmann, 2014), so motor task and audio signal are perceived concurrently.

Currently used electronic components, as for example the Sparkfun Arduino Fio v3 Board, are still relatively large in dimension. Therefore future research has to further miniaturize these technical components in order to make it embeddable in the insole.

Another focus in future research lies on the sonification of gait itself. For the purpose of rendering the sonification to an assistant augmented feedback channel for the patient, convenient parameters of gait have to be chosen depending on the specific patient group. As already quoted in chapter 3 the development of an appropriate audio design, considering particular patient demands and psychoacoustic properties, has to be one of the major future tasks.

2 http://spdf.gsfc.nasa.gov/research/sonification/ <02/06/2014>

First implementation of the system will be targeted toward a patient population that shows typical aberrations of normal gait, as for example patients with knee osteoarthritis. These patients typically show the following alterations: a decreased walking velocity, a shift in the percentage of single-limb toward a prolonged double-limb support time, decreased swing times, reduced step lengths, and an increased step width. The sonification of one or more of these parameters, such as limb support times, may enable the patient to experience inter-limb asymmetries or excessive unilateral loadings. In response to the auditory representation the patient may adjust his/her walking pattern toward a more even movement execution. In order to examine the system's usability, as well as its therapeutic relevance and its validity, different investigations with the target group have to be done.

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