DEVELOPMENT OF A SONIFICATION METHOD TO ENHANCE GAIT REHABILITATION

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ABSTRACT

In this paper, we introduce a sonification tool that facilitates the process of sonic interaction design for walking apparatuses [1]. The aim of the tool is to aid the design process through a set of experiments based on specific motor tasks guided by auditory feedback. In a future stage the goal is the implementation of an auditory feedback system for motion guidance, embedded in a robotic gait trainer for walking rehabilitation. The tool is based on previous work from our research [2] and other projects [3,4], which explored sonification from footsteps and other body motions. The hardware part of our system consists of a foot-glove-sole enhanced with sensors and a wearable IMU-System[1] for motion tracking from the lower limb. The software is composed of a motion analysis module, a sonification module and an experiment aid module. Together with the hardware, these four modules allow the researcher to filter sensory signals and make action-sound coupling decisions. Thus, a variety of settings for conducting experiments are available. We also present first examples for motor task experiments to be conducted on a larger clinical study using the presented system. During the design process, first self-tests showed the potential from the implemented motion-sound-coupling techniques and the motion-guidance-function appointed to the auditory feedback provided. This leads to conclude that the proposed strategies may succeed in the evaluation of effectiveness from auditory-feedback aiding gait training in a larger scale. Further experiments, which some of them are described here, are to be conducted during a larger clinical study.

1. INTRODUCTION

Walking, generally considered as one of the most automatic actions, consists of cyclic movements [5]. Sonic feedback for walking may be a potential motivational factor for users to improve their gait performance. The advantages of auditory feedback such as requiring less attention and allowing the user, to focus on the movement [e.g., 6] are well known. In previous research related to auditory feedback for motor training, we can identify a tendency to reduce the complexity of the body movements and to address the auditory feedback to correct specific anomalies present within a complex cyclic motion [7, 8].

Impairments when walking due to stroke are very common, for example. Stroke attacks are frequent disturbances that affect the lives from thousands of persons every year, being the second death cause worldwide and disabling the 75% of survivors [9]. While the cardiovascular health is the key to stroke prevention, motor impairments are the focus of rehabilitation. Movement rehabilitation enables stroke survivors to more quickly recover some level of independence. Existing robotic devices, which enable solely a repetition of a constant gait pattern, are essential but not sufficient for a successful therapy [10]. The quality of the rehabilitation may increase with each additional stimulation or feedback enabling the user to be aware of his or her own activity and furthermore, to be in control of the robotic device. Current gait training devices are limited in outputting feedback to the patient, which makes him or her aware about his or her own motion, thus the patient experiences a disconnection between his or her own activity and the activity being guided by the robotic device.

A promising approach to address this problem is to use an interactive task-based auditory system for motion guidance, embedded in a robotic gait trainer for walking rehabilitation. Accordingly, our goal is to implement different motivational strategies based on a feedback system aiming at guidance and correction of lower-limb performance during a gait rehabilitation therapy in order to introduce an aid that has the potential to improve the performance and to increase patients' motivation. Furthermore, such an innovative system would allow the patient to guide and to correct his or her motion, while performing exercises. Our hypothesis is that auditory feedback has a positive impact on walking performance and the capability to motivate to actively engage in exercise. The purpose of our wearable sonification prototype for gait rehabilitation therapy is twofold: the tool can be used for auditory design experimentation and it can be used as an experimental apparatus for evaluation of auditory feedback guiding motion during specific task-oriented walking activities.

After an overview of related research, we describe the developed auditory system, which intends to be used in the first studies with healthy participants and experiments with walking rehabilitation patients. We present the hardware and software parts of the system as well as some sonification models, focusing on coupling action-sound and algorithms. Two different sorts of planned experiments will be presented: those related to walking patterns and movement tasks without support, and those related to a robotic support system. We conclude by presenting first models of motor task experiments. Finally, we will outline future steps, which will lead us to both experiments without a rehabilitation device and with its integration into a novel robotic gait trainer for walking rehabilitation.

2. BACKGROUND

Most of the auditory feedback techniques that guide sensorimotor performance have been designed and evaluated in healthy users [3, 11, 12, 13]. Walking on a treadmill while obtaining kinetic guidance, participants modified their footpath to match a gait pattern. Obtaining kinetic guidance and auditory feedback (which frequency corresponds to the rhythm of the prescribed footpath) is as effective as when receiving kinetic

[1] IMU stands for Inertial Measurement Unit, which are electronic devices, like accelerometers or gyroscopes capable of reporting craft's velocity, orientation, and gravitational forces.

and visual guidance. Furthermore, receiving auditory feedback and kinetic guidance enhanced the gait symmetry after training comparing to participants receiving kinetic guidance and visual feedback. Bresin et al. [3] investigated different walking patterns with sensor-equipped shoes that provided auditory feedback. The sound of the walking surface with a higher spectral centroid such as iced snow led to a more active walking style. When walking with a lower spectral centroid such as walking on mud, walking behavior was reduced. Furthermore, whereas walking on harder texture sounds arouse a more aggressive walking pattern, softer texture sounds led to tender and sad walking behavior. Sonification in direct synthesis of footstep sounds generating auditory feedback by oneself led to intuitive walking behavior and a higher confidence in users [11]. Rhythmic auditory feedback, which was not generated by the own footsteps, resulted in no motion restrictions after user's synchronization with the system. In contrast, the rhythm of a temporally constant synthetic walking sound was not well accepted by users. Therefore, footstep-related auditory cues are one of the most promising and varied performance-related cues and are relevant for bodily self-consciousness [5].

In order to enhance learning in complex motor tasks, researchers showed that auditory feedback based on error sonification supports a three-dimensional rowing-type movement compared to visual feedback [13]. When providing concurrent augmented feedback, three-dimensional auditory feedback designs based on stereo balance, pitch, timbre and/or volume were understandable and interpretable for participants. Accordingly, subjects were able to follow different target motions. Visual feedback based on superposition of actual and target rudder orientation led to the most accurate movements. Consequently, both concurrent auditory and visual feedback systems encouraged multidimensional motions [13]. The use of auditory feedback to correct and to guide motor performance during different activities was in line with Goldbout & Boyd [7], where speed skaters corrected repetitive motions in response to continuous and real-time provided auditory feedback.

In contrast to cases mentioned before with healthy users, auditory feedback embedded in rehabilitation technologies had a marginal role in motor rehabilitation [14]. Rehabilitation patients mainly receive auditory feedback while obtaining adaptive assistance from a robotic support, such as a locomotor training. Comparing the effect of kinesthetic with visual locomotor imagery training on walking performance, kinesthetic locomotor imagery training has an increased therapeutic effect on walking performance in patients with post-stroke hemiparesis [15]. When combining the first-mentioned with auditory step rhythm, the effect can be further extended. Continuous auditory-feedback based on a proper sound cue during robot-assisted movement training has been shown to have the potential to improve stroke survivor's engagement and training performance [16]. Providing auditory feedback of tracking error allowed to simultaneously perform robot-assisted tracking tasks and distracter tasks successfully. Accordingly, by reducing tracking errors close to the baseline and increasing the effort, distracter tasks can be performed effectively. These results were significantly smaller when performing with a non-paretic arm and for non-stroke participants [17]. Thus, auditory feedback on errors requires an understanding of the presented cues in order to reinforce and stabilize the targeted walking behavior of patients.

3. SYSTEM DESCRIPTION

The sonification system presented in this paper is an experimental model of a versatile tool for sonification specific to gait patterns. This tool is designed in a modular way and it provides multiple possibilities for different motion-sound coupling settings. The system consists on four main modules: the sensory module, the motion tracking and analysis module, the sonification module and the experiment aid module.

3.1. Sensory module

The sensory module is responsible for gathering all the information and signals related to body movement and its interaction with the environment. It also serves as the bridge between the human body and the computing device. The sensory module is divided in two main parts: a foot-glove responsible for the foot-ground sensing, and a wearable IMU-System for motion tracking and analysis of the lower limb motion [see figures 1, 3]. In the foot-glove, a sensor-enhanced sole is embedded. The sole is integrated with a flex sensor and two piezoelectric elements. The sensors allow to track flexion of the foot and the impact moments from the heel and the toe areas.

Figure 1. *Foot-glove and a cased accelerometer, which is part of the IMU -motion capture system*

The IMU-System consists of seven cased accelerometers distributed along the two extremities from the lower limb of the user: on each leg, one accelerometer is located at the lateral side of the upper leg, one at the lateral side of the lower leg and one at the dorsal side. An extra accelerometer is located at the posterior side of the leg, and allows to measure tilt from the back and serves as reference system to evaluate horizontal balance between both hips. This sensor constellation enables tracking of the overall position of the lower limb and related movement analysis. The present version of the tracking module is partially wired. It is all controlled and powered by an Arduino[2] micro-controller which communicates with the computer serially through a Bluetooth module.

3.2. Motion tracking and analysis module

This module consists of signal interpretation algorithms running under diverse open source platforms[3] responsible for the

[2]Arduino is an open source electronics prototyping platform based on flexible, easy-to-use hardware and software http://www.arduino.cc/

[3]Processing is a programming language, development environment and online community created to serve as a software sketchbook.

tracking and analysis of the sensor signals gathered by the sensory module. As mentioned by Young et al.[18] , using IMUs for relative motion analysis and tracking is an effective method. This approach considers a model of the subject's body structure in order to estimate the overall posture and length from the bones being tracked.

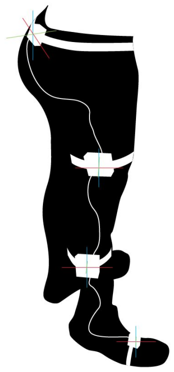

Figure 2. *Wearable IMU motion tracking system for lower limb*

In the motion tracking and analysis module presented here a similar method is implemented. Based on the fact that real body measures have no influence on the tracking system only orientation from each cased accelerometer, called *IMU,* is used to estimate roll and pitch from bones of the virtual skeleton [see figure 3]. The position of each joint from the lower limb is calculated by forcing the extended vectors from each IMU to intersect using the following formula:

$$\begin{aligned} Nx &= d\cos(\Theta) * \sin(\Phi) + Mx \\ Ny &= d\sin(\Theta) * \sin(\Phi) + My \\ Nz &= d\cos(\Phi) + Mz \end{aligned} \quad (1)$$

Where Nx, Ny, and Nz are the resulting components from the vector N. Vector N represents one of the joints in the lower limb. *Mx, My and Mz* are the given[4] or the resulting components from a previous vector M (joint) in the chain. d is the fixed distance between vectors *N and M*, and its proportional to the human body model. *Phi(Φ) and Theta(Θ)* are the pitch and roll signals read from the accelerometer.

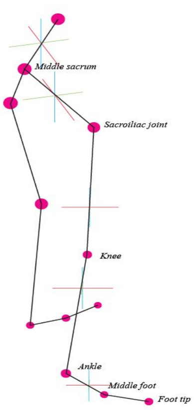

Figure 3. *Represented joints as vectors in space with given distances between them*

Analog readings, corresponding to rotation values in Z and X axes, are estimated from each IMU located between each two joints and by the algorithm as the Phi(*Φ*) and Theta(*Θ*) angles. These values are necessary for calculating a three dimensional rotation affecting two vectors. Given a fixed distance between each two joints, the overall positions from the joint constellation are calculated using sinus and co-sinus trigonometric equations for calculation of three-dimensional rotation.

Rebuilding a human body model, using the tracking system signals, allows us to measure the angles occurring in the different joints. Thus, we can measure flexion, rotation and extension values from upper and lower leg and foot. Relative velocity and acceleration from specific movements are also measurable values.

It is observed that there are limitations in the current IMUs when tracking the yaw value, or rotation in the Y axis. Thus, the orientation in this axis of the foot tip is not fully reachable. For further improvement, the current IMUs in the system are to be replaced with commercial ones, additionally equipped with gyroscope, which would allow us to read absolute position and yaw values[5].

The flex sensor is interpreted as a 2D rotation angle (Θ), affecting the vector T representing the tip of the foot and the vector A representing the middle foot joint. The roll value is calculated by adding the last joint value in the z axis (Az) to the Tz value [see figure 4].

Piezoelectric readings are interpreted as impact moments from heel and stroke, allowing us to detect when the ground has been impacted and left again, along with the strength and velocity from the impact moments. In order to have continuous signals these two elements can be replaced by force sensing resistors (FSR).

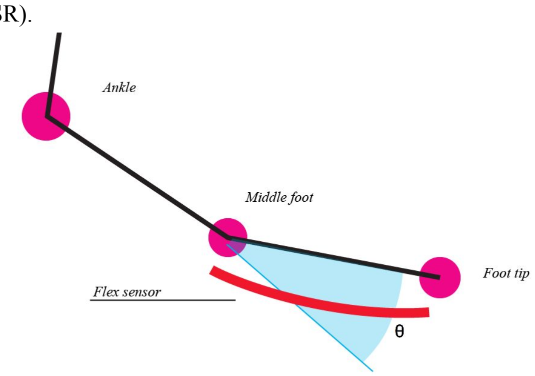

Figure 4. *The flex sensor linear readings interpreted as 2D rotation angle(Θ) affecting T(footTip) and A(middleFoot) vectors*

3.3. Sonification module

The sonification module couples motion signals to specific auditory feedback. This module offers the possibility to switch between several strategies for sonification. It is built for providing specific feedback depending on the specific motor-task experiment. The sonification algorithms, run under open source environment for audio synthesis[6]. Strategies for action-sound coupling are described below.

3.4. Experiment-aid module

This module is a basic integrated graphic environment. It is useful for visualization of real time data, analysis of information

http://processing.org/

[4]Initial values must be provided in order to initiate a reference system

[5]http://www.yeitechnology.com/yei-3-space-sensor

[6]Supercollider, open source environment for real time audio synthesis and algorithmic composition. http://supercollider.sourceforge.net/

and the design of experiments. It allows to select between several sound-coupling coupling settings and to take decisions on sensory input signal filtering (tracked motions), thus enabling development of auditory feedback for specific parts of the walking cycle or for smaller movements present in it [see figure 5].

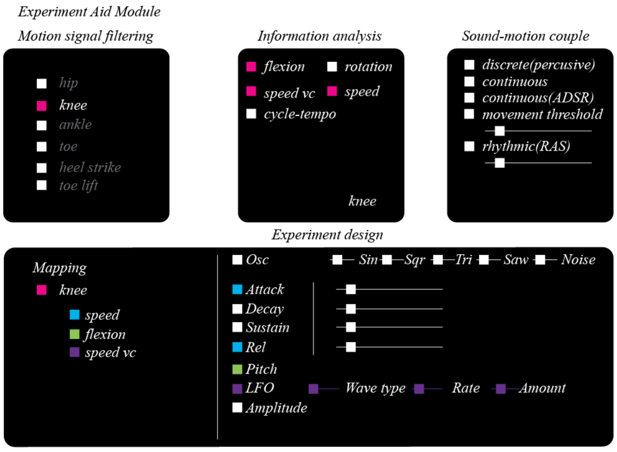

Figure 5. *Diagram from the experiment-aid module*

4. SONIFICATION

4.1. Action-sound coupling

As discussed above, the sonification module allows us to switch from several motion-sound coupling parameters. Here, we present some of the first implemented strategies.

a) Fixed movement threshold shifting for triggering discrete auditory feedback

In this sonification model, the movement deviations are dynamically measured. A threshold value is set as constant defining boundaries for detecting variations on the signal. Each time a signal reaches a boundary from the threshold a discrete auditory feedback signal is displayed and a new position is set, shifting the threshold boundaries to the new position [see figure 6].

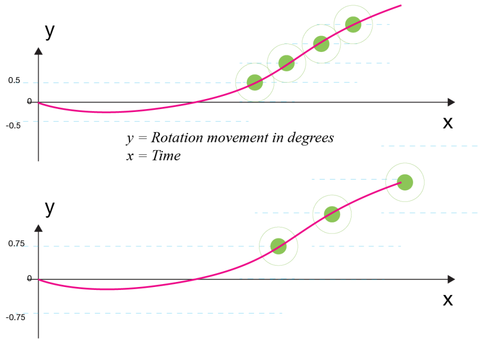

Figure 6. D*otted lines are threshold boundaries. Bigger dots are feedback being triggered. A variation in threshold is applied resulting in a variation from feedback recurrence*

The threshold shifting and the threshold size modulation allow to regulate the sensitivity of the feedback provided, thus increasing threshold spreads the recurrence of the feedback provided and it will require wider variations for feedback to be displayed. The discrete signal can have fixed envelope and pitch parameters, or it can be modulated by integrating the motion-mapping rules from the following sonification strategies.

b) Fixed movement threshold shifting for modulating continuous auditory feedback

As in the previous case, a movement threshold is shifted, and a modulation on a continuous auditory feedback occurs each time a movement deviation reaches a boundary from the threshold. This gives a stepping modulation, in which step resolution is affected by the size of the movement threshold. A radius can be applied to make the modulation smoother. The same modulation principle can be applied for discrete signals [see figure 7].

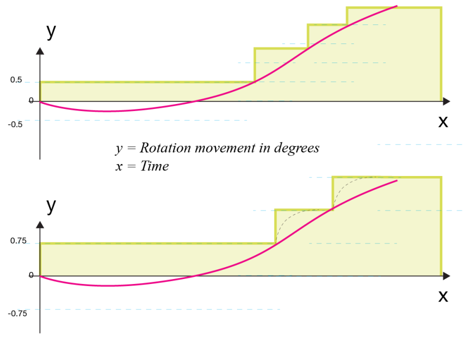

Figure 7. *The colored area is the modulated continuous feedback. A variation in movement threshold is applied, resulting in longer steps*

c) Movement range and speed deviations mapped to diverse parameters from a discrete auditory feedback

In order to provide multiple motion-sound coupling possibilities, mapping of movement signals to several parameters from the triggered auditory feedback are enabled within the sonification module and selectable in the experiment-aid module [see figures 8 and 9]. The following graphics illustrate the mapping from movement range and movement speed to pitch and attack of an acoustic envelope.

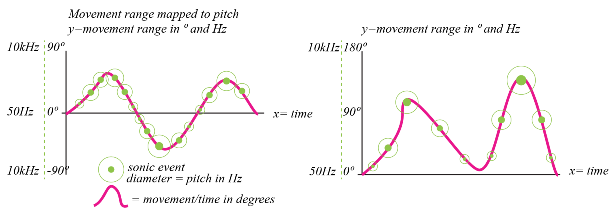

Figure 8. *Movement range mapped to pitch*

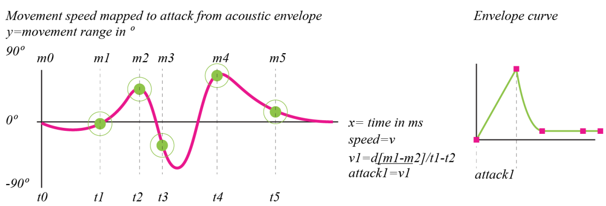

Figure 9. *Movement speed mapped to attack from acoustic envelope*

d) Modulated continuous auditory feedback triggered on movement detection and gated on movement stopped

The continuous presence of the auditory feedback is avoided in order not to disturb the user or reduce motivation. In the last examples has been shown how continuous and discrete auditory feedback can be coupled to generic body motion. In this case the focus is the modulation of continuous auditory feedback to be displayed only when a movement is performed. For that an ADSR[7] acoustic envelope is applied [see figure 10].

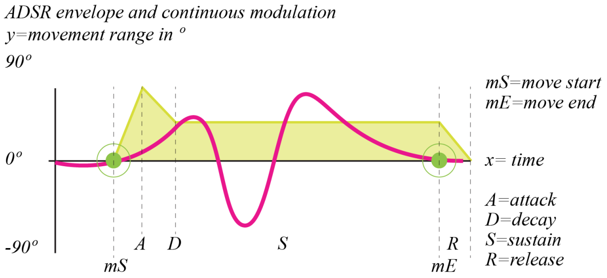

Figure 10. *ADSR applied to a continuous modulated auditory feedback*

In the graphic above the four periods corresponding to the ADSR acoustic envelope, which are coupled to the recognized movement, can be observed. Here a tracked movement is analysed as a continuous signal which has a start and an end. These end points are defined by the lack of movement, which is understood as the lack of variation between motion readings over a certain period of time. When a movement is recognized, the ADSR acoustic envelope is applied to a triggered acoustic signal, which is then continuously modulated by the tracked motion until the last stops. At the end of the movement a signal gate occurs and the release phase from the envelope affects the signal until it fades away. Each parameter from the ADSR envelope can be mapped to any tracked motion value.

4.2. Sound generation

Sound can be used as feedback for guiding performance or signalization from information or events in different contexts, but as mentioned by Seebode, Schleicher and Möller [19], so far there is no proof that interpersonal perception from functional auditory signals can be standardized. Therefore, aesthetic perception of functional sounds may vary considerably between individuals. Rather than focusing only on the quality or aesthetics of sound, this sonification system focuses on the possible ways in which sound and motion interact. In other words, it focuses on the ways in which sound can be triggered and modulated by specific body motions and how this close reciprocal relation impacts behavior. In the implemented sonification algorithms, which allow the generation of sound, aesthetics of sound is not dismissed, rather simplified by following the tradition of analog synthesizers, which are built in a modular way opening the possibilities for a wide range of sound generation.

5. EXAMPLES

5.1. Walking pattern and movement tasks

In this section, we describe prototype tasks for the planned experiments using our tools. They intend to be instruments for defining strategies and evaluating effectiveness of auditory feedback guiding body motion.

5.1.1 Ankle dorsiflexion avoiding medial-lateral rotation

A common walking problem is the control from medial-lateral foot rotation (pronation and supination) during the heel strike. From the hill strike moment till the mid-stance[8] phase, a dorsiflexion is observed in the ankle. Unbalanced rotation of the foot leads to unbalanced gait, often caused by applying more weight to one side of the sole or to the other. Approaching to correct this, our experiment has the objective to evaluate the effectiveness of auditory feedback guiding an ankle dorsiflexion straight to the *median sagittal plane* [see figure 11]. In the first part of the experiment, the participant is requested to perform a straight ankle dorsiflexion trying to avoid medial-lateral rotation. In this primary task no auditory feedback is provided. However, here and in the following tasks, we collect the tracked rotation and flexion values. In the second part, the participants are asked to perform the same movement trying to avoid rotation, which would result in the appearance of auditory feedback. In the third part, the appearance of auditory feedback is reverted. In other words, the signal is displayed only when a straight dorsiflexion is performed. The participant is requested to perform the movement by maintaining a continuous signal. In the fourth and last part of the experiment the participant repeats the same straight movement again without auditory feedback. It is expected that auditory feedback would support the participant to perform a straight flexion, and that variations would occur both in the observed behavior and tracked performance.

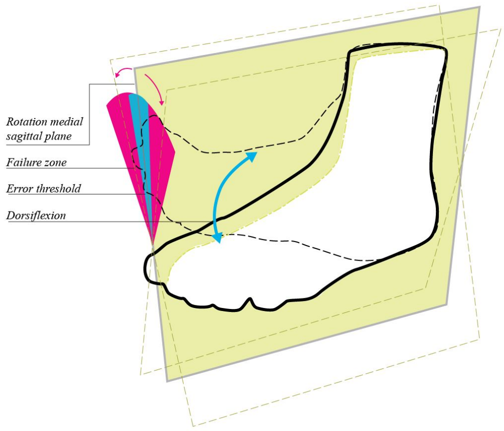

Figure 11. *Dorsiflexion and foot rotation*

5.1.2 Hyperextension from knee

Another problem observed in walking rehabilitation is the hyperextension in joints. In stroke rehabilitation this problem is recurrent in knees [1]. This experiment addresses signalization of hyperextension through gradual auditory feedback coupled to extension-flexion movements. The participant is requested to adopt a straight position. He or she is then asked to perform repetitions of knee flexion-extension. More in detail, the evaluated movement consists on a light flexion in both knees above the stress moment, and a slow extension towards the straight position [see figure 12].

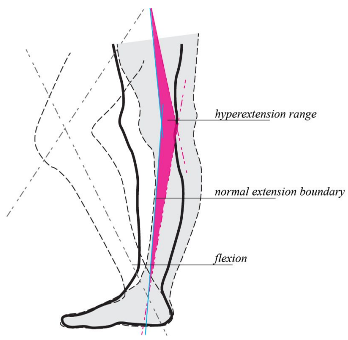

Figure 12. *Knee hyperextension experiment*

[7] Attack- Decay–Sustain -Release(ADSR) acoustic envelope

[8] As read in the literature the gait pattern is understood as a cycle composed by shorter movement periods and moments: *heel strike, stance phase, toe lift and swing phase.*

As in the last experiment, all tracked motions are stored for later analysis. In the first series of repetitions no auditory feedback is provided. In the following repetitions, auditory feedback is gradually provided when boundaries from hyperextension are reached or exceeded. In the third series of movement repetitions, auditory feedback is provided through the whole movement mapping the rotation value to some parameters form the auditory feedback. Noise is added gradually when user reaches boundaries of hyperextension or exceeded to signalize exceeded movement range. Finally the experiment is repeated without feedback support. Again, we expect to discover improvements of motion behaviour and tracked performance in the final clinical study.

5.1.3 Movement spasticity: variation coefficient approach

Movement spasticity is based on the estimation of a variation coefficient in movement speed related to the spasticity of movements, a common problem in stroke patients. The standard deviation and the mean from the last *N* speed values of tracked movements are calculated in real time performance. Increasing *N* will tend to flatten this coefficient.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\mu)^2} \tag{2}$$

The last equation is used for the calculation of the standard deviation observed in the last *N movement speed* values. Where *N* is the amount of recent speed values to be evaluated and μ is the mean of all of them.

$$c_v = \frac{\sigma}{\mu} \tag{3}$$

When dividing the *standard deviation* is divided through the *mean* the *variation coefficient* from all the *N speed* values results. This value is used as indicator from vibration or spasticity, and it is set as an accumulative signal, which can be mapped to any other parameter from the auditory feedback.

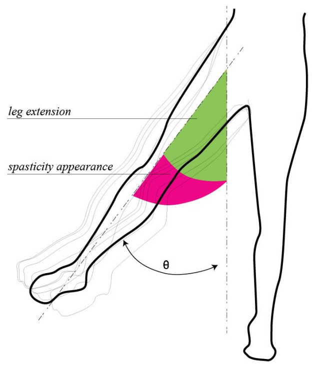

Figure 13. *Leg lateral extension and spasticity appearance*

We propose an experiment in which the subject is requested to perform any measurable movement, i.e. leg lateral rotation [see figure 13], avoiding the appearance of observable spasticity. In the next phase, the participant performs the same movement and is asked to avoid the appearance or increase of auditory feedback mapped to the variation coefficient from speed (*spasticity*). The test is performed again without the presence of any signal. From the analysis of the collected data it is expected to find a direct relation in the decrease from variation coefficient, used as indicator of spasticity, when participants intend to avoid the auditory feedback, thus leading to smoother movement.

6. FURTHER STEPS AND CONCLUSIONS

In this paper we presented a sonification tool that facilitates the process of sonic interaction design for walking apparatuses. We also presented three examples of experiments grounded in the walking rehabilitation tasks and problems. In the following stage, those experimental apparatuses and procedures will help us valuate if auditory feedback has a positive impact on walking performance with the gait trainer. We will use additional evaluation methods to study the capability to motivate the patient to actively engage in exercise. In the cases without support of a robotic device when walking, we expect that auditory feedback will help the patient to avoid medial-lateral rotation when performing ankle dorsiflexion, and therefore enhance a straight flexion. Investigating hyperextension from knee when provided with auditory feedback can be used with and without support of a robotic gait trainer. In spasticity experiment, we expect that participants will perform smoother movements when guided by avoidance of the auditory feedback.

Our design process and first prototype experiments show the potential of our tools and of the implemented motion-sound coupling techniques to guide corrective movement. We conclude that the presented sonification tools are suitable for walking rehabilitation tasks. This process of embodying motor tasks into the design of our tools helped us integrate the actual walking problems in the sonification models. We expect that the flexibility of our tools will allow us to perform a larger clinical study and quickly adapt the sonification as new problems may emerge during the testing with the patients, both with and without support of a robotic device in patients suffering from stroke. Part of the code, technical specifications, demonstration and process videos can be found at the project's page [2].

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