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Published in:
Proceedings of the SoniHED Conference on Sonification of Health and Environmental Data, 2022

DOI (link to publication from Publisher):
10.5281/zenodo.7243766

Publication date:
2022

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

Citation for published version (APA):
Kantan, P. R., Dahl, S., Rovsing Møller Jørgensen, H., Khadye, C., & Spaich, E. G. (2022). Designing Sonified Feedback on Knee Kinematics in Hemiparetic Gait Based on Inertial Sensor Data. In S. Paulett, S. D. Monach, & R. Selfridge (Eds.), *Proceedings of the SoniHED Conference on Sonification of Health and Environmental Data, 2022* Zenodo. https://doi.org/10.5281/zenodo.7243766

Designing Sonified Feedback on Knee Kinematics in Hemiparetic Gait Based on Inertial Sensor Data

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ABSTRACT

In recent years, interactive sonification based on data from wearable sensors has been explored as a feedback tool in movement rehabilitation. However, it is yet to be routinely adopted as part of physiotherapy protocols, partly due to challenges with designing solutions tailored to diverse patients. In this work, we propose a set of adaptable feedback paradigms on knee kinematics for hemiparetic stroke patients undergoing gait training. We first collected inertial data and video footage from 15 hemiparetic patients during overground walking. The video footage was then analyzed by a physiotherapist, who identified three main knee-related movement impairments - reduced range of motion, dysregulated extension, and hyperextension. Using a custom-built software architecture, we devised two music-based paradigms for providing tailored concurrent feedback on knee movement and the impairments identified by the physiotherapist based on inertial data. The paradigms will be clinically tested with patients as part of a future study, and we believe that their impairment-specificity and individual adjustability will make them an advancement of existing auditory feedback designs.

1. INTRODUCTION

The auditory medium has been increasingly explored as a means of providing interactive feedback to augment motor learning in rehabilitation [1] and sport [2]. Specifically, interactive sonification [3] has been applied as biomechanical biofeedback with the goal of enhancing self awareness by providing objective and accurate information about one's movements [4–6]. Sound has clear potential as a feedback route due to the excellent temporal resolution of the auditory system compared to vision [7], as well as the potential of sound to free up the visual route for other tasks [1, 8]. However, there are no established conventions or frameworks for how sonification should be designed and implemented in various motor learning scenarios, which likely limits the realization of this potential [1, 9]. In this work, we approach the design of sonification to aid motor learning in a specific but widespread clinical context - gait training in hemiparetic patients with a focus on knee-related impairments.

1.1 Post-Stroke Gait Disturbances

Walking is a crucial activity of daily life and is associated with longevity in older adults [10]. It is a highly complex movement whose kinematic properties are regulated by visual, auditory, tactile, and proprioceptive feedback [11,12]. Walking patterns in hemiparetic stroke patients differ from normal walkers, particularly in that they are asymmetric in terms of spatiotemporal, kinematic, and kinetic parameters [13]. This is particularly seen in their *joint kinematics*, where stroke patients also exhibit great inter-individual variability [13].

The knee joint is an important contributor to the act of walking, and it has been shown that knee muscle strength on the most affected side is significantly correlated with lower gait speed and lower performance in multiple clinical gait tests in mild to moderate hemiparesis [14]. The muscles of the lower limb can also develop abnormal muscle firing patterns post stroke [15]. This results in the formation of muscle synergy patterns which disrupt the rhythmic co-ordination of movement as observed during a normal gait cycle [16]. Stroke also causes an alteration in the afferent sensory input from the muscle to the brain, resulting in improper muscle activation and less coordination during gait [15]. Common knee kinematic problems post-stroke during gait are reduced peak flexion (bending) when the foot is in the air and poorly regulated or excessive extension (straightening) as the foot makes contact with the ground [13,17,18]. These abnormal movements at the knee joint are compensated for by abnormal motion at the ankle and hip joints on both sides [19, 20]. Therefore, we propose that addressing knee issues can contribute to improving overall lower limb joint co-ordination in hemiparetic gait.

1.2 Enhancing Multisensory Integration Through Sonification

Given that the motor execution of gait relies on the integration of feedback from multiple sensory channels [11, 12], movement sonification has clear potential to augment rehabilitation. Specifically, the auditory information it provides can be exploited by multisensory integrative brain areas and the transmodal mirror neuron system, which may lead to a more accurate representation of the movement [21,22] and benefit motor learning [23]. It is known that sound can impact bodily awareness, body movement, and body representations [24], and recent research supports the notion that when suitably designed, sonified kinematic information can have a significant impact on motor perception and estimation [22, 25, 26].

1.3 Designing Feedback for Motor Learning

Feedback design (irrespective of modality) has been found to be a key determinant of motor learning, specifically the perceptual information available to the learner while performing a task [9, 22, 23, 25–27]. Sigrist et al. [25] recommend a design approach wherein the feedback guides the learner toward desired movement patterns without diminishing the influence of intrinsic kinesthetic information (i.e. proprioception). Through the feedback, the linkage of key features of the movement to the existing kinesthetic information should be emphasized [23] - an example is feedback triggered only if a computed movement error metric exceeds a threshold [2]. Dyer et al. [9] phrase this as feedback that “draws attention to the aspects of movement that should be corrected, and can be perceived whilst maintaining attention on all intrinsic feedback sources”. Such an approach can also economize cognitive workload, which is a key consideration in feedback design, particularly when cognitively impaired users are involved [4].

The *congruency* between perceptual streams is important in multisensory integration processes as well [22]. Specifically, congruent intermodal stimuli are more readily integrated, lead to more accurate internal representations of a movement, and enhance perceptuomotor processing [22, 26]. In the context of sonified feedback, it is clear that aside from temporal proximity [28], perceived congruency is tied to the transparency of the semantic *metaphor* [29, 30] that the action-sound mapping rationale is based on. For instance, we found in a previous study that an ascending melody was largely perceived by users to be congruent with the act of rising from a chair [31]. It has been shown that incongruency can increase motor performance errors [26], worsen judgments of small velocity changes [22], and adversely affect emotional experiences [32].

The goal of the present work was to apply these feedback design principles to the process of devising paradigms for knee kinematic feedback targeting hemiparetic gait. We first recorded motion data and video data from a sample of 15 hemiparetic patients. The videos were analyzed by a physiotherapist and prevalent knee impairments during walking in each patient were documented. We then identified characteristic graphical patterns corresponding to each of these impairments in the motion data and developed patient-adjustable sonification paradigms to provide congruent music-based feedback on them. The data collection, analysis, and sonification paradigms are detailed, demonstrated, and discussed in subsequent sections.

2. MOTION DATA COLLECTION

We obtained a gait dataset from hemiparetic patients during overground walking for kinematic analysis and feedback design.

2.1 Participants

A convenience sample of 15 hemiparetic stroke patients (9 men, 6 women) aged 65.53 ± 16.48 years volunteered to participate in the motion data collection. All of them had predominantly one-sided weakness of varied severity due to ischemic/hemorrhagic strokes, intracranial hemorrhages, or traumatic brain injury, and were admitted to Neuroenhed Nord, North Denmark Regional Hospital, Denmark. Each of them was briefed about the purpose and length of their participation beforehand, and informed that their data would be anonymized, and they could withdraw at any time. All procedures conformed to the ethics code of the Declaration of Helsinki. Informed consent was obtained prior to participation, and no sensitive or confidential information was collected from the participants.

2.2 Setup

The data collection was carried out at North Denmark regional hospital at the Neuroenhed Nord department Frederikshavn and Brønderslev. An approximately 10 m long stretch was designated as a walking track in a long corridor with no obstacles. For wireless inertial measurement, we used M5Stack Grey devices equipped with MPU 9250 9-axis inertial sensors [1]. These were fastened to the trunk (lumbar spine), thighs (lateral placement, just above knee), and shanks (lateral placement, just above ankle) of each patient using elastic straps bearing a silicone housing for the sensor. The sensors transmitted the data over a dedicated 2.4 GHz WiFi network (TP Link Archer C20 router) in the form of *Open Sound Control (OSC)* packets using the UDP protocol. A Dell Inspiron 15 7000 laptop was used to stream and log the inertial data using custom software. A data sampling rate of 100 Hz was used throughout. Additionally, a Motorola G8 Power mobile handset was used to capture video recordings of the patients’ gait at a resolution of 720 × 1280 (portrait) and a frame rate of 30 Hz.

2.3 Procedure

The data collection was conducted on each patient in collaboration with a highly experienced physiotherapist. After obtaining informed consent and providing a short briefing, we calibrated the sensors for bias compensation purposes and mounted them on the patient’s body. We then directed the patient to walk through the designated corridor segment at a comfortable pace using any walking aids they were accustomed to (physiotherapist support, rollator, training bench along one side). Inertial data from all five sensors were recorded during the entirety of this phase. Video footage was also captured at such an angle

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[1] `https://shop.m5stack.com/products/grey-development-core`

that the head of the patient was omitted. The physiotherapist carefully supervised the walking activity and decided how many walking laps would be feasible depending on the abilities and endurance of the patient (minimum one lap). After completion, the sensors were dismounted from the patient's body, and all data were compressed and uploaded to a secure cloud server.

2.4 Data Analysis

To obtain a professional assessment of the gait impairments exhibited by each patient, the video recordings were sent for analysis to a physiotherapist not present at the data collection. As for the inertial data, we used an upgraded version of the technical framework in [34] to import the logs and reconstruct the gait kinematics of the patients. To study knee impairments, the following movement features were computed and subsequently logged:

- **Knee Angle:** The accelerometer and gyroscope readings were fused using the Madgwick gradient descent algorithm [35] to compute the inclinations of the thighs and shanks in the sagittal plane. The learning rate coefficient β was empirically set at 0.18 to balance the trade-off between excessive integration drift and overcorrection. The knee angle was then computed as the difference between shank and thigh inclination.
- **Knee Angular Velocity:** The bias-compensated gyroscope readings for each thigh and shank about the mediolateral axis were first smoothed using 2nd order Butterworth low pass filters (5 Hz cutoff). The angular velocity of each knee joint was then calculated as the difference between the shank and thigh reading.

The logged knee angles were then plotted in MATLAB 2018b to study whether the kinematic impairments reported by the physiotherapist for each patient were detectable in the plots (see Fig. 1).

3. RESULTS OF DATA ANALYSIS

On average, the patients traversed the path from end to end 4.13 times, and walked for a mean duration of 82.67 sec.

As summarized in Table 1, the physiotherapist identified three main knee-related impairments - *reduced range of motion* (11 patients), *hyperextension* (3 patients), and *dysregulated extension* (10 patients). We explain these below; note that the *stance phase* is when the foot is in contact with the ground, and *swing phase* is when the foot is in the air:

- **Reduced Range of Motion (RoM):** Reduced peak flexion was observed during swing and/or incomplete knee extension during stance, which led to the RoM being lower than in normal walkers [18].
- **Hyperextension During Stance:** Full straightening ($0°$) or overstraightening ($< 0°$) of the joint was observed during ground contact.
- **Dysregulated Joint Extension:** At the end of the swing phase (after peak knee flexion), some patients exhibited irregular extension of the knee joint [18], which was visible as a jerky or rapid straightening phase prior to ground contact.

The findings of our graphical analysis in context with the observations of the physiotherapist are shown in Table 1. We were able to detect the observed instances of reduced RoM and hyperextension in a reliable manner in the graphs, although this was true for 70% of the cases for dysregulated extension.

4. SONIFICATION DESIGN

4.1 Design Philosophy

Given the level of inter-individual variability prevalent in post-stroke gait [13], a foremost requirement was for the feedback to be *easily adjustable to suit the clinical profile of each patient*. This is in line with Stanton et al.'s suggestion [5] of a 'biofeedback toolbox' with options to tailor feedback parameters including feedback type, target, and method. We also decided to use *music as either the primary feedback medium or the underlying substrate* for manipulation. This was to leverage the known ability of music to motivate, monitor, and modify movement by mediating perception and action [36, 37] and induce feelings of self-efficacy [9]. As such, we devised two paradigms:

1. Continuous sonification of knee angle trajectories to generate a movement-congruent auditory representation of the joint movement. Salient (but not harsh) negative reinforcement is added to this in an on-off format to highlight dysregulated joint extension.
2. Intermittent feedback on hyperextension applied as an audio effect to user-selected music tracks.

The design rationale and technical implementation of each paradigm are detailed next.

4.2 Technical Setup

To design, develop, and adjust the sonification topologies for each feedback paradigm, we used the same technical framework [34] as mentioned earlier. This allowed us to stream the recorded raw inertial data from patients, compute and visualize the movement features, and transform them into intermediate mapping variables through a series of standard operations [38]. The mapping variables were transmitted in real-time as OSC messages to REAPER v6.23 [2], where they were mapped to relevant parameter controls of selected VST [3] synthesizers or effects for sound generation. An M-Audio M-Track Solo [4] device was used for audio I/O at a sampling rate of 48 kHz with a 256 sample software buffer. We chose this distributed software architecture to maximize freedom in terms of real-time mapping choices. Based on an assessment conducted on a system

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[2] `https://www.reaper.fm/`

[3] `https://www.steinberg.net/technology/`

[4] `https://www.m-audio.com/m-track-solo`

Impairment	**# Total Patients**	**# Detectable in Graphs**	**Detection %**	**Representative Characteristics in Graphs**
Reduced RoM	11	11	100	Reduced peak-to-peak knee angle amplitude compared to normal walkers
Hyperextension	3	3	100	Periods with knee angle close to (or saturated at) 0 degrees
Dysregulated Extension	10	7	70	Sharp slope of descent from peak flexion (crest) Fluctuations following peak extension (trough)

Table 1. A summary of the knee impairments observed by the physiotherapist, followed by an overview of their detectability in visual graphs as well as graph characteristics that we judged to represent them.

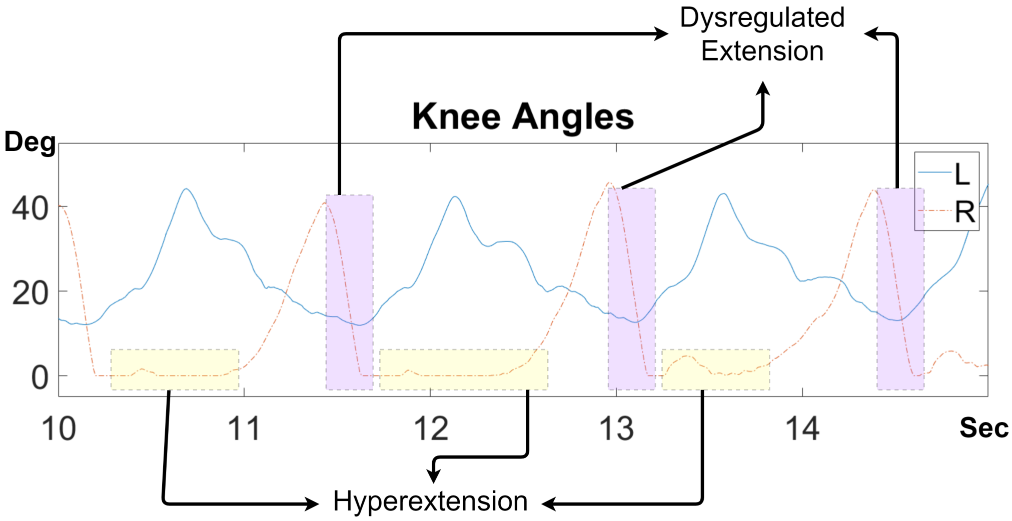

Figure 1. An illustration of the observed knee impairments summarized in Table 1. The dotted trace represents the paretic side, which exhibits both dysregulated extension and hyperextension. Both sides exhibit a reduced range of motion (max 40° compared to the normal range of about 65° [33].

with identical technical architecture, we estimate the mean round-trip latency to be 93 ms [39]. The technical framework is also capable of streaming inertial data from the sensors in real-time, making the setup viable for experimentation in clinical settings.

4.3 Paradigm 1: Knee RoM + Extension Feedback

The goal of this paradigm is to encourage knee patterns that exhibit (A) increased peak flexion during swing (compared to pre-training), (B) Left-Right symmetry, and (C) a regulated extension phase prior to foot contact.

Conceptually, the knee movement of each leg manipulates a single synthesis parameter of an ambient music piece, resulting in a continuous feedback signal whose spectral properties are directly correlated with the combination of the original knee angle trajectories. This is done in such a way that the timbre becomes brighter and richer as the flexion angle increases. This sound additionally serves as the substrate for providing feedback on dysregulated knee extension, wherein the otherwise continuous audio signal is subjected to interruptions if the knee is extended too fast (as deemed by the therapist). The block diagram of the paradigm is shown in Fig. 2.

In practice, the paradigm requires the therapist to first configure target ranges for knee flexion on either side as well as thresholds for acceptable knee extension angular velocity (see Fig. 2). As the patient walks, the mapping framework normalizes the measured knee angles within the target ranges of motion, and checks whether the angular velocity thresholds are exceeded. The normalized knee angles are sent to REAPER, where a major chord MIDI loop is synthesized using the PerFormant virtual instrument (VSTi)[5]. This instrument works by passing a set of sawtooth waves through a parallel bank of three 8^{th} order bandpass filters. The normalized knee angles are mapped to the center frequency of one of them, such that it varies from approximately 600 Hz - 4 kHz. Hence, the output sound becomes richer in high frequency spectral content as the knee angle increases, which is intended to generate an auditory reward for attaining the target flexion angle. The density of harmonics resulting from the chordal input coupled with the resonant properties of the filter ensure that the auditory changes are perceptually salient.

If the knee angular velocities during extension exceed the configured threshold, the overall audio output is attenuated to silence, leading to an audible interruption in the signal. As the phases of dysregulated knee extension tend to be rapid (see Fig. 1), the interruptions sound like brief but

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[5] `https://www.kvraudio.com/product/performant-by-elena-design`

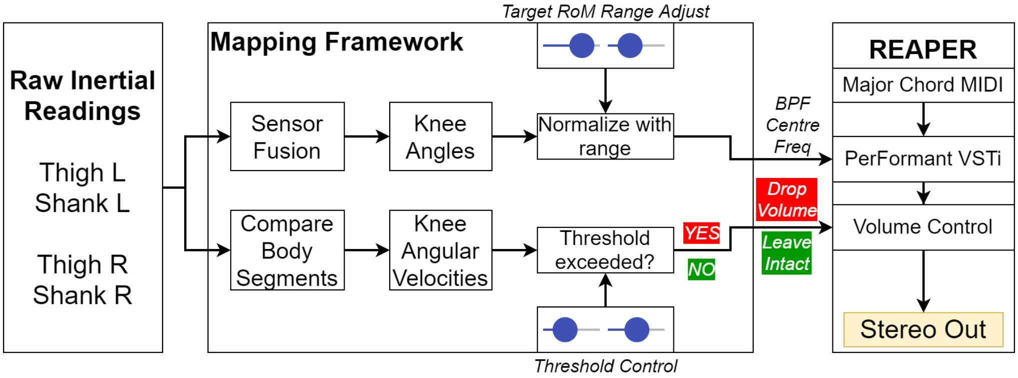

Figure 2. Block diagram of the first mapping paradigm, i.e. for reduced knee RoM and dysregulated extension feedback.

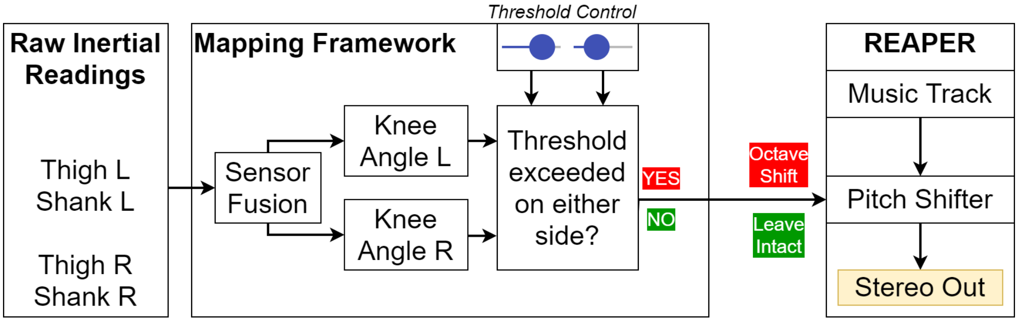

Figure 3. Block diagram of the second mapping paradigm, i.e. for knee hyperextension feedback.

clear audio dropouts. We applied the paradigm to inertial data recordings from several patients and synchronized them with the video footage, which yielded Videos 1 and 2 in the attached demo folder [6].

4.4 Paradigm 2: Hyperextension Feedback

The goal of the second paradigm is to provide clear on-off feedback that encourages the patient to avoid hyperextension by keeping the most affected knee slightly flexed during gait. The reason for the on-off choice is because it has previously been shown to be effective at reducing hyperextension [17], and would both be perceptually salient and straightforward to perceive and comprehend.

It is conceptually similar to [40] who successfully provided similar feedback but based on electrogoniometric readings as reviewed in [17]. Specifically, we designed it such that the substrate for feedback can be patient-selected music with vocals, and that the feedback is provided by applying a chipmunk-like effect to the music if (and for the entire duration that) the patient hyperextends their knee. The block diagram of the paradigm is shown in Fig. 3.

In practice, the therapist must first configure thresholds for hyperextension on either side (although the focus is typically on the most affected side). The patient-selected music track is played back in REAPER while the patient walks, and the mapping framework continuously checks whether the knee angles cross the respective hyperextension thresholds. The output is an on-off variable that is mapped to the octave shift control of a pitch shifter effect applied to the music track (REAPER's inbuilt ReaPitch in our case). If the threshold is exceeded, the music track is pitch-shifted up by an octave, or else it is left intact. Video 3 in the demo video folder illustrates this paradigm.

5. DISCUSSION

Based on inertial data and video footage from 15 patients, we developed two separate paradigms to provide real-time music-based feedback on knee kinematics in hemiparetic gait. We designed the feedback to be movement-congruent and based on transparent semantic metaphors.

Our primary design requirement for the paradigms was that they should be adjustable to suit the clinical profile of each patient. We believe that we were able to meet this through both the conceptual design and the technical implementation. Having a therapist configure the parameters of the feedback (and thereby the goals of the training session) fits well with proposed approaches in past literature [5]. As we implemented normalized feedback variables rather than absolute value mappings, it is possible to provide tailored, yet consistent feedback at a variety of impairment levels. Moreover, our mapping framework allows key parameters (i.e. target RoM, and angular velocity and hyperextension thresholds) to be adjusted on the fly, serving as a proof of concept for a future streamlined version. We also managed to integrate musical structures as core components of the feedback (our second requirement). With our distributed software architecture and the

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[6] Video Demos: `https://drive.google.com/drive/folders/1eU-3LioaiszFDl8MGSPvbduwaxKB9ixh?usp=sharing`

flexibility of modern music software at our disposal, it is possible for us to experiment with and iteratively hone the feedback paradigms [37] in a loudspeaker-based training paradigm to unlock the full potential of musical feedback in movement rehabilitation [36]. It would be conducive to widespread adoption if the final system can be made smartphone-based and utilize the same off-the-shelf sensors that we used here.

We argue that our paradigms align well with suggested design practices to enhance motor learning [9, 25, 26, 36]. The first paradigm features a direct continuous mapping between knee angle and audio spectral properties, which should readily allow the feedback to be integrated with knee proprioceptive information and help the patient form a more robust internal representation of their movements [22]. We aim to investigate the potential motor learning benefits of this in a future study. The impairment-specific feedback in both our paradigms is not provided as a continuous error signal but as an interruption or distortion to the underlying sound. This form of feedback, too, has been postulated as being potentially beneficial in the process of strengthening sensorimotor linkages [25]. Indeed, patients suffering from hyperextension were shown to benefit considerably from a threshold-based on-off feedback concept similar to our second paradigm [40], suggesting that our design can confer similar benefits but in a more pleasant and motivating format due to the use of a musical substrate.

We have not yet tested our paradigms with patients (part of future work), and therefore cannot comment on their perceived meaningfulness, pleasantness, perceptual salience, or intrusiveness, and further in the timeline, on their clinical effects. From the perspective of the patient's needs, it may not make sense to only provide feedback on hyperextension *or* dysregulated extension, so combining the paradigms may be necessary - but it is unclear whether the resulting cognitive load will be manageable for patients. It may also be necessary to design alternative sonic textures to cater to the needs of patients suffering from hearing loss in the frequency range where most of the information is conveyed by the described paradigms [41]. We aim to address these questions as part of a larger future study involving users (patients and therapists), and expect our implementation of the paradigms to function as intended in the clinical environment as they were designed based on data from patients. Lastly, we will also explore the design of feedback paradigms to address impairments in hip and ankle kinematics, as those are also relevant in restoring normal gait patterns [15].

6. CONCLUSIONS

Through this work, we developed music-based paradigms for sonified feedback on knee kinematics in hemiparetic gait based on inertial data collected from real patients. We demonstrated the sonification designs using recorded data from a group of patients with varied impairment levels, showing the feasibility of applying the paradigms as an informative feedback tool in gait rehabilitation. Future work includes testing the perceived meaningfulness, pleasantness, perceptual salience, and intrusiveness of the paradigms, as well as their clinical effects along with developing an integrated feedback system that therapists can use with ease. Overall, we believe that the impairment-specificity and individual adjustability of our paradigms can advance existing auditory feedback designs for hemiparetic gait rehabilitation.

Acknowledgments

We would like to thank the patients at Neuroenhed Nord (Brønderslev and Frederikshavn) who graciously agreed to take part in the study. This work is partially funded by by NordForsk's Nordic University Hub, Nordic Sound and Music Computing Network NordicSMC, project number 86892.

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