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Published in:
Proceedings of the 16th Sound & Music Computing Conference SMC 2019

DOI (link to publication from Publisher):
10.5281/zenodo.3249297

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

An Interactive Music Synthesizer for Gait Training in Neurorehabilitation

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ABSTRACT

Rhythm-based auditory cues have been shown to significantly improve walking performance in patients with numerous neurological conditions. This paper presents the design, implementation and evaluation of a gait training device capable of real-time synthesis and automated manipulation of rhythmic musical stimuli, as well as auditory feedback based on measured walking parameters. The proof-of-concept was evaluated with six healthy participants, as well as through critical review by one neurorehabilitation specialist. Stylistically, the synthesized music was found by participants to be conducive to movement, but not uniformly enjoyable. The gait capture/feedback mechanisms functioned as intended, although discrepancies between measured and reference gait parameter values may necessitate a more robust measurement system. The specialist acknowledged the potential of the gait measurement and auditory feedback as novel rehabilitation aids, but stressed the need for additional gait measurements, superior feedback responsiveness and greater functional versatility in order to cater to individual patient needs. Further research must address these findings, and tests must be conducted on real patients to ascertain the utility of such a device in the field of neurorehabilitation.

1. INTRODUCTION

This paper presents a novel application capable of measuring gait parameters and delivering interesting, time-evolving auditory stimuli based on gait quality for rehabilitation purposes. The primary goal is to increase engagement and enjoyment of therapy, improving patient motivation and adherence to frequent therapy, thereby leading to more favorable clinical outcomes. Brain damage from disease, infarction or infection frequently compromises gross motor function, resulting in impairments to essential activities like walking. Gait (walking) quality and mobility are important predictors of survival [1], cognitive decline [2], fall risk and perceived quality of life among older adults [1]. Besides age-related deficits, neurological conditions such as *Parkinson's Disease (PD)*, stroke, *Acquired Brain Injury (ABI)* and others have the capability to destroy gait function in an either acute or chronic manner. Prompt and regular rehabilitation has been found to be a critical determinant of long-term deficits [3]. While exercise helps preserve physical function, exercise protocols are typically not readily accessible in homes [4] and novel cost-effective rehabilitation strategies are needed [5]. In this context, the auditory modality can be advantageous over the visual and haptic ones in terms of hardware requirements and computational burdens [6]. Moreover, music-based interventions are being increasingly studied [7] and are attractive in that they can heighten enjoyment during exercise and, in turn increase exercise adherence [2].

Given the ability of rhythmic music to motivate humans and induce bodily movement [8], we propose a gait training system generating evolving musical stimuli in real-time, as well as spontaneous auditory feedback based on measured walking performance. The unique contribution lies in the direct influence of walking quality on the behavior of discrete entities within the composite auditory stimulus. Equally critical is an interface that is simple and intuitive enough for operation by a therapist, and versatile enough to tailor stimuli to a diversely afflicted patient group. The gait measurements collected are stored after each session to provide valuable information on patient progress. In the following sections we will discuss related research and present the design and implementation of multiple cohesively interacting systems for gait data acquisition, analysis and audio synthesis. As evaluation, the device was tested with six normal-walking individuals and critically reviewed by one neurorehabilitation specialist.

2. RELATED WORK

2.1 Rhythmic Auditory Stimulation (RAS)

Rhythmic Auditory Stimulation (RAS) is a rehabilitation technique of rhythmic motor cuing to facilitate training of movements that are intrinsically and biologically rhythmical, such as walking. RAS has been used in the rehabilitation of patients suffering from strokes [9], PD [10], ABI [11], and several other neurological conditions [12]. Essentially, it is the application of a rhythmic pulse (or beat) to organize periodic bodily movements in a process that occurs below conscious perception and functions to improve movement efficiency. The pulse often takes the form of a metronome click, or rhythm-based music. In PD [4] and stroke rehabilitation [9], RAS has been shown to improve numerous gait performance parameters [13]. RAS efficacy may depend on individual characteristics, disease severity and impaired beat-synchronization ability [12]. The

ISBN 978-84-09-08518-7 ISSN 2518-3672

beneficial effects of RAS reverse themselves over time if therapy is not adhered to [13]. Different individuals have different preferred movement tempi in general [2, 7] and the degree of entrainment drops significantly if the cuing tempo is over 2.5% greater or 3% less than the preferred tempo [14]. The daily administration duration of RAS is 10-30 mins, once or twice. The frequency of administration depends largely on patient endurance. A tempo increase of 5% is attainable without compromising normal walking patterns.

2.2 Movement Sonification

Sonification may be defined as the transfer of data and data relationships into non-speech audio for communication and interpretation [15]. In the rehabilitation context, the main advantage of sonification is its ability to enhance self-awareness of physiological processes and physical motion. Sonification makes it possible to be cognizant of, and control motor performance output parameters that efface themselves from conscious experience in most behavior [14]. The goal of a sonification-based system is to make distinct performance parameters explicit in corresponding auditory biofeedback systems. The 3Mo model proposed by Maes et. al. [14] suggests the use of musical biofeedback due to the potential that music has, to *motivate* physical activity, *monitor* physiological processes and *modify* these processes. A good example of this is the robotics-based system developed by Zanotto et. al [16] in which hip and knee angles during gait were sonified in real-time using formant synthesis. Previous studies have demonstrated that music listening can activate the human reward system. In line with the idea of reward-based reinforcement learning, Maes et. al. argue that pleasant and rewarding states promoted by music may function as an attractive force of motor behavior. Reward and punishment are hence considered constraints, guiding motor behavior to specific goals [14]. Optimal sonification strategies associate *wanted* motor behaviors to *pleasant* auditory states and vice versa. Musical expressiveness, novelty and surprise, along with tension and uncertainty are important elements for the sustainment of reward responses [14]. Auditory feedback may be successfully used in the rehabilitation context because it can be perceived without requiring patients to pay attention to a screen, and can be processed with relatively little cognitive effort [6].

2.3 Measures of Gait Performance

Human gait involves alternating sequences in which the body is supported first by one limb, which is contacting the ground, and then by the other [17]. For each limb, the period of support is referred to as the *stance phase*, and that of non-support is the *swing phase*. These events are separated by the instants at which the foot contacts and leaves the ground, and gait cycles are usually defined relative to these instants. A more comprehensive overview of the subject is presented in [18]. One approach to gait measurement involves a broad structural group of parameters that captures both spatiotemporal and dynamic characteristics. Lord et. al. [19] describe a 5-domain conceptual model. They identified 16 core variables explaining 84.6% of the variance between controls and 121 PD patients, which inform the measurement mechanisms of our application. Currently, only temporal parameters are considered, namely *step time, stance time and swing time*, as well as their *temporal variability and asymmetry*.

2.4 Applications for RAS-based gait rehabilitation

In recent years, some technological applications targeting gait rehabilitation based on RAS principles have been developed. The IM Gait Mate is a therapy modality to assess and treat motor planning, sequencing, coordination and balance [20]. The device targets patients suffering from PD, spinal cord injury, ABI and other related conditions. Wireless insoles are inserted in the patient's shoes to detect heel-strikes. The patient hears a beat through wireless headphones or speakers and is asked to match their *cadence (steps per minute)* to the tempo provided. Real-time speech-based audio feedback is provided related to step rate, dictated by how closely the cadence matches the auditory stimulus. A slightly different approach is used in D-Jogger, an interactive music player that aligns recorded music to the user's gait [21, 22]. Rather than asking the user to match their cadence to the music, D-Jogger adjusts the tempo of the music so that each beat coincides with a footfall. User cadence is determined in real-time using sensors, and the system automatically selects a song with similar tempo and continuously adjusts it to match cadence in an imperceptible fashion. If the user cadence changes markedly, the system switches to a different song.

The D-Jogger and similar systems are advantageous in situations where spontaneous gait synchronization does not occur [22], and can be categorized as *closed-loop* where the stimulus tempo adjusts itself to the user's cadence [12]. Conversely the IM Gait Mate would be an *open-loop* system. For both IM Gait Mate and D-Jogger the level of interaction between the user and the stimulus itself is quite limited, given the pre-recorded nature of the stimuli. Furthermore, only cadence is measured, limiting their ability to capture finer-grained gait impairments. We argue that the dynamic generation of evolving rhythmic music based on several dimensions of gait quality would be more motivating for rehabilitation, and versatile enough for useful administration to multiple patient groups.

3. DESIGN AND IMPLEMENTATION

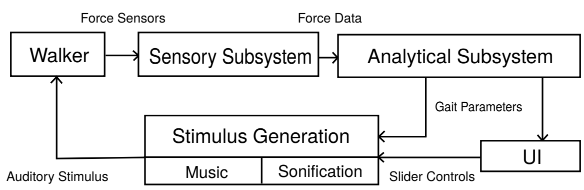

Figure 1. Block diagram displaying the overall system with its subsystems.

The design of the application is informed by prior research, and must fulfill the following requirements:

- Real-time generation of activating and motivating musical stimuli.
- Sonification of important gait parameters to provide real-time auditory feedback having customizable intensity.
- Non-invasive measurement and storage of clinically relevant gait parameters, for the monitoring of patient performance and progress.

The application is designed as a combination of functionally distinct but highly interdependent and cohesive subsystems, illustrated in Figure 1 and described as follows:

3.1 Sensory Subsection

The sensory subsystem is the data-acquisition system targeted towards gait measurement. The approach used is that of foot-based FSR sensors *(force-sensitive resistor)*. The primary hardware used is the Trigno EMG System by Delsys^{TM}, which consists of a USB-controlled Base Station unit and a wireless Trigno 4 Channel FSR Sensor^{TM} with an operating range of 20m. The Base Station acts as a receiver, and force data is transmitted to the application via TCP/IP [23]. Two force data channels are captured, from a 15 mm^2 FSR membrane on each heel. The signals are sampled at 148 Hz, and quantized to 10 bits per sample.

3.2 Gait Feature Extraction

The analytical subsystem handles the real-time extraction of clinically important gait features from the force time series supplied by the sensory subsystem. It performs footstep detection, stance/swing detection as well as gait parameter calculation and storage. It relays these values to both the user interface and the control channels of the stimulus-generation subsystem, effectively acting as the central information hub of the application. It is implemented in C++ using a JUCE timer to fetch new force samples for periodic analysis.

3.2.1 Footstep Detection

Given the implicit periodicity of walking, heel force contours appear as a series of evenly spaced amplitude fluctuations, corresponding to the support duration of that foot. Each step period can be measured as the interval between two contour points in the same phase, or simply two contour maxima. However, since the force variations across steps are neither smooth nor identical; step peaks often appear spiky with multiple local maxima per support period. Therefore, second-order IIR Butterworth lowpass filters with their -3dB frequency set at 0.5 Hz are used to smooth the force contours prior to peak detection. Peaks exceeding 14% of the maximum force range are detected as valid steps. The phase delay incurred by the IIR filter causes heel-strikes to be detected approximately 300 ms after they occur, delaying all gait parameter calculations as a result. A more recent perspective views the smoothing filter as a capacitor which *accumulates* force while foot contact is maintained. Correspondingly, the local minimum preceding each of the maxima may be detected as the instant of foot-contact, and the maxima themselves represent instants of non-contact. This approach neutralizes the filter phase delay.

3.2.2 Stance and Swing Detection

The unfiltered force time series of each foot is segmented into stance and swing phase by simple thresholding, at an empirically determined level of 20% of full-range force, to prevent false detections due to noise.

3.2.3 Parameter Calculation and Storage

The duration of each step, stance and swing period is calculated in real-time post detection and stored in separate vectors. As motivated in Section 2, the *mean-normalized variability and L-R asymmetry* for each of these (along with average stance/swing ratio) are recalculated with every newly completed step, at two different timescales:

Long Term: This timescale spans the entire training session from the first detected step. The trajectory of long-term measurements across multiple training sessions can be used by therapists to assess *improvement or deterioration* in patient gait.

Short Term: The same gait parameters are computed over an empirically determined window of only the five most recent steps, thus more numerically sensitive to new measurements. These are input to the control channels of the stimulus-generation subsystem for *sonification* purposes.

3.3 Stimulus Generation Subsystem

This subsystem generates and manipulates auditory stimuli for gait entrainment. This process involves the sequencing, arrangement and expressive interpretation of time-evolving musical layers that culminate in a well coordinated ensemble of rhythmic instrumental music. Also, the synthesizer sonifies gait performance, for which it monitors specific short term parameters and modifies the stimulus accordingly. Stylistically, the music is closest to the electronic dance music genre, which has been found to be most conducive to movement in related studies [8]. The synthesizer itself is implemented in FAUST (Functional Audio Stream), which is an audio domain-specific functional programming language. Although there exists a wealth of easily available high-quality music loops, the real-time synthesis approach is attractive due to its potential for fine parameter control and overall sonic versatility. The Faust2Api library was used to create a JUCE-compatible C++ class for the synthesizer, enabling communication with the analytical subsystem. It also allows direct user manipulation of synthesizer parameters from the same interface that displays gait parameter values, allowing for convenient operation and monitoring.

3.3.1 Structure of Musical Content

The core ensemble consists of typical percussive elements found in electronic music, as well as multiple precomposed melodies that reinforce the underlying rhythm. The time signature is 4/4 throughout, and the tempo is user-adjustable, depending on the preferred cadence of the

Track no.	Instrument	Basic Excitation	Synthesis Method	Bandwidth (Hz)	Effect Chain
1	Bass Drum	Sine Sweep	Subtractive	60-200	3dB Boost @ 70 Hz
		White Noise	Subtractive	1500-5200	Cubic Soft Clipper
2	Snare Drum	White Noise	Subtractive	100 - 8000	-
3	Hi-Hat	White Noise	Subtractive	10000 - 16000	-
4	Crash Cymbal	White Noise	Subtractive	9000 - 20000	-
5	Bass Synth	Sawtooth	Subtractive	50 - 200	8 dB Boost @ 110 Hz
6	Bass Staccato	Sine	FM	150 - 2000	-
7	Main Melody	Sine	FM	f0 - 1000	Dotted Echo, Haas Delay, Hard Clip
8	Secondary Melody	Sine	FM	f0 - 5000	-

Table 1. Synthesis methods and effect chains of each instrument in the ensemble ('f0' refers to the note fundamental frequency and FM stands for Frequency Modulation).

walker. The underlying rhythmic pattern remains uniform throughout, and musical variation is realized in the manipulation of secondary rhythms and melodic patterns. The musical characteristics are designed to match those found in [8] to be the most activating in terms of walking vigor.

3.3.2 *Clocking and Musical Timekeeping*

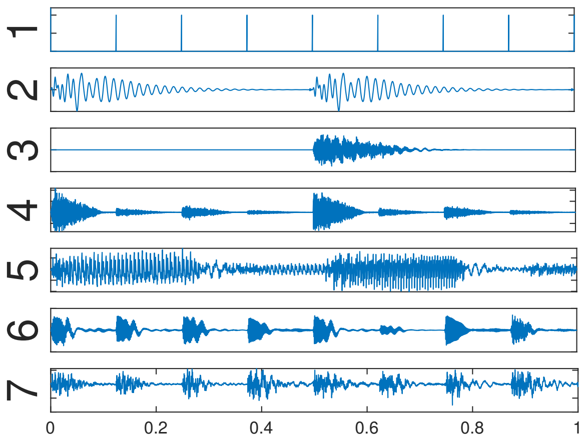

Figure 2. An illustration of how the Master Clock (1, top panel) serves as a triggering mechanism for some of the instruments (2-7) described in Table 1.

At the core lies a continuous, isochronous impulse train, whose frequency is governed by the externally configured tempo. This acts as the primary clocking and triggering mechanism and orchestrates the synchronized playback of every instrument. Its frequency is precisely four times the beat interval to enable the use of eighth and sixteenth note subdivisions in the music. External changes to the tempo alter the impulse train frequency, in turn altering the triggering rate of all instruments at once. This *master clock* is generated using a FAUST impulse train function. For musical time-keeping, there are counters monitoring the master clock to count elapsed measures and the current position within a measure. Their state is referenced during audio synthesis to determine whether to mute a track, audio effect automation, and instantaneous melody note parameters.

3.3.3 *Introduction of New Instruments*

Effort of walking is rewarded regardless of gait performance. The total *footstep count* indicates the physical work performed by a patient. The music commences with only the bass drum and the bass synth and each new instrument is added as its minimum step count condition is satisfied (snare drum, hi-hat, etc.). Boolean variables in FAUST take values of either 0 or 1, enabling step count conditions to double as instrument on/off switches. To gently fade each new instrument in as its step condition is satisfied (rather than a discontinuous and un-musical 0-to-1 transition), the Boolean variables are smoothed using a one-pole filter with a 4 second integration time. This filtering helps achieve a gradual gain increase from the instant the step condition is satisfied.

3.3.4 *Percussion Synthesis*

Most percussive rhythm patterns may be viewed as periodic arrangements of distinct impulsive sounds in a specific temporal order. The mechanism for percussion synthesis is a filtered steady-state excitation multiplied by a temporal envelope triggered by the master clock. The triggering occurs at sub-multiples of the clock frequency depending on the rhythm. An example of this is the bass drum, whose envelope is triggered every four clock pulses, or more precisely, triggered by 'the first of every four pulses'. It therefore plays on every beat. In contrast, the snare drum envelope is triggered by the fifth of every eight pulses, thus playing on the second and fourth beats of a measure (visualized in Figure 2). A large variety of rhythms can thus be easily generated. The excitation and envelope parameters vary among the percussion instruments to achieve the desired timbres. All parameters were iteratively determined using an analysis-by-synthesis method.

ISBN 978-84-09-08518-7 ISSN 2518-3672

3.3.5 *Melody Synthesis*

The paradigm employed is inspired by MIDI-based symbolic notation, in which note/velocity information is stored in relative music time. This information may then be reproduced by the synthesizer. In the current context, note number, on/off, and velocity for each melody are stored chronologically in look-up tables. Counters deriving from the master clock keep track of the number of elapsed 8th and 16th notes in the current measure. The instantaneous state of these counters is used to iterate through the look-up tables, fetching note information for each instrument. The output is a specific timbre with the required instantaneous fundamental frequency. The note on/off table specifies note onset positions within a bar, effectively serving as a trigger condition for envelope generation. Because note triggering is orchestrated by the master pulse counters, melody tempo and note length vary proportionally with the master tempo, ensuring grid-locked synchronization among all instruments. This is important in a scenario where timing precision is paramount. Overall mix clarity, transient impact and spectro-temporal separation between individual timbres are critical to the user experience. Indistinct, unclear or harsh sound can quickly become fatiguing and unpleasant, which is undesirable for training sessions over ten minutes in length. Therefore, special attention is paid to the interaction of sound sources, leveraging modern production strategies to deliver a well-balanced stereo mix. Table 1 offers a more detailed description of the synthesis methods of all musical instruments.

3.3.6 *Sonification Synthesis*

Aside from the generation of the musical elements, the Stimulus Generation subsystem also handles the sonification of various measured gait parameters. The sonification philosophy is as advocated by Maes et. al. [14], with the *addition of unpleasant stimuli, or detrimental modification of the existing music stimuli*, to 'punish' sub-optimal gait performance. In practice, this is achieved by mapping a subset of the short-term gait parameters to 'user sliders' on the synthesizer program, that control the intensity of each sonification type. Thus, the intensity is a continuous quantity, and varies in real-time with the temporal gait parameter mapped to it. The interface has a slider to scale the overall strength of punishment to optimize usability for differently severe impairments.

The applied sonifications are described as follows:

Rhythm Salience: The reduction of *step-time variability* through rhythmic entrainment is an important outcome of RAS therapy. Beat clarity is critical to effective entrainment, and the primary beat is largely carried by the percussion instruments. An increase in short-term step time variability causes an increase in the relative level of the percussive instruments with respect to the melody instruments. The *punishment* lies in the resulting attenuation of melodic content in the mix. This also serves to strengthen entrainment, ultimately improving step regularity.

Annoyance Notes: The analytical subsystem compares the measured average stance/swing time ratio with the documented ratio for normal walking - 1.61 [24]. A large discrepancy indicates sub-optimal support time distribution and is sonified in the form of random-frequency annoyance notes from a sawtooth wave generator. The intensity is directly proportional to the squared deviation from the normal stance/swing ratio. The triggering frequency of these notes is dictated by the master clock, so that they do not affect rhythm perception.

Melody Detuning: Increases in *Swing Time Asymmetry (STA)* are sonified by directly mapping it to the depth control of a ring modulator in the signal path of the main melody synth. The modulation frequency is not in the key of the music, so the effect of increased STA is increased dissonance in the reproduced melody. Symmetric walking translates to a very low asymmetry quotient, and therefore negligible modulation.

Noise: Short-term increases in *Swing Time Variability* are sonified using a white noise generator, punishing increasing variability by increasing noise intensity. The noise is processed with a high-intensity flanger with tempo-dependent sweep rate, giving it a rhythmic quality.

4. EVALUATION

To ensure that the application exhibited both the expected sonic behavior and gait measurement ranges, a walking test was conducted on unimpaired, healthy participants. Aside from this experimental evaluation, the application was demonstrated to a neurorehabilitation specialist to assess its utility as a rehabilitation tool.

4.1 Experiment

4.1.1 *Participants*

Six individuals (one female, mean age 24.8 years) with no documented neurological conditions or gait disorders volunteered themselves as participants for this study. The participants all had a prior music background and were students at Aalborg University. Informed consent was obtained, and refreshments were provided as compensation.

4.1.2 *Experimental setup*

The experiment took place in a large, quiet room with the measurement system set up in the center of a roughly circular demarcated walking track. The music was played back at a comfortable level over a set of full-range stereo loudspeakers. Due to the cyclic nature of the track, the participants heard the music at a roughly consistent loudness level throughout their traversal.

4.1.3 *Procedure*

Each participant individually tested the system in two phases. The first phase was a trial run to determine their preferred cadence. Once securely fitted with the sensor apparatus, they were instructed to walk freely, at a comfortable pace along the path. The music was played, and the tempo was adjusted manually until it matched the gait of

Gait Parameter	Measured	Reference
Mean Step Time (ms)	539 (2)	537(47)
Step Time Variability (%)	9.68 (1.07)	3.05 (1.10)
Mean Stance Time (ms)	599.7 (60.70)	688 (72)
Mean Swing Time (ms)	366 (61)	386 (30)
Stance/Swing Time Ratio	1.695 (0.414)	1.782 (0.188)
Stance Time Asymmetry (%)	12.30 (7.76)	1.29 (1.35)
Swing Time Asymmetry (%)	7.20 (2.97)	2.30 (2.43)
Stance Time Variability (%)	12.30 (4.50)	2.87 (1.16)
Swing Time Variability (%)	43.15 (41.37)	3.93 (1.42)

Table 2. Measured gait parameter values with reference values derived from [25], shown as Mean and Standard Deviation SD (in parenthesis).

the participant. After this calibration phase, the new tempo was initialized, sensor measurement was commenced, and the participant was signaled to begin walking from a designated starting point. The instruction this time was for footsteps to be actively timed to the music. Feedback sonification was enabled at the nominal intensity level without participants being informed of what it was. The duration of each trial spanned the time taken by the participant to complete 400 steps, and this was dependent on individual preferred cadence. The listed long-term temporal gait parameters were automatically measured and systematically stored at the end of the 400th step, simultaneously concluding the experiment. Following each trial, participants were interviewed in structured fashion, and key questions were put forth regarding the distinct aspects of the experiment. They were asked to rate the comfort and freedom of movement (from 1, not at all comfortable/very low freedom to 5, very comfortable/very high freedom) while wearing the apparatus. Pertaining to the music, key questions concerned appropriateness of tempo, beat clarity, enjoyability, musical evolution, and conduciveness to movement. They were asked if they noticed any unusual sounds, and if so, what their impression was of them.

4.1.4 Results

All participants reported the task simple and the pre-calibrated tempo easy to walk to. The musical beat was clearly perceived by all participants, and temporal evolution in the music was noticed. Four out of six participants found the music encouraging to move to, but half of them did not find the music enjoyable. Four of six noticed sounds that were not part of the music and one found these sounds unpleasant. Mean rating for comfort while donning the sensor apparatus was 3.92 (ranging from 3 to 4.5) while mean rating for freedom of movement was 4.42 (ranging from 4 to 5).

Table 2 shows the measured gait parameters, averaged across participants and compared to reference values derived from literature [25]. No false step detections were observed in any trial. Measured Mean Step Time showed a high level of agreement with reference figures, and Mean Stance, Swing Time and Stance/Swing Ratio were within range. On the other hand, Long term Asymmetry and Variability measures were significantly exaggerated as compared to reference values, although this discrepancy was *not* observed on the short-term timescale.

4.2 Expert Interview

In addition to the gait experiment, the application was demonstrated to a neurorehabilitation specialist by means of a walking test, simulating both normal and impaired gait modalities. The following key questions were put forth and a thorough assessment was obtained.

Clinical Role (Target Group and Use Case):
The specialist stated that the main target group would constitute PD, stroke and ABI patients, and that the most convenient therapy setting would be a treadmill protocol.
Main Benefits from a Therapist's Perspective:
The specialist envisioned the gait measurement and real-time feedback to have potential as novel aids to performance evaluation and patient self-awareness.
Detection of Impaired Gait Modalities:
The inability of the application to evaluate foot roll-over quality(owing to only a single heel sensor) was pointed out by the specialist. He also enumerated several phenomena that cannot be captured by temporal measures alone, such as low gait speed, crouch gait and limb circumduction. The use of accelerometers and force membranes with greater surface area was suggested.
Presentation of Auditory Stimuli:
The specialist pointed out problems with the sonification philosophy of punishing any deviations from parametrically normal gait, mainly rooted in the wide range of pathologies and principal gait problems exhibited by patients. He not only stated the importance of safety and balance in the short term, but also the need for individualized performance baselining and customizable sonification mapping to cater to diverse individuals. He added that the subjective definition of the term *unpleasant* would create ambiguity between the perceptual notions of punishment and reward, especially for cognitively damaged patients. The mapping of gait parameters to auditory manipulations was also not seen as intuitive by the specialist. Lastly, he noted the time-lag between a gait event (eg. an asymmetric stride) and its respective sonification, which would lead to uncertainty and confusion for the patient while experimenting with gait technique, damaging the delicate relearning process.

5. DISCUSSION

The objective of this study was to design an interactive music-based gait training application based on RAS in order to improve patient motivation and adherence to gait therapy. We presented and tested the implementation of the proof-of-concept application, generating a time evolving musical ensemble controlled by measured temporal gait parameters. It is acknowledged that an important limitation of this study is the lack of clinical trials conducted. Compared to existing systems such as D-Jogger [22] and IM Gait Mate [20], the merits of this application are seen in the detailed calculation of numerous relevant gait parameters apart from cadence and step-time variability, as well as the multidimensional influence of walking quality on the auditory stimulus. These are reinforced by the specialist's acknowledgement of the potential of the application to help individuals from our original target group, as well as the benefits of the gait measurement and real-time auditory feedback mechanisms. In practical terms, the experimental evaluation broadly showed that the application functioned as intended with multiple individuals. The suitability of the stimulus for interactive gait entrainment was corroborated by the perceived intuitiveness of walking to the generated music, the easy discernment of temporal evolution and the conduciveness to movement. High ratings of comfort and freedom encourage the future use of a force-sensor based gait measurement system.

One concern stems from the lack of agreement among participants regarding whether the music itself was enjoyable. Although this disagreement was expected due to the diversity of individual music preferences, it necessitates the design of a music synthesis system with the capability of morphing seamlessly between distinct styles while maintaining its movement-inducing quality. The average age of the target group is also higher than that of the test group used, so it is important that the trends in musical preference of target individuals are studied in greater detail. Because the test group mainly comprised normal walking individuals, there were very few instances where gait sonification was audible in the stimulus, pointing to mostly correct triggering of sonification mechanisms (or lack thereof). However, among the participants who did perceive some sonification effects, the general disposition towards these effects was neutral. Although these were designed to sound unpleasant, this disposition could be ascribed to sonic expectations in the electronic genre, where timbres are inherently noisy and bright, with more tolerated inharmonicity. Alternative sonification strategies must therefore be considered. Firstly, to cater to the wide range of principal gait problems and severity, individualized performance baselining is a necessary addition. A possible sonification alternative is to conceive of sonic reward and punishment purely in terms of musical complexity, such that good gait performance with respect to the baseline is rewarded with more interesting rhythms and melodies, and the opposite effect for deteriorating performance. Additionally, melody and percussion envelopes can be triggered by step onsets, encouraging tight synchronization and giving the user a greater sense of agency and control. This could potentially solve the problems of temporal spontaneity and reward/punishment ambiguity predicted by the specialist. Furthermore, pleasantness and relative discernibility of each sonification strategy must be investigated in more detail through experiments. Discretizing sonification intensity levels based on the measured *just-noticeable difference* could potentially make variations in auditory feedback more explicit.

The next topic is the automated gait parameter measurements. The noted discrepancies between measured values and reference values may have been caused by differences in exact sensor placement, spikes in asymmetry during turning or outliers created by initial shuffled steps. Regardless, the high step detection latency (300 ms) must be addressed; the capacitor analogy described in Section 3.2 has shown promise in initial tests. Temporal spontaneity of gait sonification is critical to the effectiveness of the application, and the short-term measurement window may be shortened to improve this. Additional membranes must be introduced to represent the forefoot for evaluating roll-over. An adjustable measurement prototype must be fabricated to ensure accurate sensor placement and reduce setup time. The initial step measurements must be discarded to obtain more accurate long-term figures for evaluation. Periodic automated cadence detection is also a necessary provision for setting music tempo. The path of traversal should be straight, to prevent turning-related inaccuracies. Accelerometers to capture gait speed and crouch gait, along with the design of a treadmill protocol for testing and therapy have been added to the scope of future studies.

6. CONCLUSIONS

The goal of this study was to develop a music-based interactive gait training device for patients suffering from neurological conditions, creating an organic and enjoyable setting capable of improving motivation and adherence to therapeutic exercise. A proof-of-concept was designed and implemented, and subsequent tests and evaluation processes on normal test participants revealed both merits and deficiencies in the auditory presentations. Practical difficulties and inaccuracies in some of the gait measurement mechanisms also came to light. The expert interview provided us with much needed feedback and insight into the rehabilitation process. Taking into account the infancy of the project in its current state, the work carried out here serves as a useful foundation for future investigation driven by the experimental findings. Given the increasing need for affordable and accessible exercise protocols for neurological patients, an interactive device wielding the universal appeal and therapeutic prowess of music may be instrumental in the recovery and maintenance of physical function and mobility among community-dwelling individuals afflicted by debilitating neurological conditions.

Acknowledgments

We are indebted to the participants in the study; J. Greve and P. Williams for assisting the fabrication of the test apparatus; D. Curtis for his valuable comments in evaluating the application, R. Jakobsen, C. Ringsted, and C. Khadye for suggestions, comments, and feedback; as well as the anonymous reviewers for their helpful comments.

Author Kantan was mainly responsible for designing, implementing, evaluating and writing this paper as part of a student project at the MSc. Program in Sound and

Music Computing, with Dahl as supervisor. The work was partially funded by NordForsk's Nordic University Hub Nordic Sound and Music Computing NetworkNordic-SMC, project number 86892.

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