A WIRELESS INSTRUMENTED INSOLE DEVICE FOR REAL-TIME SONIFICATION OF GAIT

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ABSTRACT

The treatment of gait disorders or impairments is one major challenge in physical therapy. The broad and fast development in low-cost, miniaturized and wireless sensing technologies supported the development of embedded and unobtrusive systems for robust gait-related data acquisition and analysis. Next to their application as portable and low-cost diagnosis tools, such systems bear also the capability of using them as feedback devices during gait retraining to foster motor learning processes. The approach described within this project applies movement-based sonification of gait to foster motor learning aspects during gait retraining. In detail the aim of this manuscript is threefold: (1) present a prototype (the SONIGait device) of a pair of wireless, sensor insoles instrumented with force-sensors for real-time data transmission and acquisition on a mobile client, (2) present the development of a set of sonification prototypes for real-time audible feedback and (3) evaluate the sonification prototypes as well as the SONIGait device within a pilot study.

1. INTRODUCTION

The ability to walk is an essential motor function and a basis for almost all activities in everyday life. Therefore the treatment of gait disorders or impairments is one major challenge in physical therapy. There is a vast spectrum of methods for evaluating and diagnosing several kinds of gait disorders, which reach from simple visual inspection by physical therapists to highly sophisticated, technology-assisted solutions in order to quantify biomechanical aspects of gait. This quantification is often performed by using three-dimensional motion capture systems combined with force plates to measure kinematic and kinetic aspects during locomotion. The high accuracy of such systems is accompanied by several limiting factors such as high acquisition and maintenance costs as well as large space requirements. In addition, these recordings typically take place under laboratory conditions, hence they may not reflect everyday life challenges and cover only a limited amount of footsteps.

Due to the broad and fast development in low-cost, miniaturized and wireless sensing technologies, wearable and mobile platforms for gait analysis have emerged in the field of clinical rehabilitation and tele-monitoring. This allows for the development of embedded and unobtrusive systems for robust gait-related data acquisition.

Next to the use of such systems as portable and low-cost diagnosis tools, such systems bear also the capability of using them as portable feedback devices during gait retraining to foster motor learning processes. The approach described within this project involves the use of movement-based real-time sonification of gait, based on an unobtrusive, wireless, instrumented insole system for plantar force distribution acquisition. Effenberg [1] suggests, that movement sonification can be used to enhance human perception in the field of motor control and motor learning. A possible explanation for Effenberg’s view may be the advantage of multisensory integration over solely unisensory impressions of a performed movement [2]. On this note, sonification provides additional information to the already available sensations, shifting from ‘intrinsic’ to more ‘augmented’ feedback. The predominance of the acoustic over the visual system concerning temporal discrimination [3] may be another reason for the effectiveness of sonification in supporting motor perception and learning.

Several approaches have been published in the literature proposing sonification as promising approach for training and/or rehabilitation purposes. For example, sonification applications have been used in rowing [4], [5], handwriting [6] and speed skating [7].

Next to these, a small number of approaches also exist in the field of gait retraining. These typically focused on different patient populations and in general show promising results [8]–[12]. However these systems also have several short-comings. Malucci et al. [12] and Rodger et al. [11] for example synthesize sounds by using spatial and/or temporal information of specific biomechanical gait parameters, but base their data capturing techniques on expensive and/or large laboratory equipment, such as three-dimensional motion analysis systems. Hence possibilities for the use of their systems are restricted to the laboratory settings only. In return, approaches described by Redd and Bamberg [9] or Riskowski et al. [10] are based on low cost and portable systems (such as instrumented insoles or knee braces) but use only basic auditory cues, such as error identification with distinct sounds. The system introduced by Baram and Miller [8] shows similar short-comings. They developed a small portable, ankle mounted system for people with multiple sclerosis which generates a ticking sound each time the user takes a step. By highlighting temporal aspects of the individual walking pattern, the user should be made aware of possible asymmetries and aberrations in fluency. This procedure was meant to benefit the harmonization of a non-rhythmic walking pattern. One of the strengths of this system clearly lies in its simple feasibility, which makes the system affordable for a broader population.

However, the representation of a person's temporal stepping frequency alone, may be insufficient for qualitative advances in gait rehabilitation. Considering the above mentioned approaches in gait sonification, there is a demand for the development of a system that is unobtrusive, easy to use, real-time, portable, low-cost and showing advanced sonification procedures incorporating more complex information such as temporal aspects, weight distribution or kinetics.

2. Objective and Approach

Synthesizing sounds from biomechanical gait data has manifold possibilities in how these data are processed and how audible feedback is generated. For an everyday application in physical therapy the design of the generated sounds mainly has to respect two aspects: in order to support the therapeutic process, sounds should at least not be annoying to patients and at the same time the auditory displays should give an efficacious gait representation for patients in order to foster motor learning. This research therefore aims to identify sonification types that provide an appropriate balance between pleasantness and effectiveness to patients. Based on these considerations the objective of this research is (built upon previous work) the design and manufacturing of a real-time, portable and low-cost gait sonification application for use by patients in- and outside of a traditional clinical environment, where the auditory display serves as a support for therapeutic interventions and self-directed learning at home. The actual research that is to be presented within this paper aimed at:

(1) presenting the prototyping development of a pair of wireless, sensor insoles instrumented with force-sensors for real-time data transmission and acquisition on a mobile client (SONIGait).

(2) presenting the development of a set of sonification prototypes for audible feedback on a mobile client in combination with the SONIGait device.

(3) presenting data from a pilot study targeting two primary questions: Is there a difference in self-reported scores of "pleasantness/unpleasantness" between the four different types of sonification during walking? Does one or more of these types of sonification cause any changes in specific spatio-temporal gait parameters, hence alter normal gait patterns of healthy participants walking at their self-selected walking speed?

3. DESIGN OF THE SONIGAIT DEVICE

Priorities for the design and manufacturing of the SONIGait device were as follows: besides being low-cost and affordable for a broader population, an appropriate auditory feedback system for gait analysis needs to be unobtrusive. The device must ensure natural movement execution without altering movement itself. 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 submit data with minimum latency in order to provide the user with real-time auditory information and thus enable optimum learning outcomes. As the device is meant 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.

Based on these requirements a prototype of a force-sensing insole platform with a modular and generalizable approach was developed.

3.1. Embedded Sensors

The SONIGait device (Figure 1) has two instrumented insoles, each having one processing and data transmission unit. The instrumented insoles for the left and right foot are each equipped with seven circular (diameter: 9.53mm), ultra-thin (0.2mm) and flexible force sensors with a force range of 0-445N (Tekscan, FlexiForce A301) to sample plantar force distribution during walking. These force sensors are located at the heel area and following the lateral part of the sole to the forefoot and metatarsophalangeal joints. This sensor arrangement allows for calculating several gait timing parameters as well as rough approximations of the vertical ground reaction force and plantar force distribution. Additionally a Sparkfun IMU (SparkFun Electronics, Niwot, Colorado, USA) combining an ADXL345 3-axis accelerometer (Analog Devices, Norwood, MA, USA) and an ITG3200 3-axis gyroscope (InvenSense Inc., Sunnyvale, CA, USA) allows for additional data capturing. Within this manuscript only sonification applications will be presented, which are based on the force sensor data.

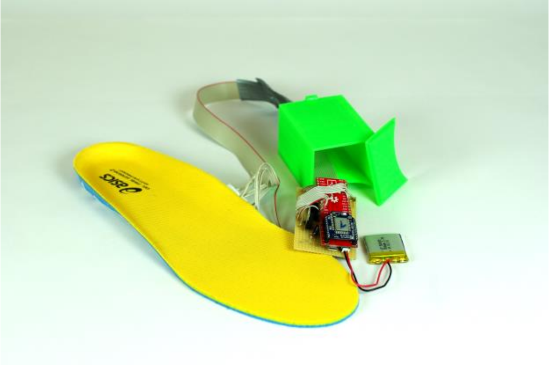

Figure 1: The SONIGait device: embedded force sensors, IMU unit, microcontroller with Bluetooth LE chip, conditioning circuit and 3.7V lithium-ion battery.

3.2. Microcontroller and Wireless Data Transmission

Data from the embedded sensors are sampled by a Sparkfun Arduino Fio v3 Board (ATmega32U4, 8-MHz processor). The SONIGait device is powered by a 3.7V lithium-ion battery supply. Through the provided XBee socket for RF communication, the Arduino Board is connected to a Bluetooth Low Energy (LE) enabled XBee module based on the BlueGiga's BLE112 Bluetooth LE. The provided firmware of the BLEBee Module was slightly modified to increase the data chunk size from 1 to 20 Byte. This allowed an increase in sampling rate to 100Hz for all sensors sampled simultaneously for both feet. The total latency for data capturing and transmission to the mobile device sums up to approximately 70ms. A scheme of the SONIGait device is shown in Figure 2.

At the present stage of development the microcontroller unit as well as the battery are not yet directly embedded into the instep of the sole. Future developments are going to focus on the refinement and miniaturization of both modules. Currently, these components are stored within an ankle or dorsum-mounted small box (7.5x5x3cm) on each leg (see Figure 1). The asset costs for the actual device for both legs are less than $500 (without the mobile device). Hence this prototype already shows promising results to fulfill the requirements of a low-cost and unobtrusive device for (more complex) gait data capturing and real-time sonification of gait.

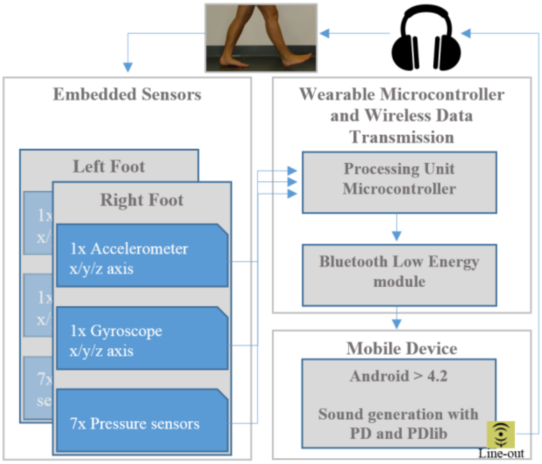

Figure 2: Embedding of the SONI-Gait device in a closed-loop interaction system based on real-time sonification of gait data.

4. SONIFICATION OF FORCE SENSOR DATA FROM THE SONIGAIT DEVICE

Appropriate sound design of footsteps has been a challenge for numerous applications in fields related to entertainment, sports training, and medical rehabilitation, the latter using sounds of footsteps in order to treat balance and gait disorders as well as motor deficiencies. In general, the sound design of these approaches can be distinguished between sample based implementations using recordings of real-life footsteps [11], [13] and synthesized sounds, which need to be further classified into models aiming to simulate real-world walking sounds on different ground textures [11], [14]–[17] and the design of abstract sounds for the purpose of providing additional information about gait characteristics to the recipient [13], [18]. Bresin et al. [19], [20] analyzed the impact of acoustically augmented footsteps on walkers and investigated in how far their emotional state was represented by the audio recordings of their walking movements. They stated that there are perceivable differences among gaits and that in a closed-loop interactive gait sonification, the sound character of the augmented footsteps influenced walking behavior.

One further conceptual distinction concerns the intended purpose of closed-loop sonifications in the context of sports training and medical rehabilitation. In order to enhance the periodicity of footsteps, Boyd & Godbout [7] used phase-locked loops to synchronize generated sound events to walking and running. Rodger et al. [11] also used computationally-generated rhythmic sound patterns to support walking actions of Parkinson's Disease patients. However, synchronization of walking periodicity isn't an issue at the present stage of the SONIGait project. The presented approach therefore focuses on the immediate acoustic mapping of the ankle-foot roll-over during walking.

4.1. Parameter Mapping of Force Sensor Data

Existing studies using force sensors for footstep sonifications implemented between one and three force sensors [13], [18], [20] for each foot. Due to the limited amount of measured force points, this approach seems more suitable for triggering sound events than for a direct mapping of the plantar force distribution data of the feet (during the ankle-foot roll-over) to a sonification model.

To get a more precise representation of the ankle-foot roll-over, 7 sensors have been used instead, which are distributed across the insole providing sufficient data for comprehensible sonifications (Figure 1, Figure 3). Thereby, the measured force values (converted to 10bit integers) of each sensor are mapped to amplitude values of the corresponding sound generators of the sonification model. The audio outputs of the 7 sound generators representing the plantar force distribution of the right and left insoles are mixed on the corresponding stereo output channel. For the presented approach, no adjustments (e.g. by adaptive calibration) of the incoming values in respect to the positions of the sensors and the weight of the test persons have been made. In order to restrict the range of the incoming data and to avoid unnecessary noise, values below 30 are cut off and values above 500 are limited to a maximum amplitude. Optionally, incoming data may be scaled ($out=in^2$, $out=in^{0.5}$) and a moving average filter (averaging 5 consecutive input values) can be applied.

Possible correlations and interdependencies between sensors have not yet been regarded for the sound design, although these aspects seem promising to clarify the acoustic information and will be included in future research.

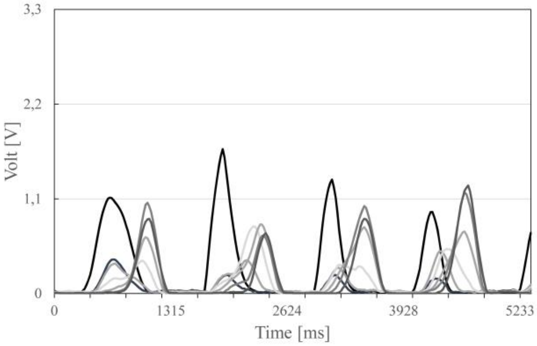

Figure 3: Raw data ('force profiles', gray shaded lines) of several consecutive steps measured by a set of 7 FlexiForce A301 sensors from one instrumented insole during walking. These data were used for the sonification process.

4.2. Aspects of Sound Design

Considerations on the sound design of sonifications depend on the defined research objectives and in particular on the addressee of the auditory display. In the SONIGait research project, sonification has the function to support patients and their physical therapists during treatment and recovery from gait disorders. Therefore the design of the auditory display needs to be more on the side of an "universal design" than on a "trained ear" approach [21]. This does not necessarily mean that there should be no learning process involved to be able to differentiate auditorily between variations of gaits. However sound design has to consider that learning progresses in many cases may be rather limited. Also, in order to support the healing process, the generated sounds should be unobtrusively, pleasant and at the same time sufficiently informative. A comparable universal sound design approach by Grosshauser et al. [18] indicated that elementary sound generation using sine and saw tooth tones outperformed more advanced synthesis methods such as granular synthesis and amplitude modulation. Therefore, we decided to keep the sound design as comprehensible and intuitive as possible.

For the two[1] sets of 7 sound generators representing insole force sensors 6 arbitrarily combinable synthesis modules (SYN1-6) were developed:

(SYN1) subtractive synthesis using band-pass filtered noise. For each sound generator white noise is filtered by a formant filter bank of 6 band-pass filters providing characteristic sounds for each of the 7 sensors of the insole. The parameters of the "heel" sensor were adapted from the formants of a wooden door panel cf. [17, p. Chapter 32]. The fundamental and formant frequencies of the generators consecutively activated during the ankle-foot roll-over were set increasingly.

(SYN 2) wavetable synthesis using a sinusoidal wave form moderately enriched by two harmonics. The attribution of individual pitches to the 7 sound generators facilitates the generation of harmonic and melodic patterns.

(SYN 3) fm-synthesis with statically defined carrier and modulator frequencies for each sound generator. The modulation index [22] is controlled by normalized incoming force sensor data.

(SYN 4) a sinusoidal oscillator, which frequency is controlled by incoming force data (force dependent frequency). Thus, other than in the modules described above, the sound generators are not characterized by their fundamental frequency.

(SYN 5) implementation of a simple Karpus Strong algorithm (Figure 4). An "impulse" (white noise) is triggered by the decrease of the force slope (change of sign of derivation). The delay time of the dampened feedback loop that determines the frequency of the sound relates to the force maximum.

(SYN 6) a procedural gait sonification model adapted from Farnell [16], cf. [11], [17], [23]. Since the implementation of modal synthesis doesn't reveal more detailed information than sound generation based on subtractive synthesis, the model was not included into the tested preset collection.

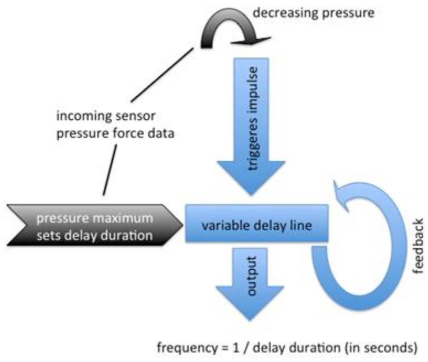

Figure 4: Implementation of Karpus Strong algorithm [24, p. 213]

In order to smoothen the audio output, a compressor[2] and an optional reverb have been implemented in the mixing section of the sonification software interface.

Based on these 5 (of 6) sound synthesis modules 18 presets were defined, of which 5 (SONI1-5) were to be selected by physical therapists for application to a group of test users. The presets differ in various filter and frequency settings, some of which are pitch related (e.g. building up fifths, chords, melodies), the amount of reverb and whether input data averaging is applied.

Combinations of sound generation modules in one preset have only been tested yet during the development phase, although some of the combinations appeared to provide promising results. Presets for left and right insole sound generation were identical. Due to restrictions of the graphical interface of the prototyped android device, presets cannot be adjusted during runtime. However, input data and generated audio are saved as text, respectively as audio files. The recorded data files can be played back at variable speed within the sonification software for further development and evaluation.

5. METHODS

To accomplish goal three a convenience sample of healthy volunteers was recruited. In total 6 male (age: 35±5yrs, height: 178±4cm, mass: 78±12kg) and 6 female (age: 38±7yrs, height: 166±5m, mass: 63±8kg) volunteers participated in this pilot study. Participants were excluded if they had any orthopedic, neurological, psychological or cognitive constrains effecting their gait. In addition participants were excluded if they were suffering from hearing deficiency.

To test if real-time sonification of gait alters the normal gait pattern the following experimental procedure was performed: In a first step each participant was introduced to the SONIGait device and its purpose. Once the initial setup was completed, participants were asked to walk at an 8-meter straight walkway for a total of 7 times. Herby they were asked to walk at self-selected walking speed and to keep on walking constantly throughout these 7 rounds. This procedure was repeated six times, using one of the sonification types described above and once without

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[1] left and right insole

[2] adapted from Frank Barknecht's rjlib (www.github.com/rjdj/rjlib)

sonification. The order in which these six situations were used, was randomly assigned using computer generated random numbers.

Spatio-temporal gait parameters of each participant were captured during the last five rounds of each type of walking (without or one type of sonification) using two synchronous FDM 1.5 systems (ZEBRIS, Germany, FDM 1.5; each 1.5m x 0.5m). Each system is constructed as 1.5m x 0.5m large electronic mat with 11264 capacitive sensors embedded into its surface. These two measurement systems were fully integrated into one walkway and even with its surface, forming a total of 3 x 0.5m of measuring area. When walking across the measurement system's surface, the force exerted by the feet is recorded by the sensors at 100Hz, allowing to map the force distribution and timing at a high resolution. These data are transferred and stored to a stationary PC via USB 2.0 for further analysis. The WIN FDM (v2.21) Software was used to extract spatio-temporal parameters of each trial and participant. For each participant and sonification situation a minimum of 15 steps were captured and used to calculate gait velocity (ms^{-1}), step time (s), step length (cm) and cadence (steps/minute) for the dominant leg. In addition the coefficient of variation (COV = SD/mean) was used to analyze variability of these parameters.

After each walking situation with one of the sonification types, each participant was surveyed. For this purpose they were given a short questionnaire comprising a total of 10 items, each having a Likert-scale with four or five points corresponding to the following scores: *not at all (1) – rudimentary (2) – good (3)– excellent (4); very pleasant (1) – pleasant (2) – neutral (3) – unpleasant (4) very unpleasant (5)*. This questionnaire aimed at capturing three main categories: (1) personal preference in sonification type, (2) how well the sonification type resembled the personal gait pattern and (3) self-reported estimate whether the sonification influenced their gait pattern.

Statistical analysis only were conducted for spatio-temporal parameters using IBM SPSS Statistics 22 (Somer, NY, USA). Initially, parameters were tested to comply with needed statistical assumptions. The level of significance was set a priori at p = 0.05 for all analyses. A one-way repeated measures ANOVA was utilized using sonification type with six levels as a within-subject factor (no sonification = SONI6, sonification type 1 to 5 = SONI1-5) for each dependent variable to identify any differences. Partial eta-squared (η) was used to calculate corresponding effect sizes. If differences were present, additional post-hoc analysis with Bonferroni adjustments were performed.

6. RESULTS OF THE PILOT STUDY

The following sections report the data acquired during the performed pilot study. These included results from the questionnaire and the spatio-temporal gait parameters.

6.1. Questionnaire

Regarding the question "*which type of sonification each participant would rate as the best or most favorable"*, 5 participants selected SONI2 (preset based on SYN3) as the most favorable one. All other types of sonification were each selected two times, except for SONI3 (based on SYN2), which only was selected once. Regarding the question "*how participants perceived the sonification type*" (ranging from *very pleasant* to *very unpleasant* on a five-point Likert scale) no clear differences were observable, and all showing a median of about 2 (*neutral*). Only SONI5 (based on SYN4) had a median of 1 (which corresponds to *unpleasant*). When asking how "*good a sonification type resembled the personal gait pattern"* (ranging from not at all to excellent on a four-point Likert scale) the median rating was 3 (corresponding to *good*) for all types of sonification, except for SONI5 which showed a median of 2 (corresponding to *rudimentary*). Regarding the question *"if the ankle-foot roll-over motion produced a comprehensible sound during walking"* (ranging from *not at all* to *excellent* on a four-point Likert scale), all sonification type showed a median of greater than 3 (corresponding to good), except for SONI5 which only showed a median of 1.5 (corresponding *to not at all/rudimentary*). The same results were true for the question *"how good were you able to match the perceived sound to your left and right foot*", were SONI5 showed the least scores again.

Regarding the questions *"if the type of sonification affected the participant's gait in respect to gait velocity, rhythm or ankle-foot roll-over motion"* in general no, to only rudimentary affects were ascribed each sonification type.

6.2. Spatio-temporal Parameters

Mauchly's test indicated that the assumption of sphericity had not been violated in any ANOVA performed. Results of ANOVA showed no significant differences in gait variability parameters (COV) when walking with the different sonification types and without sonification. However, there were statistically significant effects (Figure 5) of sonification type (including no sonification) on: cadence [$F(5,55 = 9.514$, $p = 0.00$, $\eta = 0.464$], gait velocity [$F(5,55) = 5.195$, $p = 0.001$, $\eta = 0.321$] and step time [$F(5,55) = 7.368$, $p = 0.00$, $\eta = 0.401$]. Step length did not show any significant differences.

Post-hoc analyses showed that participants had a significant increased cadence ($p < 0.01$) when walking without sonification compared to all sonification types. Walking speed was significantly increased ($p = 0.04$) when walking without sonification compared to SONI1. Step time was significantly decreased ($p < 0.05$) when walking without sonification compared to the sonification types SONI1, 2 and 4. No other differences were observed.

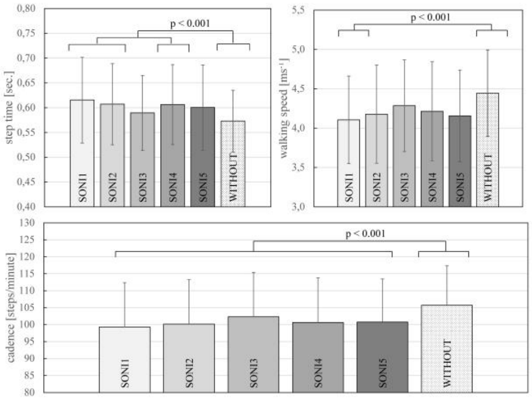

Figure 5: Results for step time [sec.], walking speed [ms^{-1}] and cadence [steps/minute] when walking with the different sonification types (SONI1 – SONI5) and without sonification (SONI6).

7. DISCUSSION

The following section represents an overall evaluation of the SONIGait device in regard to its functionality and its applicability for therapeutic use. Afterwards, the selection of the five sonification prototypes by the physical therapists will be analyzed and the results of the questionnaires will be evaluated in respect to their acceptances by the test users and their impact on spatio-temporal gait parameters.

7.1. Application of the SONIGait Device in the Pilot Study

Within this paper a prototype (SONIGait) for real-time sonification of gait related data was presented. The SONIGait device is capable of capturing plantar force distribution data from two shoe insoles, each equipped with a total of seven force sensitive sensors and an additional IMU (gyroscope and accelerometer). These data are continuously sampled at 100Hz and transmitted wirelessly via Bluetooth LE to a mobile client based on ANDROID 4.2 or greater. The SONIGait device will serve as a platform for future research pursuing the goal of providing patients with gait disorders, real-time acoustic feedback during their gait retraining process.

Priorities in the design and manufacturing of the SONIGait device were being (1) low-cost, (2) unobtrusive, (3) providing real-time acoustic feedback and (4) being able of capturing force data during the entire stance phase for both feet simultaneously. With an actual outlay of less than $500 for the entire device, this lies clear within an acceptable range for low-cost clinical devices. By using a microcontroller and wireless transmission protocol with very low energy costs, the device is capable of running more than three hours without the necessity to charge the batteries. This allows for practical use in therapeutic settings as well as in self-directed home-based training sessions. Tests showed that the overall latency in data transmission from the SONIGait device to a mobile client (in this case a Google Nexus 9 with ANDROID 4.2) is less than 70ms. Real-time auditory feedback in motor rehabilitation can be defined as the perceivable synchrony of a specific movement and its auditory synchrony. In the literature the threshold for intermodal detection of asynchrony ranges from approximately 100±70ms for musicians to 180±100ms for non-musicians [25]. Depending on the additional latency introduced by the mobile client, which is synthesizing the captured data to sound, the SONIGait device seems to serve as a promising tool for real-time sonification of gait data. This may be an advantage in rehabilitation to other devices described in the literature which use only a low number of sensors or gait data, e.g. [9], [12]. At this stage of research, the microcontroller unit as well as the battery are not yet directly embedded into the instep of the sole as desired (see Figure 6).

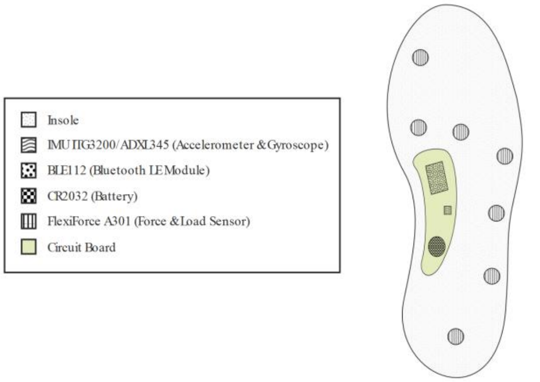

Figure 6: Desired form factor for the SONIGait device for future iterations in development.

Participants in our pilot study reported that they felt relatively comfortable with the system, and that the SONIGait device did not impede them during walking. However, the size still needs refinement and miniaturization of each module and is a next goal within this project. At this stage of prototyping it also has to be outlined that the sensors itself were not yet validated, hence absolute values for force data should not be interpreted. This also is a future goal with in this project. As described above the force sensors used within this prototype each has a size of approximately 1cm^2. Initial tests already showed that bigger sensors (circular sensing area of approx. 25mm diameter) will probably be more practicable to capture valid force distribution data of the stance phase during walking.

7.2. Selection of Sonification Prototypes and Evaluation:

Out of a set of 18 sonification prototypes (presets) based on the 6 synthesis modules introduced in Chapter 4.2, five (SONI1-5) have been pre-selected by physical therapists in order to be applied to a group of test users in the pilot study. All of the selected presets have in common that they included reverb as well as moving average filtering of the incoming data. Reverb and the data smoothening tend to settle the character of the generated sounds more on a holistic side than on a detailed analytical one. Based on the preselection by the physical therapists, this allows for the conclusion that the pleasantness of sounds may be rated as a higher selection criterion than a pure analytical display. As for the selection of synthesis modules the chosen sonification prototypes were based on two presets with melodic patterns[1] generated by wavetable synthesis, as well as one based on fm-synthesis[2], subtractive synthesis and force dependent amplitude. Here, a clear tendency towards “musical” in contrast to “realistic” sound generation was stated. Interestingly, this is in slight contrast to the study of Maculewicz [26]. They analyzed different temporal feedback forms (1-kHz sinusoidal, synthetic footstep sounds on wood and on gravel) on rhythmic walking interactions and found that participants favored more the natural synthetic sounds than the synthetic variation.

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[1] Beethoven’s „Für Elise“ and part of a boogie riff (c e g a b^{flat} c)

[2] carrier frequencies based on harmonic series, modulator using inharmonic frequencies, modulation index dependent on force sensor data

7.3. Evaluation of the Questionnaire

The above mentioned findings mostly conformed to the evaluation of the questionnaire completed by the participants within the pilot study. Although bell alike sounding fm-synthesis (SYN3) outperformed all other sonifications in terms of personal preference, and both wavetable approaches (SYN2) also were marked mostly *very pleasant, pleasant,* or *neutral,* substractive synthesis with a walking in snow alike sound character (SYN1) was also sensed as *very pleasant* by 25% of the participants. Only the sound of the sinusoidal oscillator (SYN4) that was frequency controlled by sensor force was regarded as *unpleasant* and *very unpleasant* by a majority of participants.

Also in regard to the recognition of their gait patterns by the participants themselves, the latter synthesis type (SYN4) was clearly outperformed by the others. Whereas the walking pattern could at least be recognized as *good* by most of the participants in regard to the monitoring of the ankle-foot roll-over, fm-synthesis (SYN3) was noticeably superior, followed by the two wavetable synthesis sonifications (SYN2). The gait rhythm was recognizable by a majority of participants over all sonification variants, again slightly better with fm-synthesis (SYN3) and the "Für Elise" wavetable (SYN2 with preset SONI1). Similar results were observed regarding the auditory differentiation between the left and right foot. From the view of sound design and auditory perception, it can be (like in 7.2) concluded that the sonifications based on more musical aspects outperformed both realistic (walking in snow alike) and rather abstract (frequency dependent force) sonifications. In regard to our approach to generally evaluate the impact of real-time closed loop sonifications on the participant's walking, we observed that participants perceive the various sonifications quite differently. Some participants could at least basically associate sound sequences to their gait patterns. Also the influence that the sonification type had on the gait pattern was quite diversely estimated by the participants. However, data showed that a participant either felt generally influenced by all sonification types or by none.

7.4. Gait Analysis Results

Within this pilot study also spatio-temporal parameters of gait were analyzed during walking with the different sonification types as well as without sonification. Primary aim of this analysis was to test whether or not real-time auditory display of one's gait pattern will have an immediate effect on the way of walking. The data showed notable differences in spatio-temporal parameters when walking with sonification compared to walking without sonification. The most dominant effect was present for cadence, where participants showed a clear decrease (regardless which type of sonification used) compared to walking without sonification (Figure 5). This effect was partly accompanied by a decrease in walking speed and increase of step time as well. This linkage is not a surprising finding as walking speed and cadence are strongly related to each other. Cadence is often described as one of the two key determinates (next to step length) for regulating self-selected walking speed [27].

Interestingly only significant differences were present between certain sonification types to no sonification (see Figure 5). No differences in spatio-temporal parameters were observed between certain types of sonification. This finding might support the already stated hypothesis that participants perceive the various types of sonification quite differently. However, regardless of how participants perceived real-time auditory feedback, this additional information seems to cause them to walk slower.

Typically self-selected walking speed utilizes minimal attention to gait and prioritizes automatic control mechanisms (from a motor pathway view). It is hypothesized that this may be a mechanism by which gait control is simplified or 'automated' during undisturbed, steady state walking [28]. However, when movement is novel or externally affected (e.g. through auditory display), a more 'attentional' mode is required. It is quite possible that the additional information of gait (sonification) may have forced the participants to focus the attention to one or more gait parameters (e.g. cadence, step length or the process of ankle-roll over), and therefore used a 'more attentional pathway'. This effect may be helpful to disrupt automatic control mechanisms in a variety of disease states and may support in drawing the attention to specific gait parameters of interest during gait retraining, providing external cues, augmented feedback, and hence supporting motor learning processes.

8. CONLCUSION AND FUTURE PROSPECTS

Within this manuscript a prototype platform (SONIGait) for real-time sonification of gait related data was presented. This device is capable of capturing force values from seven sensors below the left and right foot synchronously using an instrumented insole, and transmitting these data at 100Hz wirelessly to a mobile device. The SONIGait device will serve as a platform for future research and development in the field of real-time sonification of gait-relevant data for the purpose of augmented feedback during rehabilitation of gait disorders and gait retraining. In addition, several approaches have been presented how such data may be sonified and an evaluation of these sonification prototypes was performed. Interestingly all types of sonification showed remarkable changes in gait parameters. One possible explanation is that the additional information of gait may have forced the participants to draw their attention to one or more specific gait parameters such as cadence or the process of ankle-roll over. From a motor learning point of view this effect may help to disrupt automatic control mechanisms in a variety of gait disorders and may support in drawing the attention to specific gait parameters of interest and therefore support motor learning processes in general.

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