Gait Sonification for Rehabilitation: Adjusting Gait Patterns by Acoustic Transformation of Kinematic Data

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Zusammenfassung

Akustisches Feedback kann wirkungsvoll eingesetzt werden, um das Bewegungslernen sowohl im Sport als auch in der Rehabilitation zu erleichtern. Da es weniger Aufmerksamkeit als visuelles Feedback erfordert und die visuell dominierte Orientierung im Raum kaum beeinträchtigt, kann es während einer natürlichen Fortbewegung wie dem Gehen sicher und effektiv genutzt werden. Eine Methode zur Generierung akustischen Bewegungsfeedbacks ist die direkte Abbildung kinematischer Daten auf Sound (Bewegungssonifikation). Ein Einsatz dieser Methode in der orthopädischen Gangrehabilitation könnte einen wichtigen Beitrag zur Prävention von Stürzen und Folgeerkrankungen leisten. Neben dem individuellen Leid der Patienten ließen sich so auch medizinische Behandlungskosten erheblich reduzieren.

Um im Rahmen dieser Arbeit die Einsatzmöglichkeiten der Bewegungssonifikation in der Gangrehabilitation zu bestimmen, wurde eine neue Gangsonifikationsmethodik auf Basis von Inertialsensorik entwickelt. Zu der entwickelten Methodik werden, vor dem Hintergrund aktueller wissenschaftlicher Erkenntnisse zur Sensomotorik, zu Feedbackmethoden und zur Ganganalyse, in dieser Thesis drei in Fachzeitschriften publizierte Studien vorgestellt.

Die erste Studie beschreibt die Anwendbarkeit und Akzeptanz der Feedbackmethode bei Patienten in stationärer Rehabilitation nach unilateraler Hüftendoprothetik. Darüber hinaus wird der direkte Effekt der Gangsonifikation während eines zehnmaligen Gangtrainings auf das Gangmuster der Patienten deutlich. In der zweiten Studie wird der unmittelbare Nacheffekt der Gangsonifikation auf die Kinematik der gleichen Patientengruppe zu vier Messzeitpunkten nach dem Gangtraining untersucht. In diesem Zusammenhang zeigte sich ein signifikanter Einfluss der Sonifikation auf das Gangbild der Patienten, der allerdings nicht den zuvor erwarteten Effekten entsprach. Aufgrund dieses Ergebnisses wurde in einer dritten Studie die Wirkung des spezifischen Klangparameters Lautstärke der Gangsonifikation auf das Gangbild von gesunden Personen analysiert. Dabei konnte ein Einfluss von asymmetrischer Lautstärke der Gangsonifikation auf die Bodenkontaktzeit nachgewiesen werden. Die Berücksichtigung dieses Ursache-Wirkungs-Zusammenhangs kann einen Baustein bei der Verbesserung der Gangsonfikation in der Rehabilitation darstellen.

Insgesamt wird die Anwendbarkeit und Wirksamkeit von Bewegungssonifikation in der Gangrehabilitation bei Patienten nach unilateraler Hüftendoprothetik evident. Die gewonnenen Erkenntnisse verdeutlichen das Potential der Methode, die orthopädische Gangrehabilitation zukünftig effizient zu unterstützen. Ausschöpfen lässt sich dieses Potential auf Grundlage der vorgestellten Ergebnisse insbesondere anhand einer adäquaten Zuordnung von Bewegung zu Sound, einer systematischen Modifikation ausgewählter Soundparameter sowie einer zielgruppenspezifischen Wahl des Modus der Sonifikation. Neben einer differenzierten Untersuchung der genannten Faktoren, erscheint zukünftig eine Optimierung und Verfeinerung der Ganganalyse bei Patienten nach Endoprothetik unter Einsatz von Inertialsensorik notwendig.

Schlagwörter: Akustisches Feedback • Bewegungslernen • Hüftarthroplastik • Gangtrainingsintervention

Abstract

To enhance motor learning in both sport and rehabilitation, auditory feedback has emerged as an effective tool. Since it requires less attention than visual feedback and hardly affects the visually dominated orientation in space, it can be used safely and effectively in natural locomotion such as walking. One method for generating acoustic movement feedback is the direct mapping of kinematic data to sound (movement sonification). Using this method in orthopedic gait rehabilitation could make an important contribution to the prevention of falls and secondary diseases. This would not only reduce the individual suffering of the patients, but also medical treatment costs. To determine the possible applications of movement sonification in gait rehabilitation in the context of this work, a new gait sonification method based on inertial sensor technology was developed. Against the background of current scientific findings on sensorimotor function, feedback methods, and gait analysis, three studies published in scientific journals are presented in this thesis:

The first study shows the applicability and acceptance of the feedback method in patients undergoing inpatient rehabilitation after unilateral total hip arthroplasty. In addition, the direct effect of gait sonification during ten gait training sessions on the patients' gait pattern was revealed. In the second study, the immediate follow-up effect of gait sonification on the kinematics of the same patient group is examined at four measurement points after gait training. In this context, a significant influence of sonification on the gait pattern of the patients was shown, which, however, did not meet the previously expected effects. In view of this finding, the effect of the specific sound parameter loudness of gait sonification on the gait of healthy persons was analyzed in a third study. Thus, an impact of asymmetric loudness of gait sonification on the ground contact time could be detected. Considering this cause-effect relationship can be a component in improving gait sonfication in rehabilitation.

Overall, the feasibility and effectiveness of movement sonification in gait rehabilitation of patients after unilateral hip arthroplasty becomes evident. The findings thus illustrate the potential of the method to efficiently support orthopedic gait rehabilitation in the future. On the basis of the results presented, this potential can be exploited in particular by an adequate mapping of movement to sound, a systematic modification of selected sound parameters, and a target-group-specific selection of the gait sonification mode. In addition to a detailed investigation of the three factors mentioned above, an optimization and refinement of gait analysis in patients after arthroplasty using inertial sensor technology will be beneficial in the future.

Keywords: acoustic feedback • motor relearning • hip arthroplasty • gait training intervention

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Acronyms

AAF augmented auditory feedback

AF augmented feedback

ANCOVA analysis of covariance

ANOVA analysis of variance

Bf-SR mental state questionnaire (Befindlichkeits-Skala)

BMI body mass index

CG control group

CNS central nervous system

COV coefficient of variation

fMRI functional magnetic resonance imaging

G1 group 1

G2 group 2

IMS instructing model sequences

IMU inertial measurement unit

LQ left quiet

MS movement sonification

PD Parkinson's disease

RAC rhythmic auditory cueing

RMSE root mean square error

RoM range of motion

RQ	right quiet
RTF	real-time feedback
SD	standard deviation
SE	standard error
SG	sonification group
TD	touch down
THA	total hip arthroplasty
TO	toe off
TS	training session

1

Introduction

The ability to walk upright is crucial for the autonomy and safety with which we move in our environment. An unstable gait often leads to secondary diseases and falls, sometimes resulting in serious injuries (Bell et al., 2000). An annual incidence of falls of one third of people over 65 years (Kabeshova et al., 2016) highlights the need to develop efficient rehabilitation methods that enhance gait quality.

Due to the ever-improving technical possibilities, feedback methods for movement rehabilitation are increasingly developed, investigated, and applied (Pataky et al., 2009; Zeni Jr et al., 2013; Raaben et al., 2018; Richards et al., 2018; Pfeufer et al., 2019). Central to this thesis is a feedback method termed movement sonification, first published by Effenberg (2005). This is the mapping of sound to kinematic and/or dynamic data recorded with special sensors during movement execution (Hermann et al., 2011). Under real-time, low-latency conditions, movement sonification serves like an acoustic mirror, allowing continuous comparison of the executed movement with the sound fed back. Hence, the movement-inherent proprioceptive and tactile feedback of our body is supplemented by another modality, which provides new information qualities directly derived from the movement. The intention is to establish a close link between the different sensory modalities and thus affect sensorimotor function (Effenberg et al., 2016; Dyer et al., 2017a; Dyer et al., 2017b). The efficacy of movement sonification has already been demonstrated in multiple studies in the field of sport and rehabilitation (Vinken et al., 2013; Schmitz et al., 2014; Schaffert et al., 2017; Bevilacqua et al., 2018; Effenberg & Schmitz, 2018; Ghai, Schmitz, et al., 2018; Fehse et al., 2020; O'Brien et al., 2021; Liu et al., 2022; for review cf. Schaffert et al., 2019).

Also, for gait rehabilitation early approaches and pilot studies can be found that suggest the potential of movement sonification in this area (Rodger et al., 2013; Young et al., 2013;

Horsak et al., 2016; Pietschmann et al., 2019). For example, in a pilot study by Horsak et al. (2016) the immediate impact of real-time sonification using force sensors embedded in insoles on gait in 12 healthy volunteers was investigated. An immediate effect in terms of reduced cadence and gait speed was observed. However, a questionnaire provided an indication that study participants did not always clearly relate gait sonification to their own gait, so uncertainty due to lack of comprehension may underlie the observed effects. In this regard, Dyer et al. (2017a) point out the importance of mapping design. This refers to the fact that the mapping of motion parameters to sound should be made as intuitive as possible for the user to ensure comprehensibility. For example, it seems reasonable to assign a higher frequency to a spatially higher point and a lower sound frequency to a spatially lower point. Furthermore, for the comprehension and effectiveness of sound on movement, the target group seems to be particularly relevant, as is illustrated in a study by Young et al. (2014): They found that Parkinson's disease (PD) patients are able to imitate recorded, i.e., real, step sounds, but their ability to imitate artificially generated step sounds is limited. Contrary, in healthy persons this imitation ability was found to be similar under both conditions (Young et al., 2013; Young et al., 2014). It can be concluded from the literature that there is currently a lack of evidence for the use of sonification in gait rehabilitation. However, once the causal mechanisms and contributing variables are identified and understood, the method seems promising in this context.

The aim of this work is to contribute to more efficient orthopedic gait rehabilitation by developing and investigating gait sonification, focusing on answering the following four questions: **(Q 1)** What effects on the gait pattern of orthopedic patients can be achieved using gait sonification? **(Q 2)** Can a targeted effect on the gait pattern be obtained by changing certain sound parameters of gait sonification? **(Q 3)** Is it possible to develop a gait sonification method using only kinematic data captured by inertial sensors? **(Q 4)** And, is the developed gait sonification applicable in a clinical setting? To find answers, a method of gait sonification was developed and its effect on the gait pattern of healthy persons and patients after unilateral hip arthroplasty was investigated. These investigations have resulted in three scientific papers that have been published in advance in international journals and form the core of this thesis.

Before introducing the papers, chapter 2 reviews the current scientific background: Section 2.1 describes how principles of sensory perception can be used specifically for motor learning. Then, the concepts of movement sonification are introduced (section 2.2) before specifics of gait are addressed (section 2.3). Chapter 2 closes with an introduction to the new gait sonification method examined in the three following papers (section 2.4). Chapter 3 gives a brief overview of the co-authors' contributions before the published papers are presented in chapters 4, 5 and 6. A general discussion in chapter 7 classifies and analyzes the methods and results of the three papers, followed by a final conclusion (chapter 8).

2

Scientific Background

This chapter first outlines the scientific theories and findings which form the basis of the application of acoustic feedback for motor learning (section 2.1). Subsequently, findings on movement sonification are specifically addressed (section 2.2) followed by section 2.3 on relevant characteristics of gait.

The aim is to clarify the links between the domains and thus substantiate the following investigations. The chapter ends with an introduction to the self-developed method of gait sonification applied and examined in the three studies presented in this thesis (section 2.4).

2.1 Systematic Use of Sensory Perception for Motor Learning

The human sensory and motor systems are closely linked, which becomes immediately clear when considering that movement is the only way to respond to an external stimulus. The close linkage of our sensory and motor systems offers the possibility to use external stimuli in a targeted way to affect motor learning and movements.

First, the following section introduces the key concepts of sensory perception and its connection to action and movement (section 2.1.1). Then, in section 2.1.2, extended feedback in general and acoustic feedback in particular are discussed.

2.1.1 Perception and Action: Links to Create Coherence

As humans, we are able to perceive visual, auditory, tactile, vestibular, proprioceptive, gustatory, and olfactory as well as temperature and pain stimuli. Our various specialized sensory organs are constantly active to sense stimuli and simultaneously transmit the received signals to the central nervous system (CNS). Hence, our brain permanently receives multisensory impressions i.e., stimuli from at least two senses, which it processes into a coherent image of our body and our environment (Fetsch et al., 2012).

In the past two decades, it has become widely accepted that our brain does not acquire and subsequently combine sensory information from different sensory modalities independently but integrates and processes them together already during the hierarchical perceptual process (multimodal integration) (Shams & Seitz, 2008; Van Atteveldt et al., 2014; Pasqualotto et al., 2016). In this regard, integration of sensory information of different modalities was shown to occur earlier in the process than previously assumed (Ghazanfar & Schroeder, 2006; Kuraoka & Nakamura, 2007; Froesel et al., 2021). It has also become increasingly clear that brain areas formerly assigned exclusively to one sensory modality are influenced by additional sensory modalities (Amedi et al., 2001; Pietrini et al., 2004; Wang et al., 2008). It can be concluded that our brain is highly interconnected, so that the projection of an event in our brain is basically created by processing overlapping information from different sensory modalities, which is called multisensory integration. This makes our perception more accurate and reliable, since our brain does not have to rely only on the limited information from one sensory channel (Van Atteveldt et al., 2014; Müsseler & Rieger, 2017).

However, due to the close interconnection, intersensory interferences might also occur. For example, Shams et al. (2000) reported an illusion in the perception of visual flashes. Thus, instead of a single flash actually presented, multiple flashes are perceived when multiple beeps are presented simultaneously (Shams' illusion, Sound-Induced Flash Illusion). This illusion reveals how considerably unimodal sensory impressions are integrated to form an overall picture.

Regarding auditory perception, it has been shown to be particularly reliable when it comes to recognising temporal intervals and dependencies (Repp & Penel, 2002; Merchant et al., 2008). Basically, it is assumed that the processing of temporal structures occurs supramodally in the brain, but that modal-specific processes also exist, e.g., for visual, tactile, and auditory analysis (Bueti et al., 2008; Pasinski et al., 2016; Araneda et al., 2017). It is generally accepted that auditory perception is superior to other modalities in processing temporal structures. In this regard, Pasinski et al. (2016) describe that the brain is more responsive to auditory temporal information and more capable of developing temporal expectations for auditory stimuli than for visual stimuli. Furthermore, Lukas et al. (2014) were able to show that study participants are more disturbed by a simultaneously presented auditory stimulus when recognizing the duration of a visual stimulus than vice versa. This dominance in temporal processing represents an important reference point to audio-motor processes of the neuronal system.

From our ability to speak, sing, play musical instruments, or dance to music, it is apparent that we can translate auditory signals directly into movement and also associate movement with auditory signals. Based on these observations, a large number of studies were conducted investigating neuronal auditory-motor interaction (Zatorre et al., 2007; Amad et al., 2017; Dyer et al., 2017c; Nunes-Silva et al., 2021). In this regard, de Manzano et al. (2020) demonstrated in a functional magnetic resonance imaging (fMRI) study that after practicing melodies on the piano, sequence-specific activation patterns arise in the premotor cortex during subsequent listening to the practiced melodies. Consequently, an action-perception coupling emerges even in non-musically trained individuals. Although it is not yet clear to what extent the findings on audio-motor linking after audio-motor training can be transferred to gross motor skills, the studies to date provide evidence that action-perception coupling can occur after relatively short training. These neurological effects, termed neuroplasticity (Chatterjee et al., 2021), together with multisensory integration, provide a foundation for the hypothesis that motor learning and movement rehabilitation can be efficiently supported by perceptual auditory information.

2.1.2 Acoustic Feedback and Its Use for Motor Learning

In the past two decades, technological capabilities have evolved tremendously becoming less expensive and more usable in sports and rehabilitation. Compared to verbal cues and corrections that have been common and widely used for a long time, technological applications now offer similarly flexible and versatile functionalities that promise particular effectiveness in motor learning (Baca et al., 2009; Lightman, 2016; Camomilla et al., 2018; Kos & Umek, 2018; Lee et al., 2019).

Nowadays, modern computer technology even allows our entire environment to be artificially generated, which is referred to as virtual reality (Howard, 2017; Laver et al., 2017; Rose et al., 2018; Feng et al., 2019; Lei et al., 2019). This can simulate targeted motion prompts or external feedback in dimensions that were previously inaccessible. If an external source does not create a ”complete” artificial environment, but rather selectively supports, amplifies, modifies, or synthesizes partial aspects of sensory perception, this is referred to as augmented feedback (AF). Augmented feedback is designed for different sensory modalities, depending on the purpose and applicability (Sigrist et al., 2013; Chamorro-Moriana et al., 2018). In this thesis, extrinsic feedback is provided for the auditory modality, which is particularly beneficial for orientation and safety in locomotion. Therefore, acoustic feedback will be specifically addressed in this section by presenting two established research approaches: first, rhythmic auditory cueing, and second, natural movement sounds.

Rhythmic auditory feedback or rhythmic auditory cueing (RAC) can be considered particularly effective and well studied for gait rehabilitation (Thaut et al., 1996; Thaut & Abiru, 2010; Thaut et al., 2015; Murgia et al., 2018; Chang et al., 2019; Thaut et al., 2019; Belluscio et al., 2021). In this method, the patient is repeatedly given an acoustic stimulus at consistent intervals to which he or she is supposed to perform a specific movement event. In gait rehabilitation, for example, this event is the striking of the foot. It should be emphasized that this method of acoustic feedback provides feedforward information, since the auditory stimuli can be anticipated by the patient: Due to their regular temporal spacing, the occurrence of the stimuli becomes predictable and the movements to be performed can be planned according to the given meter (”forward model”) (Pizzera & Hohmann, 2015; Schaffert et al., 2019).

In a recent review article, Janzen et al. (2021) describe the effectiveness of RAC in neurorehabilitation. In particular, positive effects on motor functions have been observed in PD and stroke patients. Likewise, rehabilitation in other diseases such as traumatic brain injury, multiple sclerosis, cerebral palsy or Alzheimer’s disease seems to benefit from RAC (Ghai, Ghai, et al., 2018; Schaffert et al., 2019; Janzen et al., 2021). The effect of RAC has as well been studied in sports, often focusing on natural rhythmically occurring sounds (MacPherson et al., 2009; Pizzera & Hohmann, 2015). For example, Kennel et al. (2015) investigated the effect of rhythmic stepping sounds present during hurdling on running speed and demonstrated that delayed occurrence of stepping sounds reduced speed. A similar method was used by Pizzera et al. (2017), but study participants did not receive acoustic feedback during hurdle running, but as reafference training directly before training runs. Three feedback conditions were investigated: (1) feedback with increased speed, (2) feedback with reduced speed, and (3) feedback with original speed (control group). All groups were found to increase their performance from pre-test to post-test, but only for the increased- and reduced-speed groups performance continued to increase toward the retention test, compared to a decrease in the control group. This observed effect did not correspond to the hypotheses of the authors, who had assumed a greater increase in speed for the increased-speed group compared to the control group. In addition, the authors had suspected a decrease in speed for the reduced speed group. In this context, debriefings with the study participants revealed that the reduced speed group partly perceived the reduced speed of the auditory feedback as additional motivation to run even faster. Another explanation for the positive effect on the running speed of the reduced speed group would be that the rhythm of the movement became particularly clear due to the lower speed. In general, the authors suggested that auditory feedback may have fundamentally promoted the development of a cognitive representation of movement, particularly because of the repeated experience of the auditory rhythmic pattern of movement.

Contrary to research on the effect of RAC on movement, research on natural movement sounds tends to focus on the perception of sound-action links (Agostini et al., 2004; Thomas & Shiffrar, 2013; Cesari et al., 2014; Kennel et al., 2015; Sors et al., 2018). Research questions asked in this context often address the origin of an auditory stimulus. Specifically, it is asked whether a recorded sound is attributed to one's own or another's previous movement or at what latency a sound is attributed to one's own action that is currently taking place (Pizzera & Hohmann, 2015). Feedback is assumed to have a different effect on motor control when one's own action is considered the origin. If this is not the case, the acoustic feedback may not be relevant to the performer of a movement and accordingly might have little or no influence on motor control (Arrighi et al., 2009; Thomas & Shiffrar, 2010; Thomas & Shiffrar, 2013).

Furthermore, the question arises whether sounds that are intentionally produced by an action are perceived and processed differently from sounds that are produced unintentionally. Heins et al. (2020) investigated this question in the context of an fMRI study in which the relevance of auditory information on action ratings and the brain responses of hurdlers (by-product action sounds) and tap dancers (goal-related action sounds) were examined. The authors hypothesized that auditory information would be more relevant to tap dancers in rating their movement quality. It was also supposed that in tap dancing, sounds are part of the motor plan because they are intended and self-generated. Thus, the sounds are highly predictable, so their processing might be more efficiently attenuated at lower neuronal levels and instead areas for processing action sounds are more activated (Kaiser & Schütz-Bosbach, 2018). To investigate these hypotheses, individual videos of the participants tap dancing and hurdling were recorded. The videos were then presented to the study participants in original form and in scrambled visual, scrambled auditory or scrambled visual and auditory form during fMRI measurements. Regarding action ratings, it was found that tap dancers rated their performance significantly worse compared to hurdlers. In addition, tap dancers showed attenuated activity of the primary auditory cortex and, at the same time, greater activation of the supplementary motor area, posterior superior temporal gyrus, and cerebellum, which are considered to provide a predictive sound model. From these results, it could be concluded that processing and use of action sounds is influenced by whether the action is intended to produce a sound intentionally or whether it occurs incidentally.

Along with questions of action attribution and intention, other aspects of natural sounds and their influence on motor skills have been investigated (Agostini et al., 2004; Cañal-Bruland et al., 2018; Schaffert et al., 2020; Klein-Soetebier et al., 2021). For example, Sors et al. (2018) explored the effect of loudness on reaction time using soccer penalty shots. Participants were instructed to press a computer key as quickly as possible after hearing the shots, which resulted in varying ball speeds. It was found that the loudness of heard shot sounds had a stronger influence on the reaction time of the study participants than the pitch, which is naturally higher for more powerful shots. Furthermore, Camponogara et al. (2017) showed that basketball players are better able to predict the final direction of the opponent's run compared to non-basketball players based solely on the sounds made when an opponent attacks. This indicates that athletic training makes the assessment of movement-related sounds more accurate and auditory information more relevant.

In the studies on natural movement sounds, two variables have been identified that can influence the contribution of acoustic stimuli to movement execution: First, the spatiotemporal proximity between movement and sound, and second, the relevance of the sound to movement. Consequently, these factors can also affect the effectiveness of movement sonification and should therefore be considered when developing new sonification methods as described in section 2.4.

2.2 Principles and Efficacy of Movement Sonification

In this section, particular attention is paid to the human understanding of sound in interaction with further perceptual processes. The scientific findings explained are provided to substantiate the use of sonification for motor learning and to preface the choice of sound design and action-sound mapping of the gait sonification method developed in this thesis.

First, the relationship between movement, body and sound is discussed (section 2.2.1) before the current state of research on sonification for motor learning is concretely presented (section 2.2.2).

2.2.1 Interactions Between Modality, Body, and Sound

As described in section 2.1.1, multimodal sensory perceptions are not processed separately, but are recorded and evaluated in an integrating manner. In the context of this multisensory integration, the sensory modalities consequently affect each other. To understand this process, it is important to be aware of the associations that exist between the different sensory modalities in the perception of object attributes (crossmodal correspondence). These crossmodal correspondences, in addition to spatiotemporal proximity and semantics, support the identification of sensory impressions of different modalities to be merged and are described first in this section. Subsequently, it will be discussed how sound affects human body-perception. Since, due to action-perception coupling, it can be assumed that body-perception and movement of the body have a mutual effect, body-perception should also be considered especially in the development of concise action-sound-mapping and sound design.

In a review article, Spence (2011) describes the existence of extensive scientific research on crossmodal correspondences in a variety of modality combinations. Crossmodal correspondences include associations between different sensory modalities for different information (e.g., auditorily perceived pitch and visually perceived brightness) as well as overlapping information (e.g., visually and auditorily perceived duration of a stimulus). On this basis, it can be assumed that crossmodal correspondences exist between a multitude of possible combinations, e.g., vision and skin sensations, hearing and skin sensations, or smell and hearing. Most frequently, however, correspondences between visual and auditory perception have been examined. A correspondence between pitch and visually perceived height in space has been found to be particularly robust and evident, with a high pitch being associated with a higher position in space (Bernstein & Edelstein, 1971; Maeda et al., 2004; Widmann et al., 2004; Spence, 2011). Furthermore, a correspondence between pitch and object size – high corresponds to small – (Evans & Treisman, 2010; Tonelli et al., 2017; Cuturi et al., 2021), as well as pitch and visual brightness – high corresponds to bright – (Maimon et al., 2020) is assumed. Similarly, for the loudness of sound, correspondences to spatial distance – close corresponds to loud – (Zahorik et al., 2005; Eitan, 2013; Kolarik et al., 2016), size – large corresponds to loud – (Eitan, 2013; Hartmann & Mast, 2017; Hauck & Hecht, 2019), and muscle energy – high energy/force corresponds to loud – (Kohn & Eitan, 2009; Küssner et al., 2014; Küssner & Leech-Wilkinson, 2014) are found in particular. Küssner et al. (2014) also point out that interactions occur between the different parameters, especially between pitch and tempo and loudness and tempo in terms of their crossmodal correspondence to movement speed. If the tempo of the sounds increases, movement speed increases in principle, but if the pitch decreases at the same time, the increase in movement speed is gradually lowered. In addition, the speed of movement decreases when the sounds' volume decreases (Küssner et al., 2014). This example clearly shows that for a systematic and targeted assignment of sound to movement, it is necessary to analyze the combination and interaction of different auditory parameters and their crossmodal correspondences in detail, especially with regard to their effect on movement.

Beyond crossmodal correspondences, the perception of sensory information and the execution of movements are linked to our body perception. In concrete terms, this means that sensory information is used to develop an initially unconscious idea regarding the location of body parts in space and the spatial relationship between them. This concept of the spatial position of the body in space is referred to as body schema in the literature. As body position changes due to movement, movement affects body schema, just as body schema affects movement, since purposeful and coordinated movements can only be executed from a starting position (Schwoebel & Coslett, 2005; Palermo et al., 2018).

That sound is involved in the creation of a coherent body schema based on multisensory integration has been shown, for example, with the Rubber-Hand Illusion (Radziun & Ehrsson, 2018). This illusion is based on an experiment in which the study participants' own hand is occluded and instead they observe a plastic hand being stroked in front of their body while their own non-visible hand is being stroked in the same way simultaneously. After some time, participants perceive the plastic hand as belonging to their own body (Botvinick & Cohen, 1998). In a modified version of the Rubber-Hand Illusion, Radziun & Ehrsson (2018) supplemented the experiment described above with additional auditory stimuli that appeared either synchronously or asynchronously to the touch. Compared to a control condition (without auditory stimuli), the illusion was found to be enhanced for synchronous auditory stimuli and diminished for asynchronous auditory stimuli.

An impact of the pitch of natural step sounds on both body schema and gait pattern was found by Tajadura-Jiménez et al. (2015) in a study of 22 healthy participants. In this regard, they used three different feedback conditions in which participants either (1) heard the natural sound of their steps, (2) a higher frequency sound of their steps, or (3) a lower frequency sound of their steps. The modified conditions (2) and (3) were achieved by amplifying the corresponding frequency ranges while decreasing the opposite frequency ranges, but they were still based on the actual step sounds. It became apparent that participants perceived their bodies as lighter after walking with a higher frequency sound. Regarding their gait pattern, they moved their lower extremities upwards faster with higher frequency sound, while a longer contact time of the heels with the ground was observed with lower frequency sound. This result illustrates that the modification of individual sound parameters can cause a specific effect on gait pattern, which could be used to make gait sonification more targeted and effective.

Further studies suggest that loudness may also have a specific effect on movement. For example, Van Dyck et al. (2012) describe that increased movement activity and increased tempo adaptation were observed in study participants who danced to music with increased sound pressure levels of the bass drum. In addition, a direct influence of loud low-frequency sounds on the vestibular system and thus on the sense of motion has been discussed (Todd et al., 2000). However, as far as known, the impact of loudness on gait has hardly been reported so far. To obtain more knowledge in this regard, this thesis presents an experiment that investigates the link between loudness and gait for use in gait sonification (chapter 6).

2.2.2 Making Movement Sound: Sonification for Efficient Motor Learning

Movement sonification represents a feedback method in which movement data (independent variable) is mapped to auditory information (dependent variable). This means that kinematic or kinetic parameters are assigned to a specific frequency, timbre, sound duration, harmony and melody. In principle, the auditory information or sound is presented simultaneously with the movement as real-time feedback during sonification (Effenberg et al., 2016). Clear correspondences between movements and sonification are intended, thus an additional perception-action link is established by movement sonification. The naturally existing sensory feedback is consequently complemented by another modality, but no new information is generated, as is the case, with error feedback, for example. So, there is the advantage that no conscious processing and interpretation of the feedback is required, and a guidance effect might be avoided. Thus, the dependence on feedback is reduced and a learned movement is retained in the long term (Ronsse et al., 2011; Effenberg et al., 2016; Dyer et al., 2017a; Dyer et al., 2017c).

For unconscious processing of feedback, it is important that movement sonification is based on natural action-sound links (Effenberg, 2005; Dyer et al., 2017a). Yet, developing and systematizing a successful design for movement sonification remains a challenge and is increasingly investigated and discussed (Dubus & Bresin, 2013; Roddy & Bridges, 2018; Fitzpatrick & Neff, 2021; Kantan et al., 2021; Kantan et al., 2022). On the one hand, this development illustrates the complexity inherent in the many ways sound can be mapped to movement. On the other hand, the emergence of different design approaches also reflects the numerous options for development that underlie movement sonification. In this regard, the question arises whether a more distinct separation of disciplines, especially into artistic and scientific sonification, as suggested by Neuhoff (2019), can contribute to more plausible and coherent results. Also, reducing the myriad of movement tasks found in the literature to fixed model tasks could contribute to facilitating the ″cumulative process of science″ (Ranganathan et al., 2021).

That sonification is helpful and effective has already been shown in a great variety of studies. For example, Fehse et al. (2020) demonstrated that when using sonification, goal-directed one-handed grasping movements are performed no worse blindfolded than with full visual feedback. Ghai, Schmitz, et al. (2018) found similar results for the lower extremities in a study with healthy participants, in which a given knee angle was to be achieved blindfolded but with the help of real-time movement sonification.

In sports, real-time sonification has been examined, inter alia, in golf (O'Brien et al., 2021), cycling (Schaffert et al., 2017; Vidal et al., 2020; O'Brien et al., 2020), rowing (Dubus & Bresin, 2015; Schaffert & Mattes, 2015), running (Eriksson & Bresin, 2010; Forsberg, 2014), swimming (Hermann et al., 2011; Cesarini et al., 2014), and speed skating (Boyd & Godbout, 2010) (for review, cf. van Rheden et al., 2020). In their review article, Schaffert et al. (2019) highlight three effects in sports that can be achieved by sonification in particular: (1) improved motor control and execution, (2) improved self-awareness, and (3) improved awareness of performance errors. However, specifically in sports, the user-friendliness, user-acceptability, and implementability of real-time sonification is crucial, as reflected in multiple feasibility studies (Boyd & Godbout, 2010; Cesarini et al., 2014; Forsberg, 2014).

The application and impact of sonification on movement have also been investigated in prevention, rehabilitation, and therapy. A main focus of sonification research in the health sector, as in AF in general (section 2.1.2), is neurological and neurodegenerative diseases. In several instances, the effect of sonification in stroke rehabilitation on upper extremity movements in particular has been studied (Robertson et al., 2009; Schmitz et al., 2014; Scholz et al., 2014; Scholz et al., 2015; Scholz et al., 2016; Ghai, 2018; Schmitz et al., 2018; Nikmaram et al., 2019; Raglio et al., 2021). For example, Nikmaram et al. (2019) conducted a study of 40 patients with acute or subacute unilateral stroke. The patients practiced producing a nursery rhyme melody over several days (between 11 and 46) using musical movement sonification of the affected arm. There was a positive effect on the patients' motivation, but only a small effect on the quality of movement.

In contrast, Raglio et al. (2021) found positive effects on movement ability in a study of 65 patients with subacute stroke. The patients participated in 20 training sessions in which standardized hand and arm movements were sonified by an intuitive movement-based sound design. Most importantly, there was a significant improvement in global impairment of the upper limbs (according to the Fugl-Meyer Upper Extremity Scale). This discrepancy between the study results indicates that both the movement sound mapping and the choice of movement task are crucial for a desired rehabilitation effect. Both factors should be considered and investigated in particular for the use of sonification in stroke rehabilitation.

In the therapy of PD patients, mainly RAC has been used so far, which is not generated by movement but originate from an external source. In this way, the intention is to bypass the increased inhibition of movement that occurs in PD due to degeneration in the basal ganglia by volitional responses to external stimuli (Ginis et al., 2018). Movement sonification typically provides real-time feedback generated by the patient's own movement, so the use of sonification for PD therapy seems less obvious. Nevertheless, there are now initial studies on movement sonification in PD therapy (Rodger et al., 2013; Schedel et al., 2016; Gorgas et al., 2017; Mezzarobba et al., 2018).

In first investigations, sonification is also used in orthopedic rehabilitation. For instance, Pietschmann et al. (2019) compared the effect of different feedback modalities (visual, tactile, auditory) during gait rehabilitation in patients after total knee arthroplasty (n = 120) and total hip arthroplasty (THA) (n = 120). For movement sonification, hip angles and knee angles, respectively, were mapped directly to a pure tone. Patients were instructed to match the melody of the affected joint to the melody of the contralateral joint while walking on a treadmill at self-selected speed for twenty minutes at six training sessions. There was an overall improvement in gait in all intervention groups and the control group, but no significant improvement in gait in the sonification group compared to other groups. It was observed that shortly after gait training with sonification, during which the gait pattern improved, the patients returned to their old gait pattern. Therefore, the lack of effect of sonification was attributed, in part, to the insufficient duration of training.

2.3 Gait in Clinic and Science

Human gait is characterized by an upright posture of the trunk and a bilateral, alternating movement of the legs. Compared to quadrupedal locomotion, it requires more complex musculoskeletal and CNS mechanisms due to the reduced base of support with a higher center of gravity of the body (Dietz et al., 1986; Bruijn & Van Dieën, 2018). For this reason, diseases affecting the CNS or the musculoskeletal system often have a visible effect on gait pattern. Due to these known links between gait patterns and diseases, gait analysis enables diseases to be recognised and diagnosed. Conversely, gait analysis as a research method also provides a better understanding of the regulation and control as well as the biomechanical factors of gait.

The following section (section 2.3.1) first describes the basic process of walking from a biomechanical and neurophysiological perspective and introduces the terminology of gait analysis. Subsequently, section 2.3.2 discusses diseases affecting the gait pattern and possible rehabilitation strategies.

2.3.1 Biomechanical and Neurophysiological Principles of Human Gait

During walking, certain movement sequences are repeated again and again, for which reason we speak of a cyclic or rhythmic movement. A gait cycle begins, for instance, with the striking of the right heel, then the left leg is swung forward, the left heel is striking, the right foot is pushed off the ground, and finally the right leg is swung forward again until the next gait cycle begins with the renewed striking of the right heel (Blanc et al., 1999; Perry & Burnfield, 2010; Silva & Stergiou, 2020). Figure 2.1 (p. 15) outlines the different phases and their percentage distribution in a gait cycle. Spatiotemporal parameters typically considered in gait analysis are given in Table 2.1 (p. 15).

In contrast to discrete movements, cyclic movements involve greater regions of neuronal networks at the level of the spinal cord and brainstem. In particular, these networks include areas referred to as central pattern generators (Kiehn, 2016; Minassian et al., 2017; Côté et al., 2018; Grillner & El Manira, 2020; Grillner & Kozlov, 2021). Consequently, motor commands for cyclic or rhythmic movements arise at lower hierarchical levels, so rhythmic movements are thought to be more automated (Schaal et al., 2004; Clark, 2015; Wiegel et al., 2020). In addition, there are indications that different neuronal temporal and initiatory mechanisms underlie rhythmic and discrete movements (Lewis & Miall, 2003; R. M. Spencer et al., 2003; Huys et al., 2008).

While it is evident in discrete movements that sensory feedback is fundamental to movement execution (Johansson & Flanagan, 2009; Clemente et al., 2019; Sensinger & Dosen, 2020), the question arises how much sensory feedback is involved in the planning and control of automated rhythmic movements.

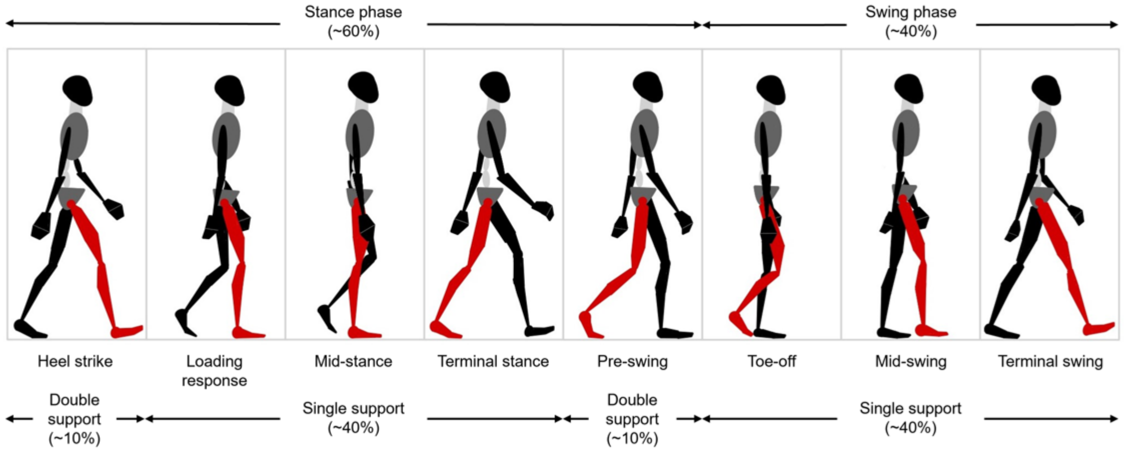

Figure 2.1: The phases of normal gait described for the leg highlighted red (cf. Silva & Stergiou, 2020).

Table 2.1: Basic definitions of spatiotemporal parameters of gait (Perry & Burnfield, 2010; Silva & Stergiou, 2020).

Spatiotemporal parameter	**Description**
Step length	Distance between the heel contact of the ipsilateral foot to the heel contact of the contralateral foot.
Stride length	Distance between one and the following heel contact of the same foot.
Stride duration	Interval between two sequential initial heel contacts by the same foot.
Cadence	Step rate at which an individual walks, commonly given in steps per minute.
Gait speed	The velocity, i.e., distance covered walking in a given time. Commonly expressed in meters per second.
Step width	Distance between the feet perpendicular to the sagittal plane of the feet during double support phase.
Ground contact time	Time during which one foot is in contact with the ground. Specifically, the interval between initial heel contact and final toe-off from the ground of one foot.

It is well known that mammals, particularly cats and mice, rely primarily on proprioceptive afferents to guide and control locomotion (Pearson, 1995; Akay, 2020). These feedbacks from the active locomotor system are necessary to temporally control the movement pattern and to switch between different phases of locomotion (Rossignol et al., 2006). Proprioceptive feedback is partly already processed and used at the spinal level, partly it is passed on to the brain. (Bosco & Poppele, 2001; Niu et al., 2013; Santuz et al., 2021).

In humans, there are indications that similar mechanisms underlie locomotion (Pearson, 2004; Kiehn, 2016; Di Russo et al., 2021). Basic gait movements are thought to be generated by central pattern generators at the spinal level, but supraspinal activation is equally necessary to initiate locomotion and respond appropriately to the environment (Norton, 2010; Frost et al., 2015). The level of relevance of proprioceptive and tactile feedback for human gait is exemplified in a study by Petrini et al. (2019): They implanted intraneural stimulation electrodes at the tibial nerve and fitted sensors to the prosthetic legs of two unilateral transfemoral amputees. The gait patterns with and without technical sensory feedback were compared. An increased gait speed, a subjectively higher perceived gait security and reduced phantom pain could be observed in this pilot study.

Further, in review articles, both Bronstein (2016) and MacKinnon (2018) describe proprioceptive, vestibular, and visual sensory information in particular as crucial for human locomotion and upright posture. In this regard, they also illustrate that multisensory integration occurs and that sensory modalities influence each other. Consequently, it can be stated that humans also rely on multisensory feedback for automated rhythmic movements and incorporate it in motor control.

2.3.2 Impairment and Rehabilitation of Gait Functions

Gait disorders that result in mobility limitations or an impaired gait pattern can be classified broadly into three categories: musculoskeletal gait disorders (e.g., osteoarthritis, skeletal deformities), neuromuscular and myelopathic gait disorders (e.g., peripheral paresis, spinal stenosis), and gait disorders due to brain dysfunction (e.g., spastic gait disorder, ataxic gait disorder, higher level gait disorder). In general, gait ability also decreases with age (Lim et al., 2007; Pirker & Katzenschlager, 2017). A specific gait disorder often manifests in a characteristic gait pattern. For example, freezing of gait is a typical symptom in PD or a slow gait speed with a high step width is characteristic of cautious gait due to anxiety. A more comprehensive overview of the appearance of different gait disorders can be found in Table 2.2 (p. 17).

Furthermore, increased gait variability is generally considered indicative of cognitive impairment and increased risk of falls (Hausdorff et al., 2005; Kang & Dingwell, 2008; Tian et al., 2017; Kalron et al., 2019; Bishnoi & Hernandez, 2021; Dragašević-Mišković et al., 2021). This can be attributed to a limitation in motor control ability resulting in more unstable behaviour (Stergiou, 2020). Though, increased gait variability can also be interpreted as a sign of reorganization of established motor processes triggered by unstable external conditions (Warren, 2006). For example, increased gait variability can be observed in children and adolescents who are still growing (Gouelle et al., 2016).

Table 2.2: Phenomenological classification of gait disorders (modified from Ružička & Jankovic, 2002).

Gait disorder	Characteristics
Hemispastic gait	Unilateral extension and circumduction
Paraspastic gait	Bilateral extension and adduction, stiff
Ataxic gait	Broad base, lack of coordination
Sensory ataxic gait	Cautious, worsening without visual input
Cautious gait	Broad based, cautious, slow, anxious
Freezing gait	Blockage, e.g. on turning
Propulsive gait	Centre of gravity in front of body, festination
Astasia	Primary impairment of stance/balance
Dystonic gait	Abnormal posture of foot/leg
Choreatic gait	Irregular, dance-like, broad-based
Steppage gait	Weakness of foot extensors
Waddling gait	Broad-based, swaying, drop of swinging leg
Antalgic gait	Shortened stance phase on affected side

In the context of this thesis, the influence of hip osteoarthritis and hip arthroplasty on gait is of particular importance. Although the symptoms and life satisfaction of patients with hip arthrosis improve significantly after THA (Zhai et al., 2019), it is known that the gait pattern of patients does not reach that of healthy people even one year after surgery. This is reflected in a lower gait speed, step length, gait cycle length and range of motion of the affected hip in the sagittal plane when walking (Bahl et al., 2018). The deviated gait pattern and the resulting altered loads on the musculoskeletal system can ultimately be seen as a contributory cause of more frequent falls in affected patients (Ikutomo et al., 2018; Ikutomo et al., 2022; Lin et al., 2022). Here, effective rehabilitation programmes can make an important contribution to preventing falls and secondary injuries. This is of particular societal relevance given that about 40% of patients report falls in the first year after surgical hip replacement (Ikutomo et al., 2015; Ikutomo et al., 2018; Lo et al., 2019) while at the same time the incidence of THA is expected to increase considerably in the coming decades (198% - 284% in the 2040s) (Inacio et al., 2017; Singh et al., 2019).

To counter this development with efficient rehabilitation programmes, it requires a good understanding of the underlying causes of the long-term gait deviation after THA. A more detailed investigation and analysis of THA and its impact on gait pattern therefore seems necessary. For example, in a recent research article, Ohmori et al. (2021) investigated the relevance of the functional status of the contralateral lower limb on gait speed after unilateral hip arthroplasty. They were able to show that single-leg stance time and knee extension strength of the contralateral leg are decisive factors for gait speed after unilateral hip arthroplasty. This finding can be used in the future, for example, to determine the most efficient period for the use of feedback methods or to analyse the effectiveness of the methods by determining and including single-leg stance time and knee extension strength of the contralateral leg.

Commonly, gait rehabilitation involves physiotherapeutic treatments to strengthen the needed muscles and practice movement patterns. Increasingly, however, automated systems are being used to help facilitate gait rehabilitation and make it more cost-effective in the long term. For example, treadmills that provide partial bodyweight support are being used (Koceska & Koceski, 2013). There is also increased research and work on automated orthoses, robotic devices, and exoskeletons, especially for stroke patients and patients with spinal cord injuries (Zeilig et al., 2012; Swinnen et al., 2014; Miller et al., 2016; Chaparro-Cárdenas et al., 2018; Cespedes et al., 2020).

For conditions that affect gait pattern yet allow independent patient locomotion, the efficacy of various feedback systems is under scientific investigation. These systems are created for patients with neurophysiological disorders (Cochen De Cock et al., 2021; Bowman et al., 2021; J. Kim et al., 2021; J. Spencer et al., 2021) but also increasingly for use in orthopedic rehabilitation (Isakov, 2006; Michelini, 2021; Castellarin et al., 2022; Müßig et al., 2022). For example, in the early gait rehabilitation (4-10 days after surgery) of patients after THA, Marin et al. (2021) used insoles that provide visual feedback on weight distribution. Compared to a control group, this led to a significant improvement in weight distribution to both legs in the experimental group. Thus, it becomes obvious that there is a potential for efficient and cost-effective gait rehabilitation in feedback systems for orthopedic diseases as well. In the future, systems that can be used by patients independently at home via smartphone or tablet could contribute significantly to achieving a long-term effect on gait without the need for permanent inpatient stay. Due to inertial sensor technology, mobile use will also be readily achievable for sonification systems.

2.4 Development and Application of the Investigated Gait Sonification

Based on the current state of scientific research, the previous sections described the close link between human auditory perception (Zatorre et al., 2007; Amad et al., 2017), other sensory modalities (Van Atteveldt et al., 2014; Müsseler & Rieger, 2017), and the motor system (Chatterjee et al., 2021) (multisensory integration and neuroplasticity). These findings substantiate the potential of movement sonification for motor learning and thus the use of sonification in gait rehabilitation.

In the following chapters (chapter 4, 5 and 6), three experimental peer-reviewed studies examine the effect of movement sonification on gait pattern in patients after unilateral hip arthroplasty and the modification of the sound parameter loudness of sonification on gait symmetry in healthy young persons. The results of the three studies are discussed and integrated in chapter 7.

The movement sonification method investigated by the studies was specifically developed to provide low latency real-time sonification of the gait pattern based on kinematic data. The MVN Awinda wireless inertial sensor system (XSens Technologies B.V., Enschede, The Netherlands) and associated MVN Studio BIOMECH software (XSens Technologies B.V., Enschede, The Netherlands) were used for data acquisition. Gait measurement requires the attachment of seven inertial sensors to the lower body. But no laboratory environment is required which made it possible for study participants to walk naturally at self-selected speed in a gym. The MVN Studio BIOMECH software allows streaming of the data pre-processed by the XSens system. The data streams were further processed using a self-developed program (The Scientific Python Development Environment, Spyder Developer Community). CSound (Csound 6, LGPL), an audio programming language, was applied to convert data into sound. A visual comparison with video recordings showed a low latency of < 100 ms for the sonification program, but no method comparison was carried out using force plates.

For a concise sound design, ground contacts of the feet and angular velocity of the knee extension were sonified. The sonification of the foot-ground contacts is based on the assumption that an action-perception coupling is already present here due to everyday experience and that the sound is rather attributed a relevance for the movement (cf. section 2.1.2; Camponogara et al., 2017). The speed of the knee extension was chosen as it emphasizes the subsequent heel strike of the foot without leading to strong overlaps between the sounds of the ipsilateral and contralateral leg. This provided additional information about the symmetry of the movement speed, but did not increase the attention on the potentially restrictive and painful hip movement. For the sonification of the feet's ground contact, threshold values for appropriate parameters, such as position, velocity, and acceleration of the feet, were determined to ensure a robust acoustic representation of ground contact time. For the sonification of knee extension, knee angular velocity was used directly. The data acquired by the MVN Awinda wireless inertial sensor system was processed in a MATLAB program using a self-developed algorithm to subsequently analyze kinematic and spatio-temporal gait parameters.

Beyond real-time sonification, instructing model sequencess (IMSs) of gait sonification were used in the clinical intervention studies on patients after unilateral THA. To adapt the IMSs for different body sizes, the gait kinematics of 18 healthy older adults (age: 69.7 ± 7.7 years, height: 1.68 ± 0.1 m, span: 1.53-1.88 m, weight: 72.7 ± 12.7 kg) were recorded and evaluated at different gait speeds. Regression analysis was used to calculate data models for gait at different body heights and speeds. These finally enabled the generation of 18 IMSs for use at different body sizes and gait speeds (see also Reh et al., 2016).

In the two clinical studies (chapters 4 and 5), a ten-day training intervention was provided to patients in inpatient rehabilitation after unilateral THA. Gait sonification was used in alternating real-time and instructional settings. Study 1 (chapter 4) illustrates the applicability and acceptance of gait sonification in a clinical rehabilitation of patients after unilateral THA. Moreover, results on the immediate effect of the two different modes on the gait pattern are presented. Study 2 (chapter 5) describes the results of the gait analysis beyond the immediate use of gait sonification, i.e., specifically at the four measurement points pre-test, intermediate test, post-test, and re-test. For study 3 (chapter 6), the sound was reduced to the sonification of ground contacts of the feet and additional asymmetric loudness conditions were created. Thus, sonification could be provided as concurrent feedback via headphones either equally loud in both ears, louder on the right than on the left, or louder on the left than on the right. The direct, short-term influence of the modified gait sonification on the gait pattern of healthy persons was analyzed.

Overall, this work provides evidence for gait pattern modification using the developed gait sonification method in patients after unilateral THA and in healthy individuals. Furthermore, it was shown that gait sonification is applicable in clinical settings and is accepted by patients. The results presented here are expected to facilitate the development of an efficient and targeted method for gait sonification, thus enhancing the orthopedic gait rehabilitation.

3

Authors' Contributions

A research group was involved in the realization and publication of the studies (chapters 4, 5 and 6). All contributors are listed as co-authors. The individual contributions were as follows:

Authors' contributions in Reh et al. (2019):

Conceptualization, A.O. Effenberg, J. Reh, and G. Schmitz;
Methodology, J. Reh, A.O. Effenberg, G. Schmitz, and T.-H. Hwang;
Software, T.-H. Hwang and J. Reh;
Validation, J. Reh, G. Schmitz, T.-H.H., and A.O. Effenberg;
Formal analysis, G. Schmitz and J. Reh;
Investigation, J. Reh;
Resources, A.O. Effenberg;
Writing – original draft preparation, J. Reh;
Writing – review and editing, A.O. Effenberg and G. Schmitz;
Visualization, J. Reh;
Supervision, A.O. Effenberg;
Project administration, A.O. Effenberg and J. Reh;
Funding acquisition, A.O. Effenberg

Authors' contributions in Reh et al. (2021):

J. Reh drafted the manuscript.

A.O. Effenberg, G. Schmitz, and T.-H. Hwang revised it critically for important intellectual content.

A.O. Effenberg developed the sonification.

A.O. Effenberg, G. Schmitz, and J. Reh developed the framework for gait sonification and participated in the development of the intervention.

T.-H. Hwang and J. Reh contributed to the software application, sound synthesis and were involved in data analysis.

A.O. Effenberg and G. Schmitz conceived, and designed the study.

J. Reh conducted the intervention and measurements.

All authors read and approved the version of the submitted manuscript.

Authors' contributions in Reh et al. (2022):

J. Reh drafted the manuscript.

A.O. Effenberg, G. Schmitz, and T.-H. Hwang revised it critically for important intellectual content.

A.O. Effenberg developed the sonification.

A.O. Effenberg, G. Schmitz, and J. Reh developed the framework for gait sonification and the experimental design.

T.-H. Hwang and J. Reh contributed to the software application, sound synthesis, and were involved in data analysis.

A.O. Effenberg, G. Schmitz, and J. Reh conceived, and designed the study.

J. Reh conducted the measurements and participant acquisition.

All authors read and approved the version of the submitted manuscript.

4

Dual Mode Gait Sonification for Rehabilitation After Unilateral Hip Arthroplasty

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Abstract

The pattern of gait after hip arthroplasty strongly affects regeneration and quality of life. Acoustic feedback could be a supportive method for patients to improve their walking ability and to regain a symmetric and steady gait. In this study, a new gait sonification method with two different modes – real-time feedback (RTF) and instructive model sequences (IMS) – is presented. The impact of the method on gait symmetry and steadiness of 20 hip arthroplasty patients was investigated. Patients were either assigned to a sonification group (SG) (n = 10) or a control group (CG) (n = 10). All of them performed 10 gait training session (TS) lasting 20 min, in which kinematic data were measured using an inertial sensor system. Results demonstrate converging step lengths of the affected and unaffected leg over time in SG compared with a nearly parallel development of both legs in CG. Within the SG, a higher variability of stride length and stride time was found during the RTF training mode in comparison to the IMS mode. Therefore, the presented dual mode method provides the potential to support gait rehabilitation as well as home-based gait training of orthopedic patients with various restrictions.

4.1 Introduction

Sensory feedback is of fundamental importance for motor learning and re-learning in rehabilitation (Henriques & Cressman, 2012). An expansion of perception beyond habitual sensorimotor feedback (i.e., augmented feedback) has the potential to improve and accelerate the rehabilitation process following various diseases of the locomotor system (Molier et al., 2010; Yen et al., 2014; Lauber & Keller, 2014; Hunt, 2013). Different sensory feedback systems have been developed for such purposes and have already been used in sports and rehabilitation (Merians et al., 2002; Zimmerli et al., 2009; Lünenburger et al., 2007; Thaut et al., 2007). Usually, visual feedback is preferred as it addresses our predominant sense and might be easier to follow, as visually perceived motion in space is unambiguously assigned and represented in the human brain (S.-J. Kim & Krebs, 2012; Van den Noort et al., 2015; Uzor et al., 2013). Vision, however, is often involved in environmental perception, which limits the potential applications of visual feedback systems for free locomotion training (Graci et al., 2009; Goodworth et al., 2015; Berard et al., 2012; Bock, 2008). In this respect, auditory feedback can be considered as an alternative, particularly related to cyclic movements, as the human auditory system is very sensitive in perceiving meter, rhythms, and time-dependent variations (Iversen et al., 2015; Grahn, 2012; Waterhouse et al., 2010). For this reason, using sound to impact movements or setting motion to music might be beneficial, specifically for cyclic movements such as walking, stair climbing, running, cycling, or swimming. There are already several studies investigating the impact of sound, rhythm, and sonification on movement types like this (Effenberg et al., 2016; Schaffert & Mattes, 2015; Cesarini et al., 2014; Eriksson & Bresin, 2010; Schauer & Mauritz, 2003).

Using sonification to improve or optimize movements can be implemented in different ways. While some studies used real-time feedback, others have shown effects of acoustic error feedback or cueing movements (Krause et al., 2018; Sigrist et al., 2013; Baram et al., 2016; Wittwer et al., 2013a; Maulucci & Eckhouse, 2001; Effenberg, 2005). A distinction can be made between these three approaches (real-time feedback, acoustic error feedback, and instructing or cueing movements). Real-time feedback reflects a movement acoustically. Kinetic or kinematic data are measured and mapped to a specific sound by a function. Thus, a movement causes an immediate change or onset of the related sound, which therefore is directly influenced and created by the user (Ghai, Schmitz, et al., 2018; Schmitz et al., 2018; Stienstra et al., 2011). Compared with this, acoustic error feedback defines a certain measuring range of a kinematic or dynamic parameter (e.g., range of motion of the elbow or knee joint, weight loading of the feet) and compares measured motion data to these (also labeled as ”bandwidth-feedback”) (Krause et al., 2018; Sigrist et al., 2013). A sound signal is only played, if a given threshold is crossed. Additionally, instructing or cueing movements means that a specific predefined sound, like the ticking of a metronome, sets a temporal structure. Consequently, movements can be aligned to the sound, but the sound cannot be influenced by the user (Rochester et al., 2010; Ford et al., 2010; Harrison et al., 2018).

As gait is a fundamental human locomotion, it has already been subject in a wide range of studies on various types of acoustic feedback (Young et al., 2013; Ghai, Ghai, et al., 2018; Fischer et al., 2017). Heterogeneous study designs and various parameters were considered in these studies, as hypotheses and methods were clearly related to the limitations or diseases of the particular patients. For instance, in a pilot study Rodger et al. (2013) examined the impact of two different sound approaches on gait disturbances of ten Parkinson's disease patients. They found decreased step length variability for step cueing (first approach) and real-time feedback (second approach) compared to a no sound condition in this patient population. Additionally, Schauer & Mauritz (2003) investigated musical motor feedback for stroke patients, which means that a song with an adjustable speed provided the gait rhythm. The results showed increased stride length and gait velocity as well as decreased gait symmetry in the test group. There are further pilot and feasibility studies examining various methods of acoustic feedback for gait (Horsak et al., 2016; Hajinejad et al., 2013; Zanotto et al., 2012), but as far as we know, only few studies on patients with orthopedic restrictions of the musculoskeletal system have been conducted (Vogt et al., 2009). Several studies examined the impact of auditory feedback on healthy persons' gait pattern (Wittwer et al., 2013a; Fischer et al., 2017; Horsak et al., 2016; Brodie et al., 2015; Tajadura-Jiménez et al., 2015). Depending on the acoustic feedback method, varying effects have been reported: Real-time sonification resulted in decreased gait speed (Fischer et al., 2017; Horsak et al., 2016) and decreased cadence (Horsak et al., 2016), auditory cues, which were adjusted to the symmetry of the participants' movement pattern, affected gait steadiness (Brodie et al., 2015), while rhythmic music cues led to increased gait speed, stride length, and cadence (Wittwer et al., 2013a). However, up to now there has been no evidence as to whether auditory cues or real-time sonification can improve gait in terms of symmetry and steadiness in healthy older persons and orthopedic patients.

Patients suffering from hip or knee arthrosis frequently develop a malfunctioning gait pattern, which is often progressing over time. Patients following unilateral total hip arthroplasty (THA) commonly show asymmetric step length (Constantinou et al., 2014; Hodt-Billington et al., 2011) causing additional long-term impairments of the musculoskeletal system. Therefore, an improved step length symmetry is an important factor in gait rehabilitation and should be considered in gait therapy. However, it is a great challenge for patients to relearn a symmetric and steady gait pattern. Usually gait rehabilitation after hip or knee arthroplasty is associated with a large effort of time and personnel (Sabeh et al., 2017; Ong et al., 2015). In addition, it must be considered that prevalence of arthrosis increases with age (Neogi & Zhang, 2013; Allen & Golightly, 2015) and thus often affects elderly patients who suffer from several co-morbidities such as cognitive impairments. In this regard, a gait rehabilitation system that does not require high attentional cost might be a powerful add-on to classical treatments.

For these reasons, we developed a new acoustic feedback approach, which is based on a combination of kinematic real-time feedback (RTF) and instructive model sequences (IMS) (Reh et al., 2016). A consistent sound in accordance with the human gait pattern was developed and applied, based on kinematic data recorded by a portable inertial sensor system. RTF is based on selected kinematic parameters (ground contact of the feet and angular velocity of the knee joint), which are clearly mapped to a sound. This means that each ground contact and each knee extension of the patient triggers the onset, frequency, and amplitude of a defined sound with low latency (sonification). On the other hand, IMS present the same sound as used for RTF, but in a predefined manner. Consequently, IMS display acoustic information at a fixed tempo, which is comparable to cueing movements. We intended to create a close motion-sound and sound-motion linkage in terms of an establishment of co-activation patterns between the auditory and motor networks responsible for audition and motor execution (Bangert & Altenmüller, 2003). To achieve a high efficiency of the method, RTF alternating with IMS was presented, enabling the calibration of the feedback to a symmetric model (Effenberg & Schmitz, 2018). Furthermore, the combination of RTF and IMS complies to the theory of modularity in multisensory integration as proposed by Tagliabue & McIntyre (2014). The theory predicts optimized multisensory integration, if the movement goal is instructed in the same modality as the own movement is perceived in. Moreover, it can be assumed that orthopedic patients in general do not show any neurological limitations, in particular regarding motor planning. Therefore, this patient group may demand for especially close links between sound and motion. However, to the authors knowledge, acoustic feedback for rehabilitation in orthopedic patients has not yet been investigated. This is why the current study provides first insights into a new application.

The developed method was applied in a two-week intervention study on patients with unilateral THA in order to examine the following two hypotheses: First, (**H 1**) the dual mode acoustic feedback method improves the patients' gait symmetry over two weeks compared to a control group without acoustic feedback. Second, (**H 2**) the effects on the gait pattern depend on the type of acoustic information (RTF, IMS).

4.2 Materials and Methods

In total, 20 patients were recruited who had undergone unilateral hip arthroplasty due to coxarthrosis 8–17 days prior to the intervention. Of those patients, 10 were assigned to the sonification group (SG) and to the control group (CG), respectively. Both groups were parallelized regarding age, duration post-surgery, sex, weight, and height. The specific characteristics of the patients are shown in Table 4.1 (p. 28).

Table 4.1: Characteristics of the sonification (SG) and control group (CG).

	SG (*n*=10)	**CG** (*n*=10)	***p***
Age [years]	64.0 ± 8.8	61.9 ± 8.4	0.591
Sex	9 male, 1 female	7 male, 3 female	-
Duration post-surgery (days)	11.5 ± 1.6	12.0 ± 2.7	0.620
Height [m]	175.1 ± 5.2	176.1 ± 4.1	0.642
Weight [kg]	84.4 ± 10.8	85.3 ± 12.4	0.864
Timed-up and go [s]	11.58 ± 3.00	13.82 ± 6.24	0.225
Functional strength [reps]	12.9 ± 2.2	9.7 ± 5.5	0.115

Values are mean ± SD. The statistical significance for an independent t-test on group differences is given.

Every patient was admitted to the same rehabilitation clinic and thus followed a similar rehabilitation program. Patients were excluded if they had multiple artificial joints, implanted pacemakers, a low fitness level (not able to walk for 20 min) or severe pain according to the statement of the patient. Prior to the start of the intervention, patients were informed of the measurements, training process, and intervention procedures, and gave their written consent to participate voluntarily in this study. The study was conducted in accordance with the guidelines stated in the Declaration of Helsinki and the regulations of the Ethical Committee of the Leibniz University Hannover (EV LUH 02/2016).

A clinical test was performed before the intervention started, including a timed-up and go test (Podsiadlo & Richardson, 1991) and a functional strength test (getting up from a chair) (Table 4.1). Hearing ability of the SG was measured using HTTS hearing test software (Version 2.10, SAX GmbH, Berlin, Germany) and cadence was determined during 1 min of walking. At baseline, no significant differences between SG and CG neither for group characteristics nor for clinical tests could be found (t-test for independent samples: timed-up and go test: t(38) = -1.614, p = 0.115, r = 0.25; functional strength test: t(18) = 1.659, p = 0.115, r 0.36). The intervention sessions were comprised of 10 supervised gait training sessions (TSs) with a duration of 20 min each (Figure 4.1, p. 30), which were completed within two weeks. Training sessions (TSs) took place in a 12 m × 15 m gym of the rehabilitation clinic. During gait training, a laptop was placed in the gym to show the patients the temporal progress of the training (Figure 4.2, p. 30). Additionally, information concerning number of steps, distance covered, and mean gait speed was given in terms of performance feedback after each TS.

Biweekly, two patients started the gait training intervention. In an admission consultation with a medical specialist of the rehabilitation clinic, patients were informed of the study design and asked to participate in the intervention. To avoid differences in the motivational attitude between the groups, patients were not informed of their group allocation at enrollment, but this information was disclosed post-intervention. On average, patients started gait training about two weeks after surgery and they were not able to walk without forearm crutches. Therefore, each patient used forearm crutches in every TS.

For capturing kinematic data, the wireless inertial sensor system MVN Awinda (XSens Technologies B.V., Enschede, the Netherlands) and the software MVN Studio BIOMECH (Version 4.1, XSens Technologies B.V., Enschede, the Netherlands) were used. The sampling rate was set at 60 Hz. Patients of both groups were equipped with the motion analysis system for gait training. Seven inertial measurement units (IMUs) were fixed to the feet, lower legs, upper legs, and pelvis by Velcro straps. Solely SG received the sound of the gait sonification by wireless headphones.

Each TS of 20 min was subdivided into four 5 min blocks consisting of 3 min RTF and 2 min IMS. RTF, providing a low-latency feedback (<100 ms) of the patients' real gait pattern, was realized by direct data streaming out of the MVN Studio BIOMECH software to Spyder (Version 2.3.5.2., The Scientific Python Development Environment, Spyder Developer Community). In Spyder, an algorithm for detecting touch-down and toe-off of the feet as well as knee extension phase of the right and left leg during gait was applied. The generated kinematic events and periods (ground contact time and knee extension) were synthesized by an implemented Csound (Csound 6, LGPL) module resulting in a succinct sound pattern: The ground contact of the foot can be described in analogy of sound emerging when walking through heavy snow. Knee extension was acoustically represented as a sequence of xylophone strokes, usually a row of 5–7 quickly ascending tones per extension for healthy gait. Consequently, a whole gait cycle resulted in two successive snow compression sounds, each complemented by the xylophone of the contralateral knee extension. To enable a clear mapping between the sound and the according side of the body, the sound of the left leg (knee extension and ground contact of the foot) was four half tones (major third) lower than the sound of the right leg. Further, only the right speaker of the headphone gave the sound of the right leg while the left speaker gave the sound of the left leg.

The same sound pattern was used to generate IMS. Consequently, during IMS mode the patients heard synthesized ″walking through snow″ sounds and ″xylophone strokes″ in a fixed tempo, which was chosen based on body height and cadence. More precisely, IMS sounds were pre-recorded based on kinematic data sets to instruct a symmetric gait pattern. RTF and IMS were displayed successively and cumulated in 5 min blocks as it was intended to use enhanced sensorimotor representations formed during RTF for motor planning and execution during IMS. Therefore, exactly the same sound pattern was applied for RTF as well as for IMS. The kinematic data sets to produce a symmetric gait pattern sound were calculated as described below. IMS data of 18 healthy older adults (age: 69.7 ± 7.7 years, height: 1.68 ± 0.1 m, range: 1.53–1.88 m, weight: 72.7 ± 12.7 kg) walking a 10 m distance at three different self-selected gait speeds (″normal″, ″slow″, ″fast″) were collected. A regression analysis was performed considering body height and gait velocity towards several kinematic and spatiotemporal parameters.

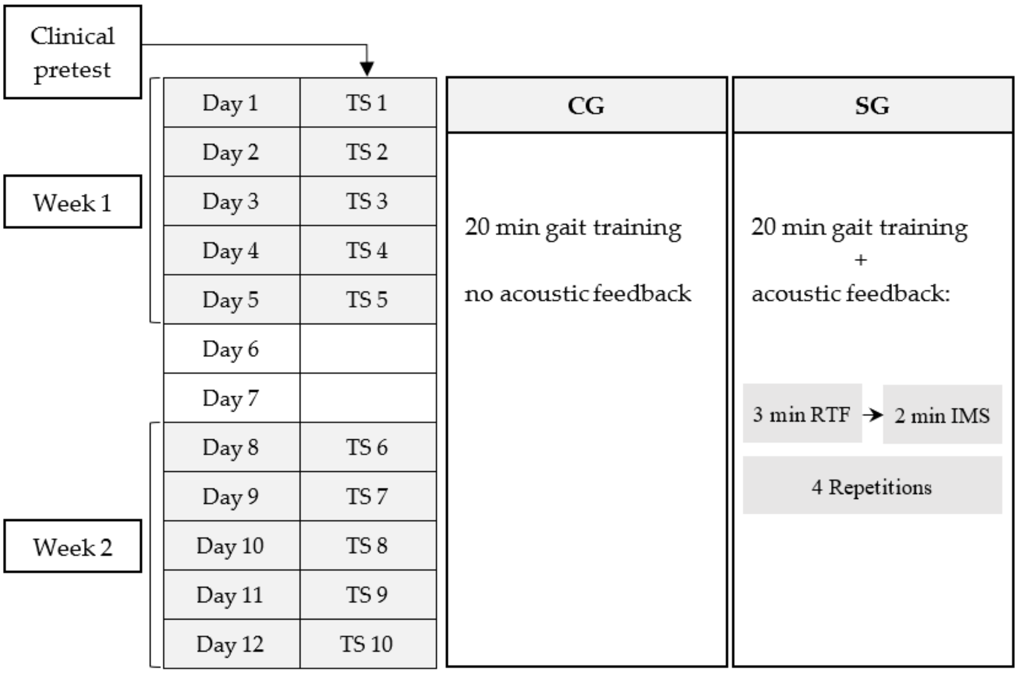

Figure 4.1: Process of intervention with ten training sessions (TSs) on twelve days. The control group (CG) did not receive any acoustic feedback, while the sonification group (SG) received real-time feedback (RTF) alternating with instructive model sequences (IMS).

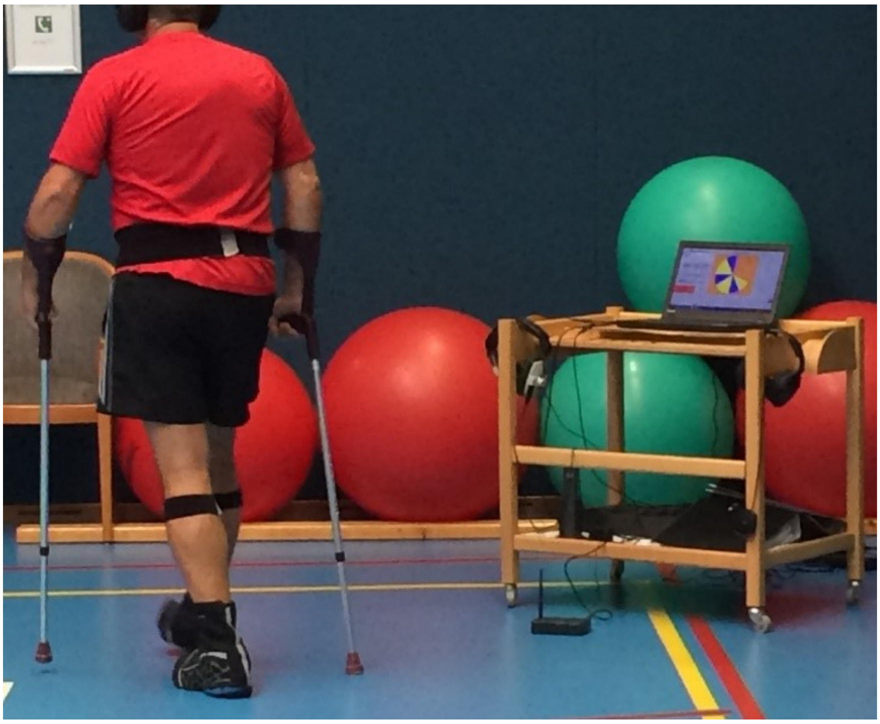

Figure 4.2: Patient of the sonification group during gait training. The temporal course can be observed on the notebook screen.

Resulting regression equations were used to calculate 18 data sets for three different body height ranges with six different cadences, respectively (Table 4.2). In this manner, during gait training IMS was chosen based on each patients' body height and the pre-training cadence. To ensure that IMS acoustically provide a symmetric gait pattern, kinematic data of the right and left leg were shifted by half a gait cycle.

The datasets were synthesized and recorded to complete the new gait sonification method. Recorded gait sequences during RTF (minutes 1–3, 6–8, 11–13, 16–18) and IMS (minutes 4–5, 9–10, 14–15, 19–20) of SG were analyzed separately from each other. To consider the temporal development, training sessions (TSs) 1–5 (week 1) and 6–10 (week 2) were clustered. This resulted in four measurement values for each participant, RTF 1–5 (RTF 1), RTF 6–10 (RTF 2), IMS 1–5 (IMS 1), and IMS 6–10 (IMS 2). To ensure comparability and considering fatigue effects, recordings of CG were also divided into RTF parts and IMS parts, even though this group did not receive any sonification. As walking direction during gait training was not specified to the patients, standing phases, direction changes, and turns with a threshold of 10° were excluded from the recordings before final data analysis.

To investigate the effects of the acoustic feedback method on gait symmetry over time (**H 1**), step lengths of the affected and unaffected leg were considered for week 1 and week 2.

Table 4.2: Cadences calculated for IMS creation of three different body height ranges and six different gait velocities.

Gait Speed [m × s $^{-1}$]	**Cadence** [steps × minutes $^{-1}$]	**Cadence** [steps × minutes $^{-1}$]	**Cadence** [steps × minutes $^{-1}$]
	155-165 cm	165-175 cm	≥ 175 cm
0.4	78	69	69
0.6	91	80	79
0.8	102	91	88
1.0	113	101	98
1.2	124	111	106
1.4	135	121	115

Besides, the coefficient of variation (COV) of stride length and COV of stride time were analyzed for RTF 1, RTF 2, IMS 1, and IMS 2 to evaluate gait steadiness and to determine if different effects on the patients' gait patterns occur depending on different types of acoustic information (**H 2**). COV was calculated for each patient as the ratio of the standard deviation (SD) divided by the mean of stride length (m) respectively stride time (ms). Resulting values were multiplied by a hundred to display COV in percent. Basic parameters as gait speed, cadence, stride length, and stride time were also analyzed, to give a general view on the gait quality of the patients, and to allow for comparability with other findings.

Parameters were calculated using a MATLAB routine (R2016a, The MathWork inc., Natick, MA, USA), in which touch-down and toe-off of the feet were detected by determining peak accelerations of the feet in z-direction (vertical). The interval between touch-down of one foot and touch-down of the contralateral foot was defined as step, and the interval between touch-down of one foot and touch-down of the same foot was defined as stride. Stride time was determined as duration between the touch-down of one foot and the following touch-down of the same foot. Stride length was defined as distance between the touch-down of one foot and the following touch-down of the same foot measured orthogonally to the movement direction.

A three factor (time, mode, and group) repeated measures analysis of variance (ANOVA) was applied to the dataset using SPSS for Windows 24.0 (Chicago, IL, USA). The significance level was set at $\alpha = 0.05$. If a significant interaction effect was observed, post-hoc t-tests using Holm-Bonferroni sequential correction were performed to identify detailed differences between conditions. Effect sizes (Pearson's r for t-tests and Cohen's effect size f for ANOVA) for the differences between the two groups, time, and mode conditions were calculated to estimate the relevance of any significant difference.

4.3 Results

Symmetry

For the affected leg there were no significant main effects of group (F (1,18) = 0.589, $p = 0.45$, $f = 0.18$) and time (F (1,18) = 0.137, $p = 0.72$, $f = 0.09$). However, a significant group × time interaction could be found (F (1,18) = 6.124, $p = 0.024$, $f = 0.58$). Both groups differed significantly in week 1 with step lengths of 0.58 m ± 0.04 m for SG and 0.54 m ± 0.06 m for CG (t(38) = 2.70, $p = 0.031$, $r = 0.26$). The affected step length of the CG increased (t(19) = -4.45, $p = 0.001$, $r = 0.44$) from week 1 (0.54 m ± 0.06 m) to week 2 (0.57 m ± 0.06 m). In contrast, on a descriptive level, but not significant a decrease from week 1 (0.58 m ± 0.04 m) to week 2 (0.56 m ± 0.07 m) was found for SG (t(1,9) = 1.655, $p = 0.114$, $r = 0.35$). As a significant increase in step length of the unaffected leg over time could be found for both groups (F (1,18) = 5.70, $p = 0.028$, $f = 0.56$), in SG the step length of both legs converged from week 1 to week 2, while a nearly parallel development of both legs could be observed for subjects of CG (Figure 4.3, p. 33). However, no significant group × side × time interaction was found.

Furthermore, no significant difference between the two modes (RTF, IMS) could be found for the affected and the unaffected step length.

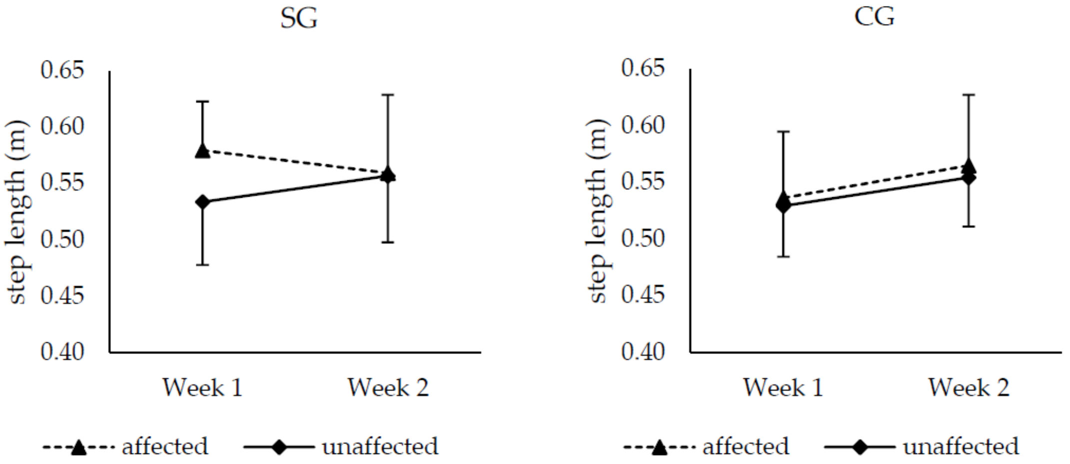

Figure 4.3: Step length of the affected and unaffected leg for SG (n = 10) (left) in week 1 and week 2, step length of the affected and unaffected leg for CG (n = 10) (right) in week 1 and week 2. Values are means ± SD. Significant difference between groups, affected leg week 1: $p = 0.031$, $r = 0.26$. Significant difference for time, CG affected leg: $p = 0.001$, $r = 0.44$, but not for time, SG affected leg: $p = 0.114$, $r = 0.35$. Significant difference for time, SG+CG, unaffected leg: $p = 0.028$, $f = 0.56$.

Variability

For the variability of stride length (COV), neither a significant main effect of time (F (1,18) = 2.08, $p = 0.166$, $f = 0.34$) nor a main effect of group (F (1,18) = 2.89, $p = 0.11$, $f = 0.40$) could be found (Table 4.3, p. 34). The variability of stride time showed a significant main effect of time (F (1,18) = 7.15, $p = 0.015$, $f = 0.63$), but no significant group effect (F (1,18) = 3.03, $p = 0.099$, $f = 0.41$) (Table 4.4, p. 34). Also, there was no group × time interaction neither for the variability of stride length (F (1,18) = 0.50, $p = 0.488$, $f = 0.17$), nor for the variability of stride time (F (1,18) = 2.37, $p = 0.141$, $f = 0.36$). As the acoustic feedback and the two different modes (RTF and IMS) were only presented to the SG, the statistical analysis of mode effects did not include the CG. For the variability of stride length (Figure 4.4, p. 35) a significant difference between the modes RTF and IMS could be found (F (1,9) = 6.50, $p = 0.03$, $f = 0.85$) (Table 4.3, p. 34). Moreover, there was a significant mode × time interaction (F (1,9) = 5.63, $p = 0.042$, $f = 0.79$) for the variability of stride length. Considering the variability of stride time (Figure 4.5, p. 35) there was no significant mode effect (F (1,9) = 4.13, $p = 0.073$, $f = 0.68$), but solely a significant mode × time interaction (F (1,9) = 7.39, $p = 0.024$, $f = 0.91$).
Both mode × time interaction effects, which were found for the variability of stride length and the variability of stride time, are due to an increase of variability from week 1 to week 2 in RTF. However, post-hoc tests did not reveal any significant effects.

Table 4.3: COV of stride length of SG, CG, and in total (SG + CG) for week 1 and week 2.

		COV Stride Length [%]		**t**	**m**	**t × m**	**m × g**	**t × m × g**
		RTF	IMS	*p*	*p*	*p*	*p*	*p*
SG (n = 10)	Week 1	11.81 ± 8.81	10.69 ± 6.84	0.242	0.031	0.042	-	-
	Week 2	17.26 ± 7.75	11.86 ± 4.81					
CG (n = 10)	Week 1	8.27 ± 5.55	8.04 ± 6.01	0.491	0.561	0.998	-	-
	Week 2	9.40 ± 5.94	9.17 ± 7.64					
SG + CG (n = 20)	Week 1	10.04 ± 7.39	9.36 ± 6.42	0.166	0.018	0.082	0.036	0.081
	Week 2	13.33 ± 7.83	10.52 ± 6.36					

The values are mean ± SD. The *p*-values of the statistical analysis (ANOVA) are given in the right table section. The factors time (t), mode (m), and the interactions time×mode (t×m), mode×group (m×g), and time×mode×group (t×m×g) were analyzed. The level of significance was set at α = 0.05.

Table 4.4: COV of stride time of SG, CG, and in total (SG + CG) for week 1 and week 2.

		COV Stride Time [%]		**t**	**m**	**t × m**	**m × g**	**t × m × g**
		RTF	IMS	*p*	*p*	*p*	*p*	*p*
SG (n = 10)	Week 1	10.55 ± 6.73	10.65 ± 5.25	0.030	0.073	0.024	-	-
	Week 2	18.12 ± 9.02	12.32 ± 7.81					
CG (n = 10)	Week 1	7.90 ± 4.80	7.86 ± 4.69	0.350	0.527	0.835	-	-
	Week 2	9.30 ± 5.87	8.94 ± 6.86					
SG + CG (n = 20)	Week 1	9.22 ± 5.85	9.26 ± 5.05	0.015	0.048	0.030	0.081	0.049
	Week 2	13.71 ± 8.68	10.63 ± 7.36					

The values are mean ± SD. The *p*-values of the statistical analysis (ANOVA) are given in the right table section. The factors time (t), mode (m), and the interactions time×mode (t×m), mode×group (m×g), and time×mode×group (t×m×g) were analyzed. The level of significance was set at α = 0.05.

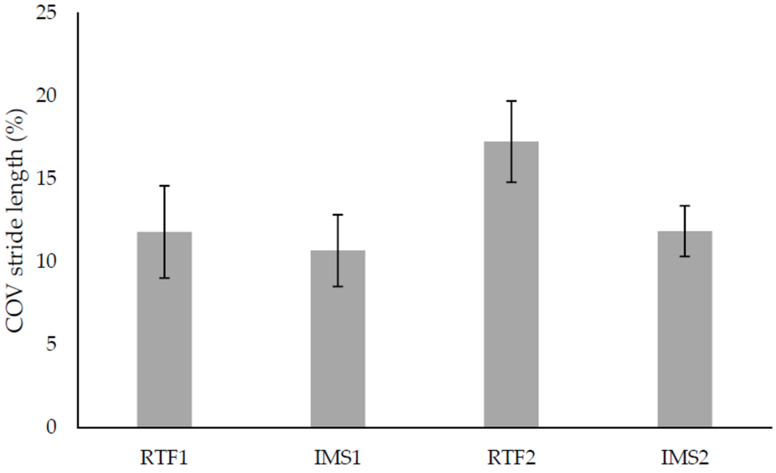

Figure 4.4: Values are means ± standard error (SE). COV of stride length for SG. Significant differences were found for mode: $p = 0.03$, $f = 0.85$, and mode×time: $p = 0.042$, $f = 0.79$.

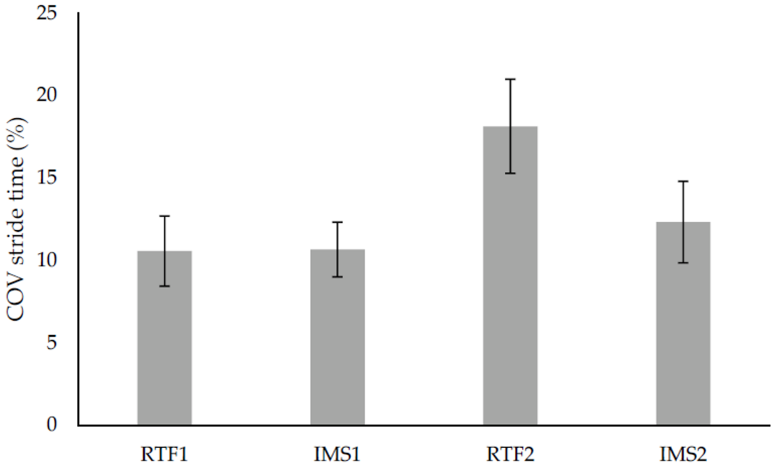

Figure 4.5: Values are means ± SE. COV of stride time for SG. No significant difference was found for mode: $p = 0.073$, $f = 0.68$, but for mode×time: $p = 0.024$, $f = 0.91$.

Temporo-Spatial Parameters

The results showed overall significant improvements from week 1 to week 2 in gait speed (F (1,18) = 15.63, $p = 0.001$, $f = 0.93$), cadence (F (1,18) = 20.68, $p < 0.005$, $f = 1.07$), stride time (F (1,18) = 12.9, $p = 0.002$, $f = 0.85$), and stride length (F (1,18) = 6.56, $p = 0.020$, $f = 0.60$) (Table 4.5). No significant differences between groups were found regarding gait speed, cadence, stride length, and stride time. For SG, a significant mode effect on stride length was found (F (1,9) = 5.199, $p = 0.049$, $f = 0.76$) (RTF mode: 1.16 m ± 0.12 m and IMS mode: 1.14 m ± 0.11 m).

Table 4.5: Gait speed, stride length, cadence, and stride time of SG and CG for week 1 and week 2.

		Gait Speed [m × s $^{-1}$]	**Cadence** [steps × min $^{-1}$]	**Stride Length** [m]	**Stride Time** [ms]
SG (n = 10)	Week 1	0.93 ± 0.14	99.32 ± 10.76	1.13 ± 0.10	1244.5 ± 136.4
	Week 2	0.97 ± 0.18	103.34 ± 14.56	1.16 ± 0.13	1218.2 ± 161.6
CG (n = 10)	Week 1	0.85 ± 0.14	94.88 ± 10.86	1.08 ± 0.10	1290.6 ± 145.1
	Week 2	0.95 ± 0.15	101.80 ± 12.64	1.14 ± 0.09	1218.2 ± 158.7

Values are means ± SD.

4.4 Discussion

In the present study the effectiveness and feasibility of a new dual mode method of gait sonification for rehabilitation following unilateral hip arthroplasty was investigated. It seems to be crucial that patients following unilateral THA relearn a symmetric gait pattern (Queen, Watters, et al., 2011; Miki et al., 2004). Therefore, we hypothesized that (**H 1**) the dual mode acoustic feedback method improves the patients' gait symmetry over time compared to a control group without acoustic feedback. Results showed converging step lengths of the affected and unaffected leg over time in SG compared to CG. In week 1 a significant higher step length of the affected leg was found for SG compared to CG. Therefore, CG did not show a clear gait asymmetry at the beginning of the intervention. Regarding the temporal development from week 1 to week 2, a nearly parallel increase of step lengths of the affected and unaffected leg could be observed in CG. In contrast in SG, a tendency toward a decrease from week 1 to week 2 could be observed for the affected leg, whereas the step length of the unaffected leg seemed to increase from week 1 to week 2. Statistically, an interaction between SG and CG over time was found for step length of the affected leg. The effect size ($f = 0.58$) indicates a large effect, which suggests that the dual mode method for gait rehabilitation affected gait symmetry. However, this finding needs to be interpreted with caution because the changes observed in step length for patients in the SG did not reach statistical significance and no group × side × time interaction could be found. These statistical results can be due to the following reasons. First, there was an initial difference between groups concerning gait performance. This means that the SG showed a slightly higher gait speed, cadence, stride length, gait variability, and worse gait symmetry, which might have resulted in a higher potential for improvement in CG. Additionally, the used gait sonification method might not yet fully meet the needs of patients following total hip arthroplasty at the time when the intervention started. Finally, it seems that the surgical procedure and the use of crutches limited the patients' ability to walk freely.

Second, it was hypothesized (**H 2**), that the effects on the gait pattern depend on the type of acoustic information (RTF, IMS). Within the SG, significantly increased stride lengths were found in RTF training mode compared to IMS mode. Furthermore, in RTF statistically significant higher variability of stride length and stride time were found compared to IMS. Due to these results, **H 2** can be accepted. The effect of mode on gait variability could be explained by a reduced stride length variability and stride time variability in IMS mode compared to RTF mode. This might be due to the additional temporal information to guide the patients' steps during IMS mode and the following elimination of the anticipatory information in RTF mode. Previous investigations have already shown that auditory cueing, which is similar to the IMS mode, improved gait variability of patients with Parkinson's disease and stroke (Hausdorff et al., 2007; del Olmo & Cudeiro, 2005; Thaut et al., 1997). However, studies examining the effects of auditory cueing on healthy older adults showed divergent results (Brodie et al., 2015; Hamacher et al., 2016). For example, Hamacher et al. (2016) found higher stride time variability when participants were walking to rhythmic auditory cues compared to normal walking (without auditory cues). Therefore, it appears that in (neurological) healthy older persons auditory feedback addresses different mechanisms and causes different effects on gait compared to patients with Parkinson's disease or stroke.

In addition, it might be assumed, that in RTF patients tried to calibrate their strides to the previously heard rhythm and tempo in IMS. More precisely, this alteration was likely induced because of the additional sensory information in RTF and the similarity of RTF sound and IMS sound. Potentially, the anticipatory information provided in IMS improved and adjusted the motion concept and motor planning (Thaut et al., 2015). This effect was used in RTF as here patients' perception of their own gait pattern was enhanced, which allowed for the comparison between the acoustic symmetric gait (IMS) and the acoustic real gait (RTF). Based on this assumption, an increased internal focus could have occurred in RTF. A resulting tighter and more conscious motor control and a reduced automaticity might have induced an over-correction and consequently the higher stride time and stride length variability in RTF (Terrier & Dériaz, 2012; Dingwell et al., 2010). Here, an increased variability should not necessarily be avoided, as during motor relearning processes of trial and error occur, which usually cause noise in the nervous system and in the motor execution (Dhawale et al., 2017). But in later stages of motor relearning, higher automaticity of gait can be achieved. Results also indicate an increase of stride variability (mode × time interaction) in RTF from week 1 to week 2, which seems unexpected, as increased muscle strength and morphologic healing must be assumed over time (Holm et al., 2013; Winther et al., 2016). However, this effect might be a result of increased perceptuomotor control and adaptability (Effenberg et al., 2016) and a greater degree of freedom due to less morphological limitations. These factors could have enhanced the conscious motor control and the resulting over-correction, as described above.

The present study investigated a new approach concerning the patient population studied and the acoustic feedback method. The results suggest an impact of the method on the gait pattern in patients with unilateral hip arthroplasty. Therefore, future studies are necessary to investigate the mechanisms (RTF, IMS, or both), that allow to modify selected gait parameter. For example, modifications of the sound and the motion-sound transformation could help to explore the effects of the acoustic feedback method more detailed. Furthermore, the order and the duration of display of RTF and IMS could be changed to investigate whether and to what extent these factors may influence the effectiveness of the method.

Finally, there are some methodological limitations that should be discussed. First, it must be mentioned that in the current study the investigated method was not compared to separate groups receiving only auditory cueing or real-time sonification. However, in this regard more patients would have had to be recruited, which was not possible in a reasonable time. Moreover, it must be considered that the intervention period of two weeks could have been too short to cause unambiguous effects. In particular, regarding the orthopedic limitations of the patients, which usually show a very strong impact on gait (Constantinou et al., 2014), a longer intervention period might have resulted in larger effects. Furthermore, the gait training took place in a gym, which allowed the patients to walk freely and consequently with a higher interindividual variability than on a treadmill. However, compared to walking on a treadmill, this setting is closer to real-life conditions of the patients and gait speed as well as gait pattern were not affected by an external device. Using a treadmill would also have increased electromagnetic disturbances, which in general impairs measurement accuracy of IMU systems. Even though electromagnetic disturbances could not be completely avoided in this study, a high quantity of reliable data was analyzed and considered. A further limitation of this investigation is the initial difference between groups concerning gait performance. Both groups were parallelized regarding age, duration post-surgery, sex, weight, and height, but an assessment test to measure initial gait speed, gait variability, and symmetry as well as mobility of the hip and muscle strength was not performed. Though, the duration of the patients' hospitalization was limited to 18 days, which were structured in terms of a prescribed rehabilitation program and did not allow for additional measurements.

4.5 Conclusions

In the present study, a clear and succinct sound setting was developed and applied, primarily to readjust the patients' gait symmetry by augmented feedback within a time sensitive perceptual system (RTF) and calibrating the internal symmetry model via IMS. It has been shown that the step lengths of the affected and unaffected leg converged over time in SG compared to a nearly parallel development of both legs in CG. Additionally, in SG a higher variability of stride length and stride time during the RTF training mode compared to the IMS mode was found. The results suggest that the new method is a promising approach, which in future could support gait rehabilitation as well as home-based gait training. Sonification allows for multiple motion sounds and varying motion-sound mappings and therefore, different gait sonification settings and their effects on the gait pattern of orthopedic patients should be examined in future investigations. The introduced method of kinematic gait sonification based on wireless inertial sensors can be easily combined with a variety of already developed motor rehabilitation settings for an enhancement of effectiveness.

5

Acoustic Feedback in Gait Rehabilitation — Pre-Post Effects in Patients With Unilateral Hip Arthroplasty

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Abstract

It is known that patients after unilateral hip arthroplasty still suffer from a deficient gait pattern compared to healthy individuals one year after surgery. Through the method of gait sonification, it may be possible to achieve a more efficient training and a more physiological gait pattern. Increased loads on the musculoskeletal system could thus be reduced and rehabilitation times shortened. In a previous investigation with this patient group, we found immediate gait pattern changes during training with dual mode acoustic feedback (real-time feedback (RTF) and instructive model sequences (IMS)). To determine whether an effect persists without the immediate use of acoustic feedback, we analyze data from four times of testing. Following unilateral hip arthroplasty 22 patients participated in an intervention of ten gait training sessions of 20min each. During gait training the sonification group (SG) (n = 11) received an acoustic feedback consisting of RTF and IMS compared to a control group (CG) (n = 11). Pre-test, intermediate test, post-test, and re-test were conducted using an inertial sensor-based motion analysis system. We found significant effects (α = 0.05) regarding step length and range of motion (RoM) of the hip joint. Step length of the affected leg increased in the SG from intermediate test to post-test but decreased in the CG (intermediate test: (SG) 0.63 m ± 0.12 m, (CG) 0.63 m ± 0.09 m; post-test: (SG) 0.66 m ± 0.11 m, (CG) 0.60m ± 0.09 m). However, from the post-test to the re-test a reverse development was observed (re-test: (SG) 0.63m ± 0.10m, (CG) 0.65m ± 0.09m). Also, from post-test to re-test a decrease in the RoM of the unaffected hip for the SG but an increase for the CG could be observed (post-test: (SG) 44.10°± 7.86°, (CG) 37.05° ± 7.21°; re-test: (SG) 41.73° ± 7.38°, (CG) 40.85° ± 9.28°). Regarding further parameters, significant interactions in step duration as well as increases in stride length, gait speed, cadence, and a decrease in ground contact time from pre-test to re-test were observed for both groups.

5.1 Introduction

After unilateral hip arthroplasty, many patients still suffer from an unphysiological gait pattern even after several years (Queen, Butler, et al., 2011; Kolk et al., 2014; Leijendekkers et al., 2018; Cezarino et al., 2019). This not only increases the strain on previously unaffected joints and other physiological structures, but also the risk of falling (Ninomiya et al., 2018). In order to return to a healthy gait, regular training is required beyond the usual rehabilitation period of about 4–8 weeks duration. New technological developments that can be used independently by the patient could provide efficient support for training and recovery (Krishnan et al., 2016; Chamorro-Moriana et al., 2018; Escamilla-Nunez et al., 2020). In this context, new feedback technologies make use of the fact that the human nervous system continuously compares its own motion with incoming somatosensory information and adjusts accordingly. This is exploited by either amplifying or artificially generating relevant external stimuli so that a comparison between motor behavior and visual, tactile, kinaesthetic or auditory perception is enhanced. The described method is called augmented feedback, which is a generic term for a wide variety of procedures including verbal feedback, error feedback and real-time feedback (Ronsse et al., 2011; Gilgen-Ammann et al., 2018; Bigras et al., 2019). It can generally be assumed that augmented feedback can improve motor learning (Sigrist et al., 2013) as extended feedback for rehabilitation has already been investigated in various clinical and applied studies (Storberget et al., 2017; Kearney et al., 2019; Melero et al., 2019).

In addition to visual, kinaesthetic and tactile feedback, acoustic feedback systems have also gained increasing interest in recent years in research on gait rehabilitation. Since walking is a cyclical movement that is determined by a rhythmic, reciprocal heel strike, research in this area has mainly focused on rhythmic auditory stimulation. For example, Thaut et al. (1996) were able to show early on that rhythmic auditory stimulation positively influences spatio-temporal gait parameters of Parkinson's patients. Positive effects of auditory cues could also be found in stroke patients (Shin et al., 2015; Mainka et al., 2018) and patients with multiple sclerosis (Baram & Miller, 2007). Recent studies, such as those by Dotov et al. (2017), indicated that the gait of Parkinson's patients benefits more from rhythmic auditory cues with a physiological variability compared to isochronous cues and Bella et al. (2015) have found a positive effect of signals that adapt to the gait kinematics of Parkinson's patients. Furthermore, in a gait study with healthy participants, Wu et al. (2020) were able to show that a change in cadence is better achieved by adapting acoustic cues than by fixed cues. This study (Wu et al., 2020) is an indication that a more targeted use of acoustic feedback, made possible by new motion analysis and sound systems, might provide further benefits for gait rehabilitation.

The study presented here is based on another form of acoustic feedback called motion sonification (Effenberg, 1996). It allows to reflect movements by sound in real time and thus to provide direct sensorimotor feedback that goes beyond the usual perception (augmented feedback). Kinetic or kinematic data are measured and mapped to sound by a defined function. Thus, a movement causes an immediate change or onset of the related sound, which therefore is directly influenced and created by the user. In order to create a succinct sound pattern and to achieve a close mapping between motion and sound, various musical parameters are used. Previous studies that investigated movement sonification could show that it can improve motor learning and motion adaptation in sports and rehabilitation (Schmitz et al., 2013; Schmitz et al., 2014; Effenberg et al., 2016; Schaffert & Mattes, 2016; Schaffert et al., 2019).

To effectively use sonification for patients after hip arthroplasty we developed a new acoustic feedback approach, which is based on a combination of kinematic real-time feedback (RTF) and instructive model sequences (IMS). A consistent sound in accordance with the human gait pattern was developed and applied, based on kinematic data recorded by a portable inertial sensor system. RTF is based on selected kinematic parameters (ground contact of the feet and angular velocity of the knee joint), which are clearly mapped to a sound. This means that each ground contact and each knee extension of the patient triggers the onset, frequency, and amplitude of a defined sound with low latency. On the other hand, IMS present the same sound as used for RTF, but in a predefined manner. Consequently, IMS display acoustic information at a fixed tempo, which is comparable to cueing movements.

Though, as far as known, there have been only a small number of studies investigating the influence of gait sonification in orthopedic patients (Yang et al., 2012; Pietschmann et al., 2019). In addition, very different study designs related to general acoustic feedback in gait training are reported in the literature, raising the question of the extent to which habituation to acoustic feedback and intervention sequences and durations are critical for effective use. For example, there are some studies referring to the immediate influence of acoustic feedback on gait pattern (Baram & Miller, 2007; Dotov et al., 2017). Others, however, are designed as intervention studies and compare pre-test and post-test data after 2 weeks (Pietschmann et al., 2019), 3 weeks (Thaut et al., 1996) or 4 weeks (Bella et al., 2015; Shin et al., 2015; Mainka et al., 2018) of gait training of varying frequency (3–7 times per week). In order to provide more detailed information on the effectiveness of gait sonification beyond the direct use (as published previously in Reh et al., 2019), this study presents results on pre-, post- and retention effects of the intervention with regard to the gait pattern of patients after unilateral hip arthroplasty. Due to the unilateral restriction of the patients, the gait symmetry in particular will be considered in the analysis. Furthermore, the aim is to determine whether a possible effect on the gait pattern can still be observed 2 days after the end of the intervention (re-test).

5.2 Materials and Methods

Patients

Twenty-two patients after unilateral hip arthroplasty were randomly assigned to either a sonification group or a control group. The patient recruitment and the study intervention were conducted in cooperation with a local rehabilitation clinic (Rehabilitationsklinik Niedersachsen, Bad Nenndorf). Every patient was admitted to the same rehabilitation clinic and thus followed a similar rehabilitation program. A pre-selection of the patients was carried out by the initial medical examination of the clinic, so that patients who showed additional medical risks or had severe pain were not admitted to the study. The inclusion criteria were defined as unilateral hip arthroplasty between 1 and 8 weeks ago, hospital admission for rehabilitation in the clinic for at least 2 weeks, walking ability with walking aids, and an age between 35 and 75 years. Patients with further arthroplasties, severe overweight, pacemakers, neurological diseases or hearing impairment were not recruited for the study. The study was conducted in accordance with the guidelines stated in the Declaration of Helsinki and the regulations of the Ethical Committee of the Leibniz University Hannover (EV LUH 02/2016). A total of 22 patients participated in the measurements and the 10-day gait intervention over a period of 8 months. Each participant received a written and oral explanation of the course of study and gave his or her written consent to participate voluntarily. Patients were divided into a sonification group ($n = 11$) and a control group ($n = 11$) and were parallelized according to age, height, body mass, gender, and the results of two clinical tests (timed-up and go test and sit-to-stand test within 30 s). The basic characteristics of the groups are shown in Table 5.1 (p. 46) and the results of the clinical tests are given in Table 5.2 (p. 46).

Intervention

Both the SG and CG participated in 10 gait training sessions (TSs) of 20 min each during a two-week intervention. Only the SG received dual-mode acoustic feedback during training. A pre-test was performed before the intervention started, including a timed-up and go test and a sit-to-stand test (Table 5.2, p. 46). In addition, a kinematic gait analysis was performed using MVN Awinda (XSens Technologies B.V., Enschede, Netherlands). Hearing ability of the SG was measured using HTTS hearing test software (Version 2.10, SAX GmbH, Berlin, Germany) and cadence was determined during 1min of walking. At baseline, no significant differences between SG and CG neither for group characteristics nor for clinical tests could be found (days post-surgery: $p = 0.561$, age: $p = 0.815$, height: $p = 0.247$, body mass: $p = 0.972$, BMI: $p = 0.541$, sit-to-stand test: $p = 0.237$, timed-up and go test: $p = 0.262$).

Table 5.1: Basic characteristics of the SG and CG.

	SG (n = 11)	**CG (n = 11)**	p
Days post-surgery	15.27 ± 10.75	13.18 ± 4.67	0.561
Age [years]	62.9 ± 11.6	61.9 ± 7.9	0.815
Height [cm]	174.7 ± 5.3	178.0 ± 7.4	0.247
Body mass [kg]	86.4 ± 11.7	86.6 ± 12.5	0.972
Gender	9 male/2 female	8 male/3 female	-

Values are mean ± SD.

Table 5.2: The results of the clinical tests (timed-up and go and sit-to-stand test) for the SG and the CG.

Clinical test/group	**Pre-test**	**Interm. test**	**Post-test**	**Re-test**	**t**	**t × g**
Timed-up and go *[s]*						
SG	11.78 ± 2.78	10.37 ± 3.69	8.74 ± 2.38	8.54 ± 2.36	0.033; $1-\beta$: 0.94	0.354; $1-\beta$: 0.99
CG	13.85 ± 5.93	10.64 ± 2.97	10.63 ± 4.51	9.18 ± 1.51		
Sit-to-stand test *[reps. per 30s]*						
SG	12.3 ± 4.5	14.5 ± 5.5	16.2 ± 6.5	17.8 ± 7.5	0.041; $1-\beta$: 0.99	0.756; $1-\beta$: 0.16
CG	9.7 ± 5.3	12.4 ± 4.7	13.8 ± 5.2	15.4 ± 4.1		

The p-values of the statistical analysis (ANCOVA) are given in the right table section. The factors time (t) and time×group (t×g) were analyzed. Values are mean ± SD.

In each gait training session, patients walked for 20 min in the rehabilitation clinic's 12 m × 15 m gym. During gait training, a laptop was placed in the gym to show the patients the temporal progress of the training. To enable sonification and motion analysis during training, patients in the SG and patients in the CG wore the wireless inertial sensor system MVN Awinda with inertial measurement units (IMUs) at the default specified by the system (sacrum (1 IMU), lateral side of femoral shafts (2 IMUs), medial surface of tibias (2 IMUs) and both feet (tarus) (2 IMUs)) (Figure 5.1, p. 47). After each TS, patients in both groups received feedback on the distance covered, the steps taken and the gait speed.

Kinematic gait data was recorded at four measurement dates. The first measurement (pre-test) took place directly before the first training session. Subsequently, a second measurement took place after the fifth training session (intermediate test), followed by a third measurement after the tenth training session (post-test). On the second day after the end of the intervention the fourth measurement (re-test) was conducted (Figure 5.2, p. 47). The wireless motion analysis system MVN Awinda (Xsens Technologies B.V., Enschede, Netherlands) and the software MVN Studio BIOMECH (Version 4.1., Xsens Technologies B.V., Enschede, Netherlands) were used to record kinematic data of the lower body. The patients walked a straight distance of 10m with walking aids at a self-selected speed six to eight times at each measurement date. In addition, a timed-up and go test and a sit-to-stand test were performed.

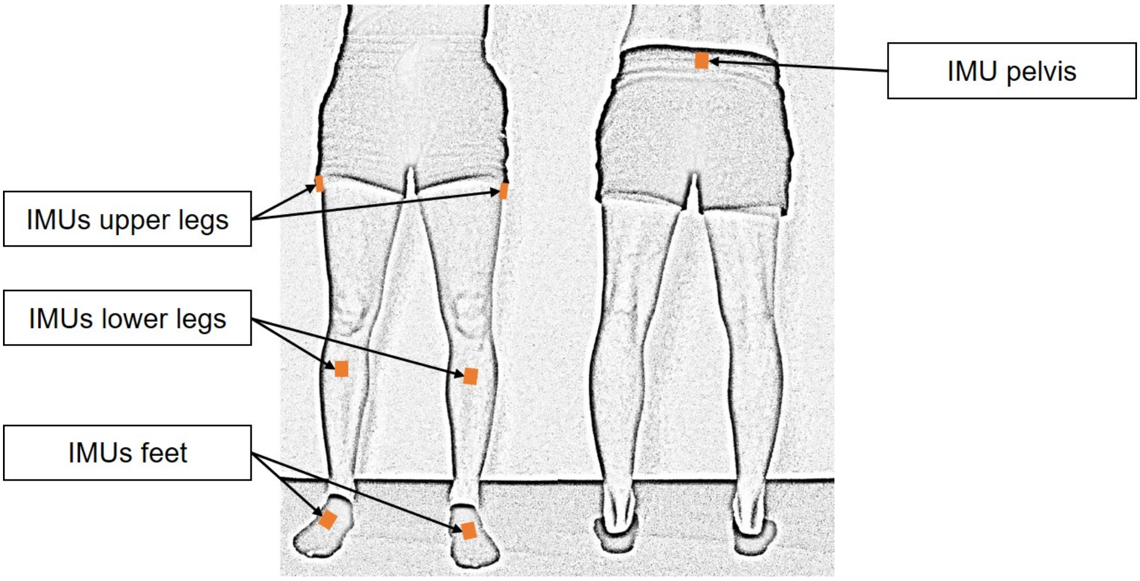

Figure 5.1: Positioning of the inertial measurement units. Seven sensors were fixed to the patient’s body with Velcro straps according to the specifications of the MVN Awinda system.

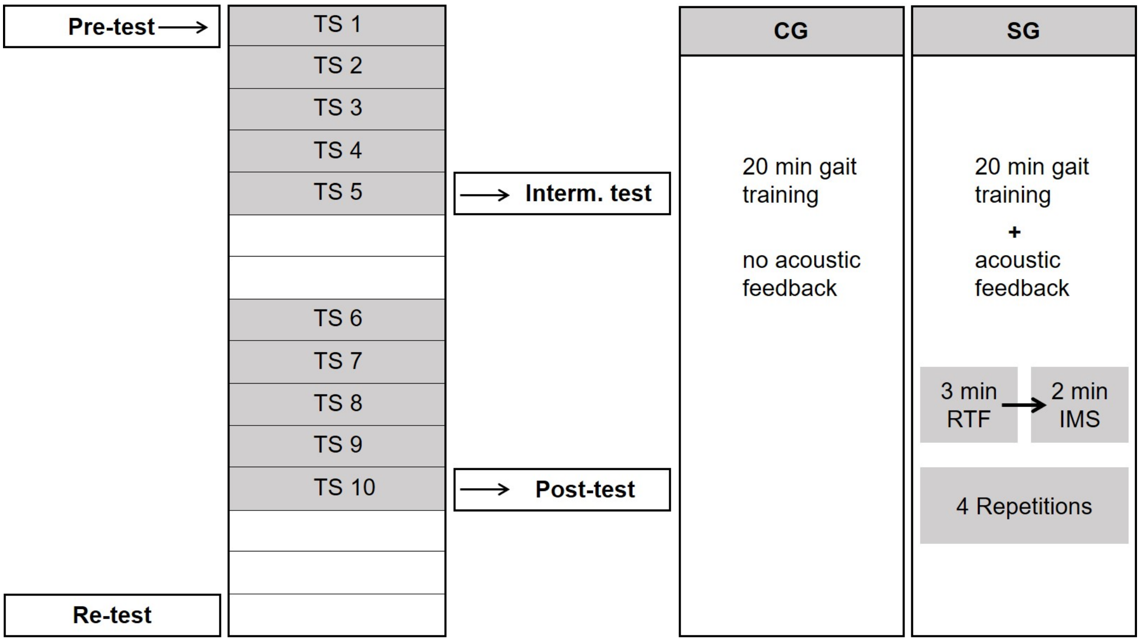

Figure 5.2: Process of intervention with 10 TSs spread over 12 days. The CG did not receive any acoustic feedback, while the SG received real-time feedback (RTF) alternating with instructive model sequences (IMS).

Dual Mode Acoustic Feedback

Due to the sequences of the acoustic feedback the gait TS of the SG were divided into 4-min blocks: Each block consisted of 3 min RTF and 2 min IMS. RTF, providing a low-latency feedback (<100 ms) of the patients' real gait pattern, was realized by direct data streaming out of the MVN Studio BIOMECH software to Spyder (Version 2.3.5.2., The Scientific Python Development Environment, Spyder Developer Community). In Spyder, an algorithm for detecting touch-down and toe-off of the feet as well as knee extension phase of the right and left leg during gait was applied. The generated kinematic events and periods (ground contact time and knee extension) were synthesized by an implemented Csound (Csound 6, LGPL) module resulting in a succinct sound pattern: The ground contact of the foot can be described in analogy of sound emerging when walking through heavy snow. Knee extension was acoustically represented as a sequence of xylophone strokes, usually a row of 5–7 quickly ascending tones per extension for healthy gait. Consequently, a whole gait cycle resulted in two successive snow compression sounds, each complemented by the xylophone of the contralateral knee extension. To enable a clear mapping between the sound and the according side of the body, the sound of the left leg (knee extension and ground contact of the foot) was four half tones (major third) lower than the sound of the right leg. Further, only the right speaker of the headphone gave the sound of the right leg while the left speaker gave the sound of the left leg.

The same sound pattern was used to generate IMS. Consequently, during IMS mode the patients heard synthesized "walking through snow" sounds and "xylophone strokes" in a fixed tempo, which was chosen based on body height and cadence. More precisely, IMS sounds were pre-recorded based on kinematic data sets to instruct a symmetric gait pattern. RTF and IMS were displayed successively and cumulated in 5 min blocks as it was intended to use enhanced sensorimotor representations formed during RTF for motor planning and execution during IMS. Therefore, exactly the same sound pattern was applied for RTF as well as for IMS. The kinematic data sets to produce a symmetric gait pattern sound were calculated as described in Reh et al. (2019). To ensure that IMS acoustically provide a symmetric gait pattern, kinematic data of the right and left leg were shifted by half a gait cycle. The datasets were synthesized and recorded to complete the new gait sonification method.

Data Acquisition and Data Processing

The wireless motion analysis system MVN Awinda (Xsens Technologies B.V., Enschede, Netherlands) and the software MVN Studio BIOMECH (Version 4.1., Xsens Technologies B.V., Enschede, Netherlands) were used to record kinematic data of the lower body. This is an IMU based motion analysis system that can be used outside of laboratory conditions. A study by Zhang et al. (2013) indicates a high correlation (coefficient of multiple correlation > 0.96) for joint movements of the lower body in flexion-extension compared to a camera-based system. The gait events touch down (TD) and toe off (TO) were defined based on the acceleration data of the foot sensors. A self-developed MATLAB algorithm (R2016a, The MathWork Inc., Natick, MA, USA) was used for the standard detection of the gait events. In this algorithm a TD is defined as the minimum vertical foot acceleration provided that the corresponding foot is in front of the other foot. A TO is defined as the maximum vertical foot acceleration provided that the foot is behind the other foot. Due to this definition, steps are only included if one foot has passed the other. In this respect, the new algorithm differs from that used in the previous article (Reh et al., 2019), which limited search fields for peak detection solely by the position and speed of the respective foot sensor. A comparison of the two algorithms with optically evaluated TD (n = 1998) (and TO) events showed a significant higher accuracy of the new algorithm with a root mean square error (RMSE) of 0.75 ms for the old algorithm and 0.03 ms for the new algorithm. To assess the effect of the gait sonification method on the gait pattern, the parameters range of motion (RoM) of both hip joints, step length, stride length, step duration, stride duration, gait speed, cadence, and ground contact time were calculated and used for statistical analysis.

We defined one stride as the range between the TD of one foot to the following TD of the same foot. The hip angle of each stride was normalized to one hundred frames. One step was defined as the range from the TD of one foot to the following TD of the other foot. The gait speed is the average speed that the patients reached when walking the 10m distance and the cadence is the step frequency as number of steps per minute.

Statistical Analysis

The results of the parameters are presented as mean values and standard deviations (mean ± SD). A three-factor mixed analysis of covariance (ANCOVA) was applied to the parameters step length, step duration, RoM of the hip and ground contact time considering the factors time (pre-test, intermediate test, post-test, re-test), side (affected leg, unaffected leg), and group (SG, CG) as well as days post-surgery as covariate. A two-factor mixed ANCOVA was applied to stride length, stride duration, gait speed, and cadence considering the factors time (pre-test, intermediate test, post-test, re-test) and group (SG, CG).

All data were checked by a ShapiroWilk test for the condition of normal distribution. Data distribution normality was not fully met for step length and ground contact time. Therefore, the relevant data were transformed inversely for statistical analysis. The assumption of normal distribution was accepted for all other parameters, so they were not transformed. Levene's test indicated that the assumption for homogeneity of the variances was accepted for all parameters ($p > 0.05$). The analyses were performed using the SPSS version 26 (Chicago, IL) and level of significance was set at $\alpha = 0.05$. If a significant interaction effect was observed using ANCOVA, it was then investigated to which differences in the data this effect can be attributed. To detect within-persons effects, post-hoc tests with sequential Bonferroni correction were performed in MATLAB. In addition, to specify interaction effects between the two groups, ANOVAs were performed over two measurements each (pre-test/intermediate test, intermediate test/post-test, post-test/re-test), which were also corrected using sequential Bonferroni correction.

5.3 Results

For the results of the clinical tests (sit-to-stand and timed-up and go) which are given in Table 5.2 (p. 46), a significant time effect could be found: a decrease in the time required for the timed-up and go test (F(1.79, 32.22) = 3.945, $p = 0.033, f = 0.469$) and an increase in the sit-to-stand test (F(1.57, 28.26) = 3.912, $p = 0.041, f = 0.467$) became obvious. No time × group interaction (timed-up and go: F(1.79, 32.22) = 1.051, $p = 0.354, f = 0.241$, sit-to-stand test: F(1.57, 28.16) = 0.213, $p = 0.756, f = 0.110$) was observed.

Spatial Gait Parameters

The results of the spatial gait parameters are shown in Table 5.3 (p. 52). For stride length no significant effects could be observed. For step length there were no significant main effects of time and group, but a significant side effect (F(3,54) = 5.573, p = 0.030, $f = 0.243$) was found. Additionally, an interaction effect of time × side × group (F(3,54) = 3.106, $p = 0.034, f = 0.149$) could be observed. This interaction confirms that step length developed differently between groups across the four measurements.

For the CG, post-hoc tests revealed significantly increased step length of the affected leg from pre-test to intermediate test ($p < 0.001$) and pre-test to re-test ($p < 0.001$).

The SG showed significantly increased step length of the affected leg from pre-test to post-test ($p < 0.001$) and of the unaffected leg from pre-test to re-test ($p = 0.001$). A different progress between groups became evident for the affected leg from intermediate test to post-test (F(1, 20) = 9.514, $p = 0.018, f = 0.69$) with an increase in the SG and a decrease in the CG as well as from post-test to re-test (F(1, 20) = 21.732, $p < 0.001, f = 1.04$) with a decrease in the SG and an increase in the CG.

Temporal Gait Parameters

The temporal gait parameters are given in Table 5.4 (p. 53). For gait speed, cadence, and ground contact time significant time effects could be revealed across groups. No significant effects were found for stride duration. For step duration significant interactions of time × side × group (F(3,54) = 3.532, $p = 0.021, f = 0.166$) and time × side × group × days-post-surgery (F(3,54) = 3.47, $p = 0.025, f = 0.164$) were found.

The interaction effects observed for step duration could be explained by post-hoc tests as follows: For the SG, post-hoc tests revealed significant decreased step durations from pre-test to post-test ($p = 0.037$) and from pre-test to re-test ($p < 0.001$) for the affected leg. The same development could be observed for the unaffected leg with decreased step durations from pre-test to post-test ($p = 0.015$) and pre-test to re-test ($p = 0.003$).

For the CG, post-hoc tests revealed significant decreased step durations from pre-test to re-test ($p = 0.016$) but not from pre-test to post-test for the affected leg. Though, for the unaffected leg again a decreased step duration from pre-test to post-test ($p = 0.029$) and from pre-test to re-test ($p = 0.001$) could be found.

RoM of Hip Joint Angle

The measured values of the range of motion are given in Table 5.3 (p. 52) and mean hip joint angles of the affected and unaffected leg standardized to one stride are shown in Figure 5.3 (p. 54).

The results of the RoM of the hip joint angle revealed a significant side effect (F(3,54) = 7.541, $p = 0.013$, $f = 0.647$). Additionally, a significant side × time × group × days-post-surgery interaction (F(3,54) = 2.996, $p = 0.039, f = 0.409$) was found. Post-hoc tests showed a significant increase of the RoM of the affected hip joint angle of the CG from pre-test to intermediate test ($p = 0.018$, $r = 0.425$) and from pre-test to re-test ($p = 0.018$, $r = 0.584$). For the SG, post-hoc tests revealed no significant within-person effects.

Furthermore, the RoM of the unaffected leg developed significantly differently between groups from post-test to re-test (F(1,20) = 12.315, $p = 0.007, f = 0.89$). In the SG, the RoM decreased from post- to re-test, but in the CG it increased.

Table 5.3: Spatial gait parameters at the four test dates for the affected and unaffected leg of the SG and the CG.

	Pre-test		**Interm. test**		**Post-test**		**Re-test**		**t**	**s**	**t×(s)×g**	**t×(s)×g×d**
	affected	unaffected	affected	unaffected	affected	unaffected	affected	unaffected	*p*	*p*	*p*	*p*
RoM hip												
SG [°]	22.91 ± 6.48	39.55 ± 7.62	23.05 ± 6.65	43.94 ± 6.48	27.04 ± 5.91	44.10 ± 7.86	26.20 ± 5.66	41.73 ± 7.38	0.509; $1-\beta$: 0.21	0.013; $1-\beta$: 0.82	0.209; $1-\beta$: 0.99	0.039; $1-\beta$: 0.99
CG [°]	22.14 ± 7.31	35.79 ± 7.81	27.28 ± 5.97	38.27 ± 7.50	26.70 ± 7.08	37.05 ± 7.21	27.73 ± 5.06	40.85 ± 9.28				
Step length												
SG [m^{-1}]	1.83 ± 0.03	1.73 ± 0.23	1.65 ± 0.32	1.65 ± 0.22	1.56 ± 0.28	1.55 ± 0.27	1.64 ± 0.30	1.47 ± 0.26	0.179; $1-\beta$: 0.18	0.03; $1-\beta$: 0.56	0.034; $1-\beta$: 0.99	0.201; $1-\beta$: 0.99
CG [m^{-1}]	1.89 ± 0.19	1.70 ± 0.20	1.61 ± 0.22	1.69 ± 0.23	1.70 ± 0.26	1.56 ± 0.13	1.57 ± 0.22	1.60 ± 0.27				
Stride length												
SG [m]	1.15 ± 0.17	1.15 ± 0.17	1.25 ± 0.19	1.25 ± 0.19	1.32 ± 0.21	1.32 ± 0.21	1.33 ± 0.21	1.33 ± 0.21	0.204; $1-\beta$: 0.17	-	0.699; $1-\beta$: 0.94	0.759; $1-\beta$: 0.87
CG [m]	1.13 ± 0.11	1.13 ± 0.11	1.23 ± 0.13	1.23 ± 0.13	1.25 ± 0.13	1.25 ± 0.13	1.29 ± 0.16	1.29 ± 0.16				

The values are mean ± SD. The step length is inversely transformed due to the lack of a normal distribution. The *p*-values of the statistical analysis (ANCOVA) are given in the right table section. The factors time (t), side (s) the interactions time × side × group (t × s × g), and time × side × group × days post-surgery (t × s × g × d) were analyzed. The level of significance was set at $\alpha = 0.05$.

Table 5.4: Temporal gait parameters at the four test dates for the affected and unaffected leg of the SG and the CG.

	Pre-test		**Interm. test**		**Post-test**		**Re-test**		**t**	**s**	**t×(s)×g**	**t×(s)×g×d**
	affected	unaffected	affected	unaffected	affected	unaffected	affected	unaffected	*p*	*p*	*p*	*p*
Step duration												
SG [ms]	640 ± 96	631 ± 78	577 ± 86	560 ± 75	560 ± 84	544 ± 75	538 ± 58	535 ± 63	0.067; 1–β: 0.25	0.708; 1–β: 0.07	0.021; 1–β: 0.99	0.025; 1–β: 0.99
CG [ms]	653 ± 104	651 ± 90	602 ± 101	582 ± 61	584 ± 73	570 ± 60	566 ± 62	548 ± 52				
Stride duration												
SG [ms]	1270 ± 171	1268 ± 171	1135 ± 159	1136 ± 159	1103 ± 157	1103 ± 155	1072 ± 120	1072 ± 119	0.075; 1–β: 0.24	0.708; 1–β: 0.07	0.375; 1–β: 0.99	0.289; 1–β: 0.99
CG [ms]	1.89 ± 0.19	1.70 ± 0.20	1.61 ± 0.22	1.69 ± 0.23	1.70 ± 0.26	1.56 ± 0.13	1.57 ± 0.22	1.60 ± 0.27				
Ground contact time												
SG [ms^{-1}]	0.0013 ± 0.0002	0.0013 ± 0.0002	0.0015 ± 0.0002	0.0014 ± 0.0002	0.0015 ± 0.0002	0.0015 ± 0.0002	0.0016 ± 0.0002	0.0015 ± 0.0002	0.010; 1–β: 0.57	0.932; 1–β: 0.05	0.917; 1–β: 0.28	0.904; 1–β: 0.31
CG [ms^{-1}]	0.0012 ± 0.0002	0.0013 ± 0.0002	0.0014 ± 0.0002	0.0014 ± 0.0002	0.0014 ± 0.0002	0.0014 ± 0.0002	0.0015 ± 0.0002	0.0015 ± 0.0002				
Gait speed												
SG [$m*s^{-1}$]	0.91 ± 0.24		1.11 ± 0.28		1.20 ± 0.31		1.23 ± 0.28		0.010; 1–β: 0.42	-	0.911; 1–β: 0.32	0.969; 1–β: 0.16
SG [$m*s^{-1}$]	0.84 ± 0.16		1.02 ± 0.21		1.06 ± 0.20		1.13 ± 0.22					
Cadence												
SG [$steps*min.^{-1}$]	88.95 ± 12.43		101.23 ± 12.98		103.21 ± 11.82		104.24 ± 9.09		0.003; 1–β: 0.50	-	0.781; 1–β: 0.50	0.608; 1–β: 0.86
CG [$steps*min.^{-1}$]	86.47 ± 11.91		94.74 ± 12.02		96.25 ± 9.79		100.16 ± 9.61					

The values are mean ± SD. The ground contact time is inversely transformed due to the lack of a normal distribution. The *p*-values of the statistical analysis (ANCOVA) are given in the right table section. The factors time (t), side (s) the interactions time × side × group (t × s × g), and time × side × group × days post-surgery (t × s × g × d) were analyzed. The level of significance was set at $\alpha = 0.05$.

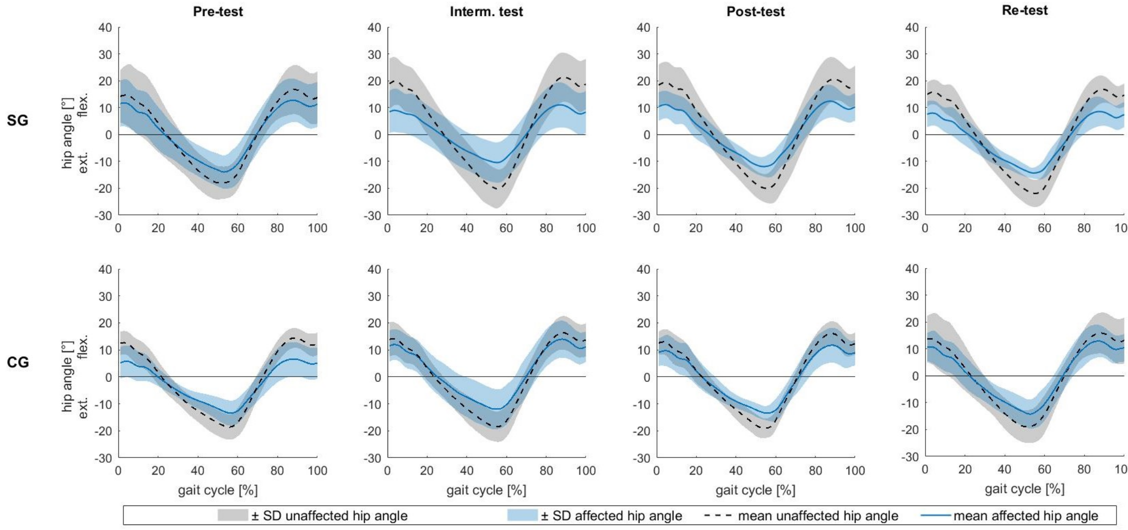

Figure 5.3: Hip joint angle over a gait cycle normalized to 100%. The lines (black: unaffected leg, blue: affected leg) are mean values. The shaded area above the line is the mean + 1 SD, the shaded area below the line is the mean -1 SD. The upper row shows the results of the SG, the bottom row shows the results of the CG for the four test dates. Significant differences were found for the RoM of the hip joint for side ($p = 0.013, f = 0.647$), and side×time×group×days post-surgery ($p = 0.039, f = 0.409$). Post hoc tests: affected hip CG: pretest - intermediate test $p = 0.018$, $r = 0.425$ and pretest - retest $p = 0.018$, $r = 0.584$.

5.4 Discussion

Our results indicate an effect of the sonification method on the gait pattern of patients after unilateral hip arthroplasty. In particular, a significant effect of sonification on step length and RoM of the hip joint was found. An increase of step length of the affected leg in the sonification group from intermediate test to post-test, but a decrease in the CG could be observed (Figure 5.4, p. 55). However, the re-test subsequently showed a reversal again, with a decrease in the step length of the affected leg in the SG and an increase in the CG. Additionally, a decrease in the RoM of the unaffected hip joint was noted for the SG from post-test to re-test in contrast to an increase for the CG. This is particularly noticeable because the post-test measurement took place directly after gait training, but the re-test was not preceded by gait training. For this reason, at least a short-term effect of gait sonification on the gait pattern can be assumed. Though, it can also be concluded that the acoustic dual-mode feedback did not lead to a stable change in gait pattern after 2 weeks of intervention. The observed step length asymmetry of the SG in the re-test is mainly due to an increased step length of the unaffected leg. In contrast, the CG showed improved step symmetry in the re-test. It can thus be stated that the method, in the context in which it was applied in the present study, did not lead to a clearly and sustainably improved gait pattern of the patients.

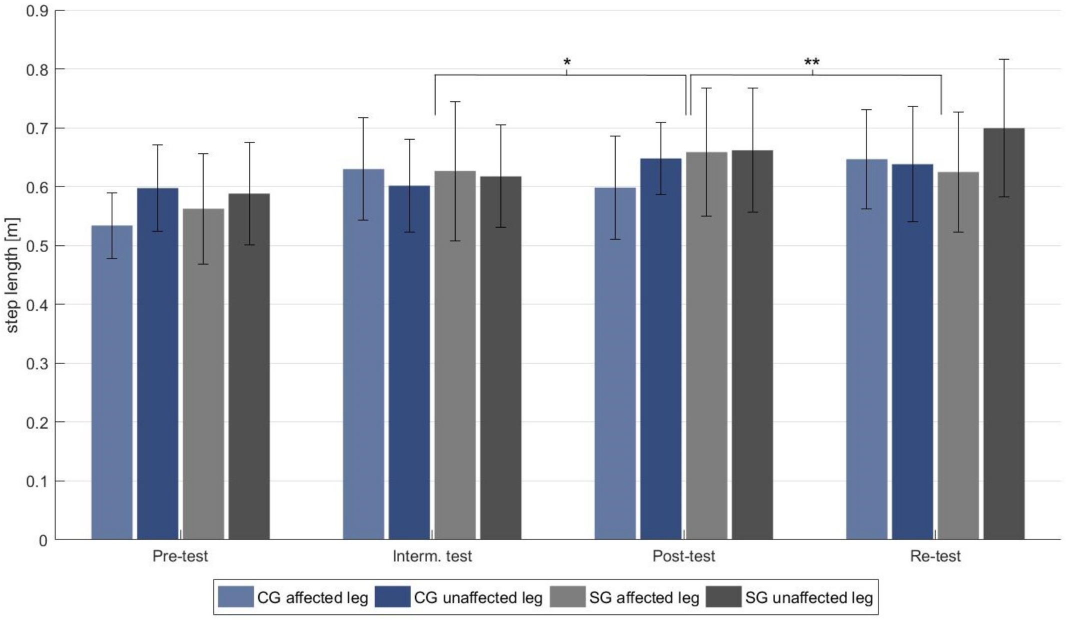

Figure 5.4: Step length of the affected and unaffected leg for the four test dates. Significant differences are marked with a * $p < 0.05$ and with a ** $p < 0.001$. The marked significant differences concern the affected leg: Interm. test - Post-test: $p = 0.018, f = 0.69$, Post-test - Re-test: $p < 0.001, f = 1.04$.

Currently, the use of the method in clinical rehabilitation does not seem to be recommendable. However, the data provide first indications that the method is effective, since different developments between the groups could be observed in a short period of time (5 days each from intermediate test to post-test and post-test to re-test), so that further research in this field seems reasonable.

A basic improvement of general gait parameters (gait speed, cadence, stride length) and gait symmetry was expected in both subgroups, as they were recovering from a surgical procedure on the hip joint and usual training measures took place in the rehabilitation clinic. In this regard, Bahl et al. (2018) demonstrated improvement in gait speed, stride length, step length, and hip RoM 6 weeks after surgery in patients following hip arthroplasty. Rapp et al. (2015) also found increasing improvement in gait speed and gait symmetry in 29 patients after total hip arthroplasty when measured at days 15, 21, and 27 after surgery. In our study, the improvement in both groups might be attributed to the additional gait training through the participation in the study.

However, it is also known that even 12 months after surgery, deficits in gait can be found compared to healthy individuals of the same age (Queen et al., 2014; Bahl et al., 2018) indicating that it is a great challenge for patients to relearn a symmetric and steady gait pattern. Usually gait rehabilitation after hip or knee arthroplasty is associated with a large effort of time and personnel (Ong et al., 2015; Sabeh et al., 2017). In addition, it must be considered that prevalence of arthrosis increases with age (Neogi & Zhang, 2013; Allen

& Golightly, 2015) and thus often affects elderly patients who suffer from several comorbidities such as cognitive impairments. In this regard, a gait rehabilitation system that does not require high attentional cost might be a powerful add-on to classical treatments. The present study can only provide a first insight into the use of gait sonification for patients after unilateral hip arthroplasty, and the results only provide information about a short period after surgery, though, they do provide clues to future targeted applications of this method.

Although previous studies on the effect of acoustic feedback have shown positive effects (Thaut et al., 1996; Aruin et al., 2003; Schmitz et al., 2014; Bella et al., 2015; Bella et al., 2018; Park et al., 2015; Shin et al., 2015; Young et al., 2016; Dotov et al., 2017; Ghai, Ghai, et al., 2018; Chang et al., 2019; Van Criekinge et al., 2019), clear evidence in patients undergoing gait rehabilitation with orthopedic diseases or (neurologically) healthy individuals is still lacking at the current time. In this context, (Yang et al., 2012) investigated the influence of acoustic error feedback during walking on three unilateral transtibial amputated patients. The ground contact time was measured in real time by means of insoles containing force sensitive resistors. A signal tone was generated in case of an unequal relationship between right and left ground contact time. In this way it was possible to improve the gait symmetry in terms of trunk sway and ground contact time ratio from pre-test to post-test by training six times for 30 min. However, a comparison with a control group is missing, so that it cannot be excluded that regular gait training alone has a positive effect on gait symmetry even without additional feedback. In our study exactly this could be observed, since the control group also shows an improved symmetry of the ground contact time and of several other parameters at the end of the intervention.

Horsak et al. (2016) also used force insoles containing seven force sensors in a pilot study to investigate the effect of sonification of ground contact times on the gait of 12 healthy, younger persons. However, there was no intervention, but the immediate influence of five different sounds on the gait of the participants was investigated. The five sounds differed in terms of their synthesizing (bandpass filtered white noise, wavetable, fm-synthesis, sinusoidal oscillator, Karpus strong algorithm), the assignment of frequencies or pitches to the seven force sensors, and ultimately in their timbre. Under the gait sonification conditions, a reduced cadence and gait speed was observed compared to a condition without sonification. A similar result was obtained by Fischer et al. (2017) with a comparable methodology in 22 participants over 50 years of age. However, this effect may be due to the short duration of sonification, what might have led to that the participants were not yet fully accustomed to the acoustics and concentrated more on the sound during sonification conditions. The present study, on the other hand, could not show an influence on cadence and gait speed after a two-week intervention, which could be due to a longer period of habituation and the different population investigated.

One of the few studies investigating the influence of acoustic feedback on patients after unilateral hip arthroplasty was published by Pietschmann et al. (2019). Patients of a rehabilitation clinic with unilateral hip arthroplasty (*n* = 120) were included. The patients were divided into six different groups, each comprising 20 patients (visual feedback, virtual feedback, tactile feedback, acoustic feedback, no additional feedback, control group), and participated in a 14-day intervention. This consisted of six 30-min gait training sessions on a treadmill. A pre-test was performed at the beginning and a post-test at the end of the intervention. The gait parameters gait speed, stride length, ground contact time and RoM of hip and knee joints were analyzed. It became clear that only the gait speed of the groups changed significantly different, while otherwise improvements were observed for all groups. The acoustic feedback group showed better results in terms of hip RoM and stride length, but these effects were not significant. In comparison to the present study, it should be emphasized that Pietschmann et al. (2019) chose a quite similar approach.

With regard to the results, it can be said that the present study also shows a strong basic effect of gait training which is not due to additional feedback. Indeed, patients after hip arthroplasty seem to be severely restricted in relearning a physiological gait pattern during rehabilitation. This is probably due to structural limitations and/or previous and current pain, which is why this population seems to benefit above all from functional gait training. Nevertheless, it should be noted that significant effects on the gait pattern due to acoustic feedback were clearly shown in the current study. This difference in results from the study by Pietschmann et al. (2019) might be caused by the free walking in a gym (not on a treadmill) and the use of walking aids in the present study, which may have led to greater freedom of movement beyond the automated gait pattern. Another reason could be the different mapping of the sound to the movement. Pietschmann et al. (2019) focused on the sounding of the hip joint angles. In contrast, we chose a more distal approach with the sonification of ground contact duration and knee extension. Here, the primary intention was not to adjust or improve the parameters selected for sonification, but to provide a clear and concise temporal feedback for the patient.

In a previous study (Reh et al., 2019), we investigated the immediate effect of gait training with dual-mode acoustic feedback in the same patient group. The results indicated that RTF leads to greater step variability compared to IMS. The previous study also showed an effect on stride length. This finding is supported by the current results. Although there was a significant improvement in the affected leg step length of the SG from pre- to post-test, it is noticeable that a deterioration in step length symmetry of the SG was observed from post- to re-test. This could indicate that at this point there was still a close dependence between the new gait pattern learned during the intervention and gait sonification. For this reason, the gait pattern could probably be maintained only for a short time after the end of the gait training, but not until the re-test two days after the end of the intervention. It would be interesting to investigate in a future study, whether an intervention period of at least 4 weeks would have resulted in a long-lasting change in gait pattern. This could provide important new insights since it can be assumed that walking

tends to perpetuate previously learned motor representations, as walking involves a high number of repetitions of the same motor pattern over and over again.
In addition, it can be surmised that the effect on step length symmetry would have been more apparent if the intervention had been scheduled later in the rehabilitation process and the walking aids could have been omitted. This should be considered as a limitation of the study, as at the chosen intervention time, the use of walking aids, pain, and severe structural injuries may have affected motor relearning. In addition, it should be taken into account that the size of the sample examined in this study was small, although the power of the results is not limited due to the high power of the statistical analysis regarding important effects. Nevertheless, it might be necessary to repeat the study over a longer period of time with a larger selected sample size and considering comorbidities and duration after surgery. This would allow a more extensive evaluation of the effectiveness of the sonification method. In a further step, gait sonification could be used in conjunction with mental training to establish the desired individual and physiological gait pattern.

5.5 Conclusions

Dual-mode acoustic feedback training shows first indications of an influence on gait pattern in patients after unilateral hip arthroplasty. A short-term improvement of the gait pattern in terms of optimized gait symmetry is supported by the present results, especially with regard to step length. Future studies could help to shed deep light on these indications and thus clarify how acoustic feedback can efficiently and permanently influence the gait pattern of patients after unilateral hip arthroplasty. In this regard, the time period of an intervention and the precise association of kinematics to sound should be considered more comprehensively. We consider it likely that the reorganization of a physiological gait pattern representation can be accelerated by complementary mental training with a model sound. This relationship should be investigated predominantly with further scientific studies, because physical training is usually closely limited for the patients and the establishment of a robust auditory model gait pattern via concomitant mental training should be helpful for a better assessment of one's own gait pattern to get back to a symmetrical physiological gait.

6

Loudness Affects Motion: Asymmetric Volume of Auditory Feedback Results in Asymmetric Gait in Healthy Young Adults

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Adapted from: Reh, J., Schmitz, G., Hwang, T.-H., & Effenberg, A. O. (2022). Loudness affects motion: Asymmetric volume of auditory feedback results in asymmetric gait in healthy young adults. *BMC Musculoskeletal Disorders*.

Abstract

The potential of auditory feedback for motor learning in the rehabilitation of various diseases has become apparent in recent years. However, since the volume of auditory feedback has played a minor role so far and its influence has hardly been considered, we investigate the volume effect of auditory feedback on gait pattern and gait direction and its interaction with pitch.

Thirty-two healthy young participants were randomly divided into two groups: Group 1 (n = 16) received a high pitch (150-250 Hz) auditory feedback; group 2 (n = 16) received a lower pitch (95-112 Hz) auditory feedback. The feedback consisted of a real-time sonification of the right and left foot ground contact. After an initial condition (no auditory feedback and full vision), both groups realized a 30-minute habituation period followed by a 30-minute asymmetry period. At any condition, the participants were asked to walk blindfolded and with auditory feedback towards a target at 15 m distance and were stopped 5 m before the target. Three different volume conditions were applied in random order during the habituation period: loud, normal, and quiet. In the subsequent asymmetry period, the three volume conditions baseline, right quiet and left quiet were applied in random order.

In the habituation phase, the step width from the loud to the quiet condition showed a significant interaction of volume×pitch with a decrease at high pitch (group 1) and an increase at lower pitch (group 2) (group 1: loud 1.02 ± 0.310, quiet 0.98 ± 0.301; group 2: loud 0.95 ± 0.229, quiet 1.11 ± 0.298). In the asymmetry period, a significantly increased ground contact time on the side with reduced volume could be found (right quiet: left foot 0.988 ± 0.033, right foot 1.003 ± 0.040, left quiet: left foot 1.004 ± 0.036, right foot 1.002 ± 0.033).

Our results suggest that modifying the volume of auditory feedback can be an effective way to improve gait symmetry. This could facilitate gait therapy and rehabilitation of hemiparetic and arthroplasty patients, in particular if gait improvement based on verbal corrections and conscious motor control is limited.

6.1 Introduction

The ability to perceive noise and sound is of great importance for our everyday interaction with the environment. For example, auditory perception helps us to recognize and determine distances, speeds, obstacles, materials, and our own position in space (Giordano et al., 2010; Grassi et al., 2013; Houben et al., 2004; Houix et al., 2012). In sports, acoustic signals, sounds, verbal agreements, and music are often used to synchronize and modulate movements. Sounds are produced by movement, e.g. when bouncing off spring floors, hitting balls and when arms and legs hit water, or are consciously generated, e.g. when the starting shot is given or when shouting in team sports. The volume of sounds is often causally related to the intensity of movement. Thus, greater energy means increased power and acceleration or deceleration resp., which results in increased volume.

Possibly due to these physical correlation between movement and sound, neurophysiological findings suggest a close relationship between the movement system and auditory brain areas. Several imaging studies have shown that noises or sounds produced by a known movement induce neuronal activation in the human brain that resembles the neuronal activation during execution of the action. This simulation can be observed especially in the mirror neuron system and has become known in recent years under the term "action-listening" (Bangert et al., 2006; Haslinger et al., 2005; Lahav et al., 2007; Pizzamiglio et al., 2005). Furthermore, Chen et al. (2008) showed in two fMRI experiments that rhythmic sounds generally cause an activation of the motor cortex in humans. The participants of experiment 1 knew the task of tapping on a right mouse button in synchrony to different rhythms given by a computer and via headphones from an exercise session on the day before the fMRI measurements. In contrast, participants of experiment 2 did not know that they were supposed to tap to the rhythms during the course of the fMRI measurement. Since no practice session was conducted on the previous day, they only learned about the tapping task after they had passively listened to the rhythms once. Under both conditions, listen with action anticipation and passive listening, the supplementary motor area, mid-premotor cortex, and the cerebellum were activated.

It also became clear that people are better able to recognize the sound pattern generated by their own actions than a sound pattern generated by other persons actions and to assign it to themselves (Justen et al., 2014; Kennel, Hohmann, & Raab, 2014; Murgia et al., 2012; Sevdalis & Keller, 2014). For auditory perception, therefore, a close perception-action link can be assumed in humans. Due to the intrinsic connection between sound and movement in space and time (Maes et al., 2014; Parise et al., 2014; Rusconi et al., 2006; Sievers et al., 2013) and the neural connectivity described above, it seems reasonable to use auditory information to provide targeted and effective feedback for sports training and motor (re-)learning.

In the research on motor behavior, there exist many different approaches regarding the artificial generation of augmented auditory feedback (AAF). The following AAF methods were mainly considered: natural movement sounds (Kennel, Pizzera, et al., 2014; Murgia et al., 2016; Pizzera et al., 2017), error feedback (Ferrigno et al., 2016; He et al., 2019; Wentink et al., 2015), rhythmic auditory stimulation (Song & Ryu, 2016; Thaut et al., 2001; Willems et al., 2006; Wittwer et al., 2013b), sonification (Dyer et al., 2017c; Dyer et al., 2017a; Effenberg et al., 2016; Effenberg & Schmitz, 2018; Reh et al., 2019; Reh et al., 2021; Schmitz & Effenberg, 2012) and musical movement feedback (Nikmaram et al., 2019; Scholz et al., 2015; van Vugt et al., 2016). It has been shown that AAF is effective in a wide variety of application areas. There is evidence of efficacy in sports, e.g. rowing (Schaffert et al., 2010; Schaffert & Mattes, 2011), skiing (Hasegawa et al., 2012), golf (O'Brien et al., 2021), cycling (Schaffert et al., 2017), and swimming (Cesarini et al., 2014), and also in movement rehabilitation, particularly in Parkinson's disease (Mezzarobba et al., 2018; Scholz et al., 2016; Thaut et al., 2019) and stroke patients (Chen et al., 2016; Schmitz et al., 2018).

So far, the choice of one of the aforementioned AAF methods and the mapping of acoustic parameters to specific movements, seems to be based primarily on the assessment of the movement or disease under investigation. For example, for gait rehabilitation in Parkinson's patients (Ghai, Ghai, et al., 2018), rhythmic-auditory stimulation was investigated above all, since walking is an intrinsically rhythmic and repetitive movement. For movements with more degrees of freedom, such as attack-and-release actions (e.g. grasping), studies were conducted more frequently using real-time movement sonification or musical sonification (Cesarini et al., 2014; Scholz et al., 2016).

Movement sonification (MS) means the transformation of kinematic human motion data into sound, resulting in multidimensional motion acoustics. So far, research on gait sonification mainly considered timbre and pitch (Gomez-Andres et al., 2020; Horsak et al., 2016; Tajadura-Jiménez et al., 2015; Young et al., 2016), rhythm (Brodie et al., 2015; Dotov et al., 2017; Ghai, Ghai, et al., 2018; Rodger et al., 2013; Wright & Elliott, 2014) and tempo (Ford et al., 2010; Roerdink et al., 2011). As far as known, even if correlations of volume and distance (Blauert, 1996), volume and size of objects (Grassi et al., 2013; Grassi, 2005; Lipscomb & Kim, 2004), volume and direction and speed of movement (Eitan et al., 2008; Eitan, 2013) as well as volume and articulatory kinematics (Darling & Huber, 2011) are known from other research areas, these have hardly been included when using gait sonification. However, due to the known correlations, volume could be an easy-to-use parameter, for example, to specifically treat rehabilitation patients with asymmetrical gait (stroke patients, unilateral arthroplasty) with the help of well-shaped auditory feedback. In a recent review paper, Schaffert et al. (2019) point out that the question of "what auditory components and amount of information are most relevant for motor training and rehabilitation" has not yet been sufficiently investigated. Among other things, it is unclear what effect individual parameters of sound (e.g., pitch, volume, timbre, tempo, rhythm) have on the execution of movement and motor control (Vinken et al., 2013).

However, knowledge of the concrete impact of the various sound parameters in AAF considering different target groups would make the use of auditory feedback more purposeful and efficient in the future. This work aims to contribute to the clarification of the sound-parameter-motion relationship in AAF. For this purpose, we consider the parameters volume and pitch and their possible influence on the gait pattern of healthy young persons. These two parameters are taken into account since pitch and loudness perception are correlated due to the perceptual range of the human auditory system: We hear sounds loudest at frequencies between 2000 and 4000 Hz, and sounds below or above are perceived more quietly at the same sound pressure level (Robinson & Dadson, 1956). Furthermore, correlations between pitch and range and direction of motion (Rusconi et al., 2006; Cabrera & Tilley, 2003; Eitan & Granot, 2006; Kohn & Eitan, 2012; Singhal et al., 2018) are well known and clearly described in the literature. A higher pitch is usually accompanied by an increase in height and velocity which also indicates a similarity to volume perception.

This study intends to investigate the influence of different volume and its interaction with pitch of real-time sonification of the ground contact on the gait pattern of healthy persons.

First, the overall volume was varied by 6 dB in three steps (loud 0 dB, normal -6 dB, quiet -12 dB) to determine its influence on participants' gait pattern (stride width, stride length, gait speed). Second, we hypothesized that the asymmetric loudness of sonification influences the gait symmetry of the participants. In this regard, the volume difference was varied between the right and left channel of the headphone used. Furthermore, to investigate whether pitch interacts with volume, the volume changes were applied to two groups (G1: $n = 16$, G2: $n = 16$) with different sonification pitches: G1 received a sound with a base frequency of 150-250 Hz and G2 received a sound with a base frequency of 95-112 Hz.

6.2 Materials and Methods

Participants

A total of 32 young, healthy volunteers participated in the study. Each participant was informed about the general course of the study and the handling of the data collected before the start of the measurement. Written informed consent was obtained from each participant. The study was conducted in accordance with the guidelines stated in the Declaration of Helsinki and the regulations of the Ethical Committee of the Leibniz University Hannover (EV LUH 15/2019). Volunteers aged 18-35 years with normal physiological walking and hearing ability were included in the study. Acute injuries or pain of the lower extremities and diseases affecting hearing, vision or balance were defined as exclusion criteria. The criteria were checked by means of a questionnaire, which was completed by the participants before the start of the measurements. In addition, each participant obtained a hearing test (HTTS hearing test software, Version 2.10, SAX GmbH, Berlin, Germany) to ensure sufficient hearing ability and well-balanced hearing in both ears.

Participants were randomly divided into two groups. G1 (n = 16, gender: 8 m/8f, age: 23.6 ± 3.4 years, height: 178.3 ± 9.7 cm, weight: 71.3 ± 15.6 kg, weekly sport activity: 6.4 ± 3.8 h) received a high pitch sonification and G2 (n = 16, gender: 9 m/7f, age: 25.2 ± 3.3 years, height: 180.1 ± 7.1 cm, weight: 73.3 ± 10.0 kg, weekly sport activity: 6.2 ± 2.9 h) received a lower pitch sonification. T-tests for independent samples of the baseline characteristics of both groups revealed no significant differences between G1 and G2 (age $p = 0.202$, height $p = 0.552$, weight $p = 0.669$, weekly sport activity $p = 0.836$). The proportion of right- and left-handed and right- and left-footed participants was approximately balanced in G1 and G2 (G1: 14 right-handed, 2 left-handed; 7 support leg right, 9 support leg left; G2: 13 right-handed, 2 left-handed, 1 ambidextrous; 5 support leg right, 11 support leg left).

In order to capture whether there are different emotional responses in participants due to the different pitch of sonification, a mental state questionnaire (Befindlichkeits-Skala, Bf-SR) was used to assess mental state [validated German questionnaire Bf-SR (Zerssen & Petermann, 2011)]. The questionnaire was filled out by the participants once before the start of the gait measurements and once after the gait measurements.

Experimental Design

The measurements took place in a quiet gym of the Leibniz University Hannover. Each participant participated in one 90-minute measuring session. A randomized single-blinded design was chosen. Unlike the supervisor of the experiment, the participants were not informed in advance about their group allocation and the different volume conditions. Each participant went through all of the conditions presented below in random order.

The measurements began with an initial condition: the participants walked four times straight from a start mark towards a target at a distance of 15 m with full vision and without sonification. The further course of the experiment was divided into two periods: a habituation period and an asymmetry period. In both periods the participants received sonification via headphones while walking. The sonification of the right ground contact was played only on the right speaker of the headphone and the sonification of the left ground contact on the left speaker of the headphone. In detail, the sonification mappings are described in section Ground contact sonification. Both periods consisted of three blocks each. During the habituation period, the volume was varied symmetrically on both sides: (1) loud, (2) normal, (3) quiet. During the asymmetry period, the volume was varied asymmetrically: (1) right quiet (RQ), (2) left quiet (LQ), (3) right and left equal (baseline). In the habituation period, one block consisted of a five-minute walking phase in which the participants walked back and forth between start and target with full vision and sonification (loud, normal, quiet). This was followed by four times walking blindfolded from the start towards the target under the same volume condition as during the five-minute gait phase. In the asymmetry period, one block consisted of four blindfolded walks from the start to the target with wave noise. This was followed by four blindfolded walks from the start to the target with sonification (RQ, LQ, baseline). The course of the experiment is shown in Figure 6.1.

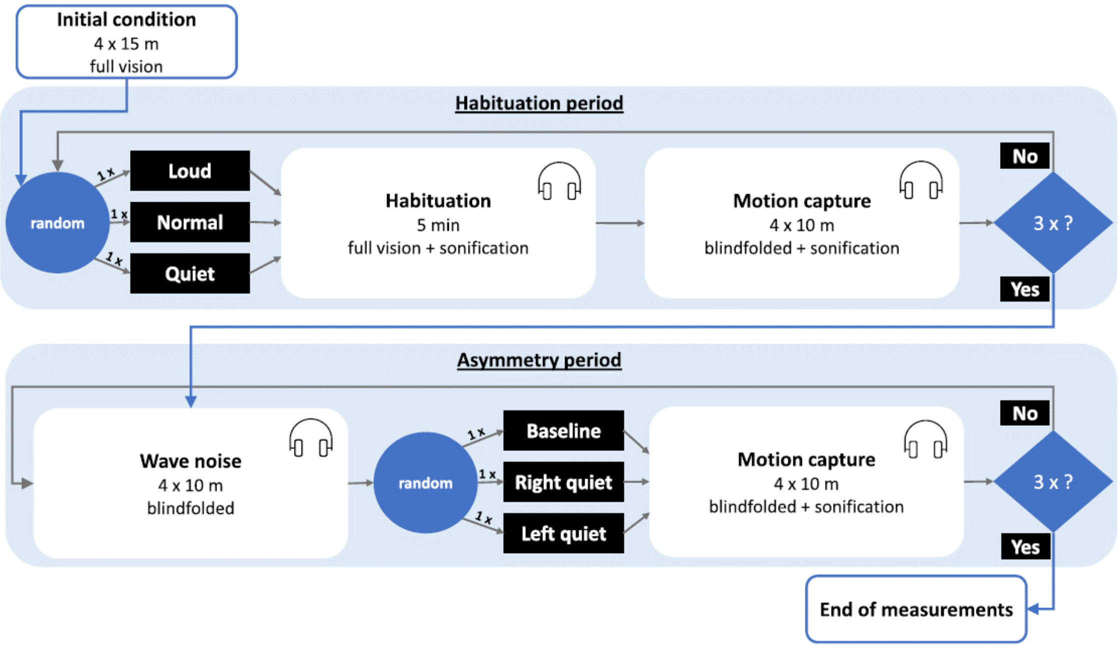

Figure 6.1: Experimental design. The experiment starts with an initial condition, followed by the habituation period (top) and the asymmetry period (bottom), each consisting of three repetitions (blue diamond). The three repetitions include three different volume conditions in the habituation period (loud, normal, and quiet) and in the asymmetry period (baseline, right quiet, left quiet), each run once in randomized order.

Gait Analysis

To ensure consistent walking conditions, the test persons were provided with anti-slip socks in which they could walk safely in the gym. A start marker was attached to the floor and a red target point was attached to a box (70 × 50 × 40 cm) to clearly delimit the walking area Figure 6.2 (p. 66). The markings indicated a distance of 15 m. Furthermore, a white line drawn in an arc on the ground marked a distance of 10 m from the starting point. The participants were fitted with the wireless motion analysis system MVN Awinda (XSens Technologies B.V., Enschede, the Netherlands). Seven inertial measurement units (IMUs) were attached to the sacrum (1 IMU), lateral side of both femurs (2 IMUs), medial surface of tibias (2 IMUs), and middle arches of the feet (2 IMUs) using Velcro straps. The data acquisition was carried out using the software MVN Studio BIOMECH (Version 4.1, XSens Technologies B.V., Enschede, the Netherlands), which stores the data at a frequency of 60 Hz. Before each gait recording, the motion analysis system was calibrated directly at the marked starting point to ensure the highest possible measurement and sonification accuracy.

The measurements started with an initial condition without visual restriction and without sonification. The participants approached the target four times at a selfselected average speed and stopped about 5 cm before the target mark. The kinematics of the total distance of 15 m was recorded. This was followed by the habituation period. For the five-minute walking phases without visual restriction the participants were instructed to put on the wireless headphones after calibration and to walk back and forth between the start and finish markings for 5 min each. All other conditions (loud, normal, quiet, wave noise, baseline, RQ and LQ) were performed blindfolded.

Before each condition, the participants were instructed to first concentrate visually on the target point, second to put on headphones, third to put on the sleeping mask and fourth to start walking within 5 s. In all blindfolded conditions, the participants were stopped at a 10 m line by a touch on their back to achieve a standardized walking distance.

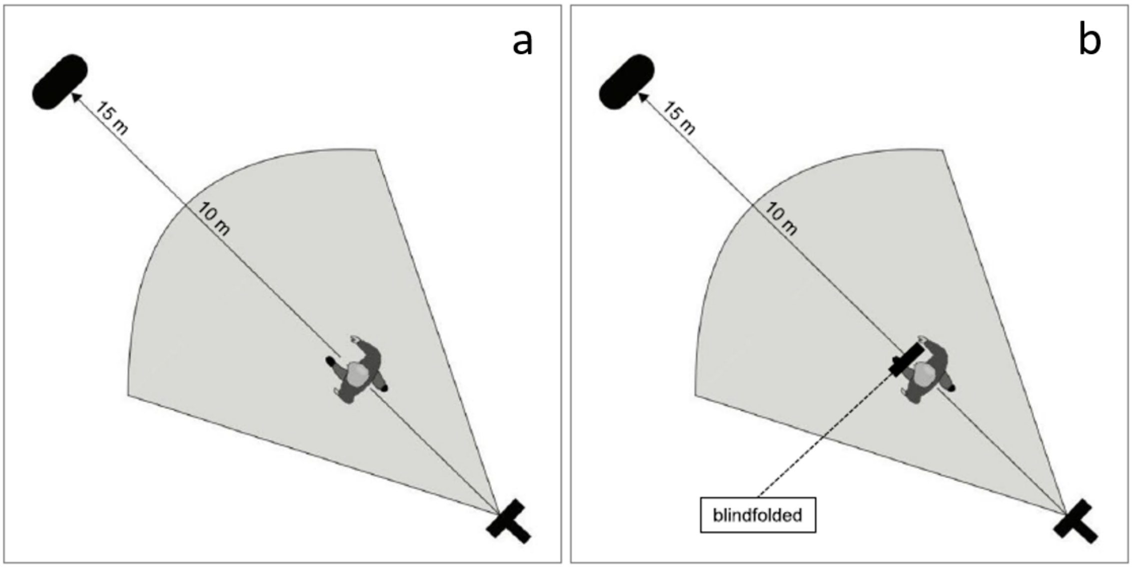

Figure 6.2: **(a)** Experimental setup for the gait measurements. The start-calibration mark is on the bottom right. At the top left is the target marking and the 10 m distance is marked by an arc line. **(b)** In the initial condition and habituation, participants walk with full vision. Right side: In the conditions loud, quiet, normal, baseline setting, RQ setting, LQ setting, and wave noise, participants walk blindfolded.

Data acquisition was also stopped at this point. The headphones were removed from the participants heads, but not the sleeping mask, in order to avoid the possibility of conscious directional correction during subsequent attempts. The participant was guided back to the starting point via the touch on the back, where the sleeping mask could be taken off again.

Ground Contact Sonification

For sonification, the kinematic data was streamed in real time from the MVN Biomech software to a self-developed Spyder program (Version 3.3.1., The Scientific Python Development Environment, Spyder Developer Community). Latency from touch down to sound occurrence was less than 100 ms.

An algorithm was used to determine the gait events touch down (TD) and toe off (TO) using the acceleration data of the feet. The sonification of the ground contact time (from TD to TO) was performed by an implemented CSound module (Csound 6, LGPL). One channel was used for each foot, so that on the left ear only the ground contacts of the left foot and on the right ear only the ground contacts of the right foot could be heard. The pitch was the same on both sides. G1 received sonification of ground contact times with a base frequency of 150-250 Hz. The sound resembles the noise produced when walking through snow. However, the sound has more characteristics of a tone. G2 received sonification of ground contact time with a base frequency of 95-112 Hz. Due to the narrower frequency setting, the sound appeared deeper and softer, and its frequency spectrum was more clearly delineated from the first one. Both sounds are visually contrasted in a Melodic Range Spectrogram in Figure 6.3.

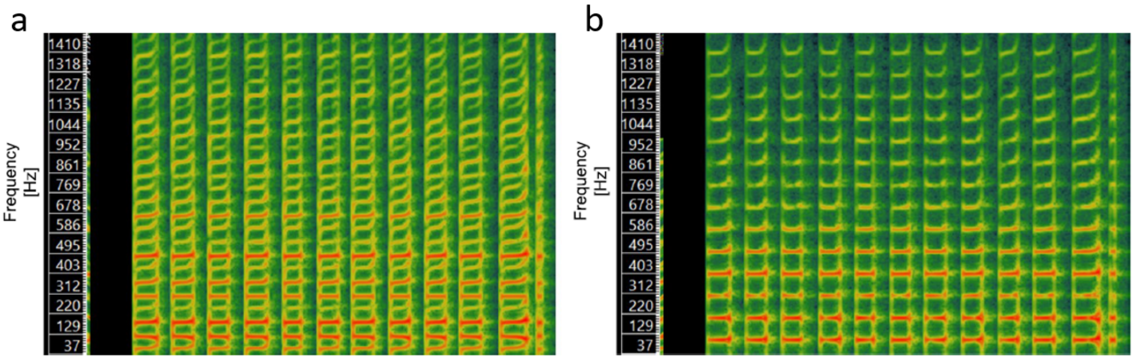

Figure 6.3: **(a)** Melodic range spectrogram of the sound used for the sonification of the ground contact for G1 (base frequency of 150-250 Hz) and **(b)** melodic range spectrogram of the sound used for the sonification of the ground contact for G2 (base frequency of 95-112 Hz). Only one channel is shown at a time. The spectrograms were generated using Sonic Visualiser (Release 4.3, Centre for Digital Music at Queen Mary, London, GB).

The loud volume level (59.0 dB) was determined by pilot measurements in which five young healthy participants were asked whether they perceived the sound clearly when walking 10 m. If the sound was perceived as too loud, they were immediately stopped, and the volume was reduced gradually via the headphones. Steps of volume decrease was chosen such that differences were not clearly noticeable to avoid participants responding with a deliberate change in gait pattern. After the measurements, participants were asked whether they perceived differences in gait sonification, which was the case for only three of the 32 participants (G1: 1; G2: 2).

The volume change of the ground contact sonification was implemented by a decibel change in CSound. This change was based on the inverse square law, which according to Blauert (1996) states that the sound pressure level decreases by approximately 6 dB when the distance is doubled. The loud setting was defined in CSound as 0/0 dB (sonification 1/1 = 100%), the normal setting as -6/-6 dB (sonification 0/0 = 50%) and the quiet setting as -12/-12 dB (sonification -1/-1 = 25%). Accordingly, the RQ setting was defined as -12/-6 dB and the LQ setting as -6/-12 dB. This resulted in actual mean sound pressure levels of 52.0 dB (quiet), 55.5 dB (normal), and 59.0 dB (loud). The volume settings of the headphones and the laptop used were kept the same throughout the experiment.

Data Processing

Six middle steps of each gait recording were cut in MVN Studio BIOMECH and included in the evaluation in order to exclude any falsification by accelerating and stopping at the beginning or end of the walk. The gait events TD and TO were determined using a self-developed algorithm in MATLAB (R2016a, The MathWork inc., Natick, MA, USA) and the gait parameters stride duration, percentage step duration in relation to stride duration, percentage ground contact time in relation to stride duration, stride speed, cadence, stride length, step length and step width were analyzed. We defined one stride as the range between the TD of 1 ft to the following TD of the same foot. One step was defined as the range from the TD of 1 ft to the following TD of the other foot and the ground contact time was the time between TD and TO of the same foot. The percentage step duration and the percentage ground contact time were considered in relation to the stride duration, i.e. the stride duration was defined as 100%. The step width is the distance between both feet orthogonal to the direction of gait and the cadence is defined as number of steps per minute.

For the evaluation of the gait direction the recordings were not cut. The target position is the position of the participants' feet in the initial condition, which was measured for each participant at the beginning. The stop position is the final foot position of the participants in the habituation period and asymmetry period, when walking blindfolded. The direction of gait was determined in MATLAB by establishing a line equation based on the start position and target position of the feet (Equation 6.1). The amount of the angle between the two vectors target position and stop position was determined by Equation 6.2.

$$\Delta y = y_{stop} - \left(\frac{y_{target} - y_{start}}{x_{target} - x_{start}} \cdot \left(x_{stop} - x_{start} \right) + x_{start} \right) \tag{6.1}$$

$$\alpha_{dev} = \arccos \left(\frac{\overrightarrow{\Delta s} \cdot \overrightarrow{\Delta t}}{\|\overrightarrow{\Delta s}\| \cdot \|\overrightarrow{\Delta t}\|} \right) \tag{6.2}$$

In Equation 6.1, Δy is the difference between the y-coordinates of the stop vector and target vector at the same level, y_{stop} is the y-coordinate of the stop vector, x_{stop} is the x-coordinate of the stop vector, y_{target} is the y-coordinate of the target vector, and x_{target} is the x-coordinate of the target vector. A $\Delta y > 0°$ was defined as a deviation to the left, a $\Delta y < 0°$ was defined as a directional deviation to the right. In Equation 6.2, α_{dev} is the amount of the directional deviation, $\overrightarrow{\Delta s}$ is the stop vector, and $\overrightarrow{\Delta t}$ is the target vector.

To determine the ratio the data of the conditions RQ and LQ were each divided by the baseline condition (asymmetry period) and the data of the conditions loud and quiet were each divided by the normal condition (habituation period). For the statistical analysis, the ratio of stride duration, step duration, ground contact time, percentage step duration, percentage ground contact time, stride speed, cadence, stride length, step length and step width were considered. For the gait direction, the angles of the conditions RQ and LQ were subtracted from the angles of the baseline condition. The differences were used for the statistical analysis.

Statistical Analysis

The results of the parameters are presented as mean values and standard deviations (mean ± SD). Only the deviation of the gait direction in Figure 6.4 (p. 70) is given as mean values and standard error (mean + SE). A mixed ANOVA was applied to the temporal, spatial and directional parameters. The mental state (Bf-SR score) was analyzed using a sign test.

The data were checked by a Shapiro Wilk test for the condition of normal distribution. A Levene's test was used to check for homogeneity of variances. The analyses were performed using SPSS (IBM SPSS Statistics, Version 26, Chicago, IL) and level of significance was set at $\alpha = 0.05$. If a significant interaction effect was observed, post-hoc t-tests using Bonferroni correction were performed in MATLAB to identify detailed differences between conditions.

6.3 Results

Habituation Period

Considering the temporal parameters of the habituation period, no significant effects were found for step duration, ground contact time, cadence, and stride speed (Table 6.1, p. 72).

For the spatial parameters, no significant effects were found for stride length and step length. Regarding step width, no main effect of volume was found. However, an interaction effect of volume×pitch was found (F(1,30) = 4.39, p = 0.045, f = 0.38). This effect can be explained by a decrease in step width for G1 (high pitch) and an increase in step width for G2 (low pitch) from loud to quiet (Figure 6.4). However, post hoc tests show no significant differences between the respective conditions.

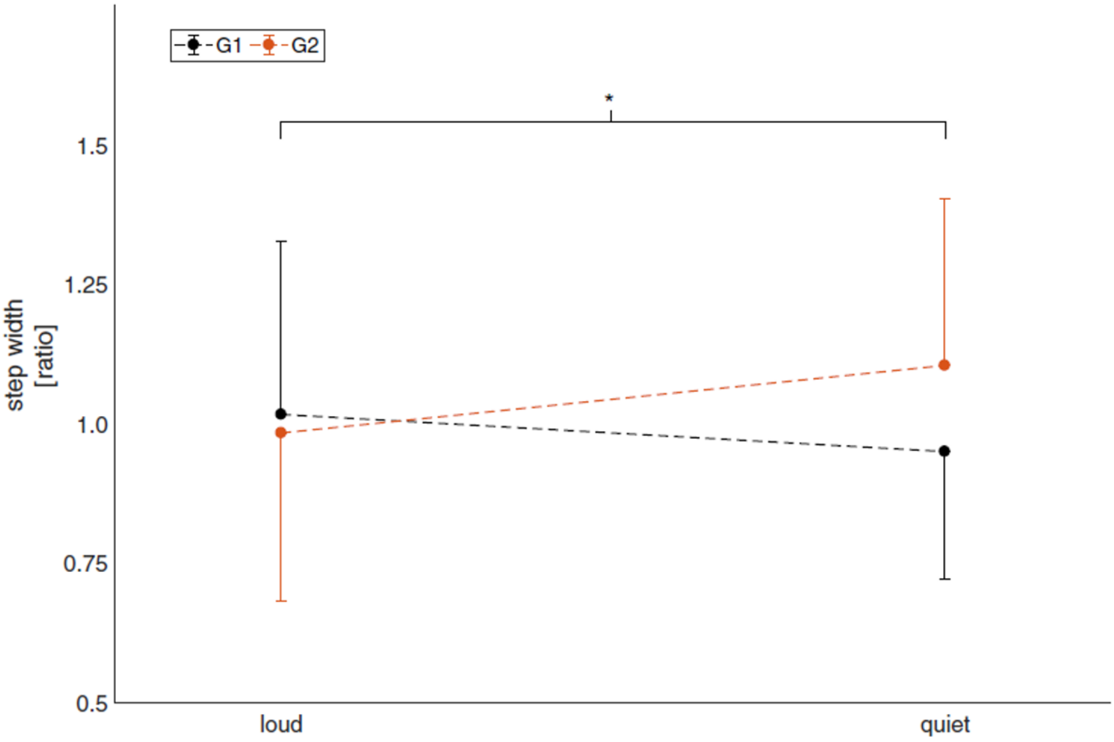

Figure 6.4: Values are mean ± SD. Step width of G1 and G2 at loud and quiet settings during the habituation period. Significant interactions are marked with *. Volume × pitch: p = 0.045, f = 0.38.

Asymmetry Period

In the asymmetry period, there were no main effects of volume or side on the temporal parameters stride duration, step duration, ground contact time, stride speed, and cadence (Table 6.2, p. 73). However, an interaction effect of volume×side (F(1,30) = 5.027, $p = 0.033$, $f = 0.41$) was found for ground contact time. Post hoc tests show a significantly higher ground contact time of the left leg of G1 ($p = 0.046$) for the LQ (1.004 ± 0.045) condition compared to RQ (0.978 ± 0.026). A similar trend can be seen for G2 (LQ: 1.004 ± 0.024, RQ: 0.997 ± 0.037), but here no significant difference can be found post hoc. The described effect is shown in Figure 6.5 (left).
For the spatial parameters stride length, step length, and step width, neither main nor interaction effects appeared in the asymmetry period.
Also, no significant main and interaction effects could be found for gait direction. Purely descriptively, however, a tendency of the study participants to walk in the direction to which the louder ground contact sound was heard can be detected (Figure 6.5, right).

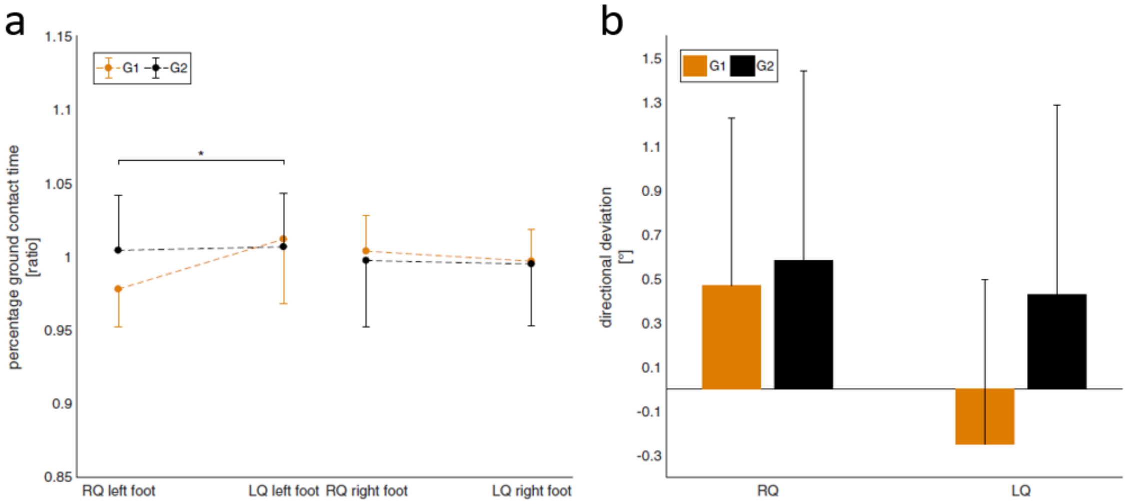

Figure 6.5: **(a)** Values are mean ± SD. Ground contact time of G1 and G2 at right quiet (RQ) and left quiet (LQ) settings during the asymmetry period. Significant interactions are marked with *. Volume × side: $p = 0.033, f = 0.41$, post hoc left leg RQ - LQ: $p = 0.046$.
(b) Values are mean + SE. Directional deviation of G1 and G2 at right quiet (RQ) and left quiet (LQ) settings during the asymmetry period. A positive value is defined as deviation to the left, a negative value as deviation to the right. No significant differences could be found: side: $p = 0.245, f = 0.217$, pitch × side: $p = 0.455, f = 0.139$.

Assessment of Mental State

There was a significant decrease in the Bf-SR score (pre: 12.44 ± 7.28, post: 11.19 ± 7.29) from before measurements to after measurements ($p = 0.045$) indicating an improvement in mental state.

Table 6.1: Results of the habituation period.

	loud		quiet		v	s	v×p	s×p	s×v	v×p×s
	left	right	left	right	*p*	*p*	*p*	*p*	*p*	*p*
Stride length										
G1	1.005 ± 0.035		1.013 ± 0.045		0.919	–	0.226	–	–	–
G2	0.996 ± 0.027		0.989 ± 0.040							
Step length										
G1	0.996 ± 0.049	1.006 ± 0.049	1.017 ± 0.074	1.007 ± 0.050	0.965	0.512	0.148	0.533	0.351	0.320
G2	0.991 ± 0.033	1.003 ± 0.043	0.980 ± 0.055	0.993 ± 0.052						
Step width										
G1	1.02 ± 0.310		0.98 ± 0.301		0.184	–	0.044*	–	–	–
G2	0.95 ± 0.229		1.11 ± 0.298							
Gait direction										
G1	-0.53° ± 3.60°		0.06° ± 3.29°		0.619	–	0.521	–	–	–
G2	0.36° ± 2.48°		0.30° ± 2.28°							
Stride duration										
G1	1.001 ± 0.050		1.001 ± 0.053		0.989	–	0.974	–	–	–
G2	1.999 ± 0.036		0.999 ± 0.039							
Step duration										
G1	0.992 ± 0.057	1.014 ± 0.052	1.001 ± 0.056	1.005 ± 0.048	0.572	0.880	0.596	0.269	0.535	0.660
G2	1.007 ± 0.041	0.991 ± 0.042	1.013 ± 0.039	0.994 ± 0.050						
Ground contact time										
G1	1.015 ± 0.053	0.999 ± 0.042	1.008 ± 0.039	1.005 ± 0.041	0.822	0.847	0.752	0.410	0.334	0.605
G2	0.992 ± 0.035	0.996 ± 0.032	0.994 ± 0.054	1.002 ± 0.032						
Gait speed										
G1	1.009 ± 0.082		1.018 ± 0.091		0.957	–	0.438	–	–	–
G2	0.996 ± 0.048		0.989 ± 0.066							
Cadence										
G1	1.006 ± 0.090		0.992 ± 0.085		0.531	–	0.399	–	–	–
G2	1.003 ± 0.028		1.005 ± 0.035							

Values are mean ± SD. Gait direction is the difference of loud and quiet to the normal setting. All other parameters are loud and quiet relative to the normal setting. The *p*-values of the statistical analysis (ANOVA) are given in the right table section. The factors volume (v), side (s), the interaction volume×pitch (v×p), side×pitch (s×p), side×volume (s×v), and volume×pitch×side (v×p×s) were analyzed. The level of significance was set at α = 0.05. Significant differences are marked with a *.

Table 6.2: Results of the asymmetry period.

	RQ		LQ		v	s	v×p	s×p	s×v	v×p×s
	left	right	left	right	*p*	*p*	*p*	*p*	*p*	*p*
Stride length										
G1	1.000 ± 0.022		0.996 ± 0.026		0.768	–	0.883	–	–	–
G2	1.003 ± 0.019		1.002 ± 0.019							
Step length										
G1	1.002 ± 0.035	0.997 ± 0.033	0.992 ± 0.033	1.002 ± 0.041	0.970	0.226	0.435	0.287	0.806	0.178
G2	0.988 ± 0.047	1.016 ± 0.044	0.997 ± 0.037	1.016 ± 0.042						
Step width										
G1	1.048 ± 0.311		1.027 ± 0.281		0.314	–	0.641	–	–	–
G2	1.026 ± 0.350		0.963 ± 0.225							
Gait direction										
G1	0.47° ± 3.61°		-0.25° ± 3.44°		0.245	–	0.455	–	–	–
G2	0.58° ± 2.08°		0.43° ± 1.52°							
Stride duration										
G1	1.001 ± 0.020		1.002 ± 0.022		0.594	–	0.983	–	–	–
G2	1.002 ± 0.015		1.004 ± 0.013							
Step duration										
G1	1.008 ± 0.049	0.974 ± 0.064	0.990 ± 0.041	0.993 ± 0.050	0.400	0.930	0.357	0.239	0.318	0.286
G2	0.998 ± 0.038	1.014 ± 0.065	0.993 ± 0.025	1.006 ± 0.033						
Ground contact time										
G1	0.978 ± 0.026	1.012 ± 0.044	1.004 ± 0.045	1.007 ± 0.042	0.098	0.541	0.373	0.206	0.033*	0.084
G2	0.997 ± 0.037	0.995 ± 0.036	1.004 ± 0.024	0.997 ± 0.022						
Gait speed										
G1	0.993 ± 0.029		0.992 ± 0.038		0.617	–	0.747	–	–	–
G2	1.004 ± 0.034		0.999 ± 0.028							
Cadence										
G1	1.003 ± 0.049		1.005 ± 0.073		0.968	–	0.748	–	–	–
G2	1.002 ± 0.021		1.000 ± 0.013							

Values are mean ± SD. Gait direction is the difference of right quiet (RQ) and left quiet (LQ) to the baseline setting. All other parameters are RQ and LQ relative to the baseline setting. The *p*-values of the statistical analysis (ANOVA) are given in the right table section. The factors volume (v), side (s), the interaction volume×pitch (v×p), side×pitch (s×p), side×volume (s×v), and volume×pitch×side (v×p×s) were analyzed. The level of significance was set at $\alpha = 0.05$. Significant differences are marked with a *.

6.4 Discussion

The present study intended to investigate the influence of the volume of real-time gait sonification on the gait pattern and gait direction of healthy young persons. The results show that an asymmetric volume of ground contact sonification directly influences the ground contac time unilaterally, which results in a temporal gait asymmetry. It can be seen that the ground contact time of the quiet foot is increased. However, no effects of the asymmetrical volume on spatial parameters of the gait, such as step length, and walking direction when walking blindfolded were found. Considering the overall volume during the habituation phase an effect on the step width was revealed, which seems to interact with the pitch of the gait sonification: for G1 (high pitch) a positive relationship between volume and step width, but for G2 (low pitch) a negative relationship becomes apparent. In addition, the Bf-SR survey showed that the mental state of the study participants improved from the beginning to the end of the measurements. It is clear that this development is not due to the sound of the sonification, as no differences between the groups can be detected in this development. Presumably, the improvement in mood is rather due to the task itself or to its accomplishment.

Previous studies on volume indicated an influence of this parameter on spatio-temporal perception (Grassi et al., 2013; Blauert, 1996; Grassi, 2005; Lipscomb & Kim, 2004; Eitan et al., 2008; Eitan, 2013) and, to a limited extent, on human kinematics (Darling & Huber, 2011). However, we are currently not aware of any studies investigating the influence of volume in gait sonification. In order to make a first step towards a better general understanding of the influence of volume on the effectiveness of MS, explorative hypotheses were tested.

In a first consideration of the results, it seems surprising that volume modification in the asymmetry period did not affect spatial parameters, although volume is predominantly associated with spatial distances, directions, and velocities (Eitan et al., 2008; Eitan, 2013; Küssner et al., 2014). The reason why the volume affected the gait pattern of the participants only in the habituation period might be due to a high degree of automation of the gait, which prevented an adjustment to a possibly less economical gait pattern. Also, the unilateral modification of the auditory stimulus in the asymmetry period might have been too small to affect spatial parameters and/or might have been overlaid by proprioceptive, tactile, and vestibular afferences.

We tried to make the volume difference between the two sides as large as possible but still not noticeable to avoid participants' intentional motion adaptation. Only three of the 32 participants reported having detected a volume difference after the measurements. Several questions follow in this regard. First, whether knowledge of or recognition of asymmetric volume interferes with (unconscious) motor adaptation. And, if this is the case, to what extent verbal instruction (e.g., "Do not consciously adjust your movement to the sonification.") could counteract this. Second, the question of optimal volume difference arises. It is possible that, similar to reaction time tasks where lower reaction times are associated with louder acoustic stimuli, ground contact time is influenced by the magnitude of the volume resp. loudness difference (Brown et al., 2008; Marshall & Brandt, 1980; Sors et al., 2018). If increasing ground contact time asymmetries could be reliably determined with increasing volume differences, the use of gait sonification in rehabilitation could be optimized.

However, it should be noted in this context that elderly patients in particular, who could benefit from gait sonification e.g. after stroke, Parkinson's disease, or arthroplasty, often suffer from hearing loss. If this hearing loss is more pronounced on one side, the volume difference must be adjusted accordingly or even overcompensated to compensate for habituation effects. Finally, based on the results presented here, it can be assumed that the gait pattern of patients with unilateral hearing loss might suffer from the hearing impairment. Although no studies are currently known on laterality, preliminary evidence suggests that hearing impairment leads to increased risk of falls in the elderly (Criter & Gustavson, 2020; Xu et al., 2021). Again, the use of gait sonification with volume settings adapted to the user could potentially counteract deterioration of gait due to hearing impairment.

With regard to the impact of volume on step width, which occurs contrarily for the two different pitches, the influence of pitch on movement and a possible interaction between pitch and volume should also be considered. In an early work by Wood (1973) it became evident that in human perception there is an interaction between pitch and volume that can affect movement reactions. In the experiment, reaction times were measured after hearing a simple syllable that varied in pitch and volume. One-dimensional changes in pitch and volume showed shorter reaction times than orthogonal-dimensional changes in pitch and volume. Similar psychophysical correlations between pitch and volume could also be found for non-speech-related sounds (Neuhoff et al., 2000; Neuhoff et al., 2002). This interdependency of pitch and volume might be an explanation for the divergent step width change at low vs. high pitch and increased volume.

Gomez-Andres et al. (2020) also showed that the overall pitch of acoustic gait feedback influences the gait symmetry of stroke patients. Here, a high pitch of amplified footsteps sounds increased the asymmetry of the patients' ground contact times, while a low pitch reduced the asymmetry. Although a different method of sound generation respectively amplification and other participants were chosen in Gomez-Andres et al. (2020), the current results show similarities regarding the effect of different pitches on gait symmetry.

Furthermore, in the present study, the results of the asymmetry period show a clear effect on the temporal parameter ground contact time. Since only the ground contact time was presented acoustically, it can be assumed that the sound-motion relationship was clearly recognizable to the participants and that sonification had a direct influence on gait pattern. The mechanism underlying this influence of gait sonification has been investigated and discussed in previous studies. It is hypothesized that the mapping of sound to movement leads to audio-motor coactivation in the CNS. This coactivation occurs because the acoustic stimuli are directly generated by the user's movement, probably unconsciously (Bangert et al., 2006; Effenberg et al., 2016; Bangert & Altenmüller, 2003). Due to this close audio-motor coupling, it is possible that continuous sensorimotor adaptation takes place and, as explained by the forward model, movement adaptation occurs (Gomez-Andres et al., 2020). Regarding the observed effect on ground contact time, it should additionally be considered that the human auditory system perceives rhythmic information and temporal structures particularly clearly (Barton et al., 2012; Boemio et al., 2005; Giraud et al., 2000), which might have led to a stronger effect on motor timing compared to range and direction of motion. Thus, the temporal increase in ground contact time might have been favored with reduced volume.

In the present study, it can also be assumed that a comparison of the actually perceived sensory information (afferent input) with the expected sensory information (efference copy) led to a discrepancy. An attempt was made to compensate for this by changing the ground contact time. Since the participants were not informed about the volume modification, it can be assumed that the processes described were mainly unconscious. The forward model could therefore explain the observed effects in the case of a repetitive and automated movement such as the human gait. Especially since in the present study visual information was reduced during walking and subjects relied heavily on sonification as auditory information to maintain automated processes (Clark, 2015).

It must be regarded as a limitation of this study that it cannot be assessed whether the ground contact time was a result of altered ground reaction forces due to the lack of force/pressure measurement. Possibly a stronger heel strike or a more intensive push off led to an extension of the ground contact time during the quiet sound condition. The participants (unconsciously) could have tried to produce a louder sound by applying more force. An additional use of force or pressure plates should clarify this question in the future. Furthermore, it might be useful to replicate the results using a larger sample. This could also clarify whether there might be a statistically significant effect of volume on gait direction when walking blindfolded.

6.5 Conclusions

The present study showed that the volume of gait sonification has directly affected the gait pattern of healthy young persons. At asymmetrical volume, a unilateral increase in ground contact time was observed on the side with reduced volume. Also, an interaction of pitch and volume was observed mainly with an overall change in volume. This could be explained in terms of psychophysical perception, which should be considered when using volume for gait sonification. We thus provide first clues for an appropriate sound-motion mapping and a targeted use of volume. Based on the present results, we would recommend for gait sonification that temporally asymmetric parameters be presented directly acoustically on both sides and that the side on which the movement is performed in a shortened manner be presented more quietly than the other. In this way, the user would respond by amplifying the movement, i.e., increasing its duration, which would improve temporal movement symmetry. A lasting effect of volume modification must be investigated in future intervention studies. In this context different patient groups should be considered. The available findings can be helpful to improve the effect of gait sonification in patients with asymmetrical gait pattern and thus to return to a physiological gait more quickly and easily.

7

General Discussion

In the following, the results of the publications are briefly summarized. Then, the studies are classified according to the current state of science (cf. sections 2.1 - 2.3), considering the limitations of the studies. Table 7.1 provides a supplementary overview of the different studies.

Table 7.1: Overview of the three different studies.

	Study 1	**Study 2**	**Study 3**
Study design	Intervention: 20 minutes, 10 gait training sessions (TSs)	Intervention: 20 minutes, 10 gait TSs	Cross-sectional
Measuring system	MVN Awinda (XSens Technologies B.V., Enschede, the Netherlands)	MVN Awinda (XSens Technologies B.V., Enschede, the Netherlands)	MVN Awinda (XSens Technologies B.V., Enschede, the Netherlands)
Reported results	Gait analysis during real-time feedback (RTF) and during instructing model sequences (IMS)	Gait analysis and clinical measurements at four measurement time points	Gait analysis under loud, quiet, and normal as well as right quiet, left quiet and baseline conditions
Study participants	20 patients after unilateral THA (10 sonification group (SG), 10 control group (CG))	22 patients after unilateral THA (11 SG, 11 CG)	32 healthy participants (16 higher frequency, 16 lower frequency)
Sound	Sonification of ground contact and knee extension speed	Sonification of ground contact and knee extension speed	Sonification of ground contact, modification of volume conditions

7.1 Conclusion of the Research Findings

Study 1: *Dual Mode Gait Sonification for Rehabilitation After Unilateral Hip Arthroplasty*
In this study, the immediate impact of dual mode gait sonification on the gait pattern of orthopedic patients was assessed. For this purpose, 20 unilateral THA patients were divided into a SG (n = 10) and a CG (n = 10). The intervention for both groups consisted of ten gait TSs of twenty minutes each. Only the SG received dual mode acoustic feedback, while kinematic gait data were captured equally for both groups. Total data from week 1 (TSs 1-5) were compared to the data from week 2 (TSs 6-10).

The following hypotheses were examined: (1) "[T]he dual mode acoustic feedback method improves the patients' gait symmetry over two weeks compared to a control group without acoustic feedback" (Reh et al., 2019). (2) "[T]he effects on the gait pattern depend on the type of acoustic information (RTF, IMS)" (Reh et al., 2019).

Considering hypothesis 1, there was an effect on the step length symmetry, which differentially developed in the CG and the SG. An improvement in step length symmetry of the SG on a descriptive level was observed, as the step length of the affected leg decreased from week 1 to week 2 (week 1: 0.58 m ± 0.04 m; week 2: 0.56 m ± 0.07 m), while it increased for the unaffected leg (week 1: 0.53 m ± 0.06 m; week 2: 0.56 m ± 0.06 m). Though, a high step length symmetry was shown for the CG from week 1 onwards. In contrast to the SG, an increase in step length of both legs was found (affected leg week 1: 0.54 m ± 0.06 m; week 2: 0.56 m ± 0.06 m; unaffected leg week 1: 0.53 m ± 0.04 m; week 2: 0.55 m ± 0.042 m). Overall, an improvement in gait was observed in both groups.

Considering hypothesis 2, there was greater variability in stride length in the RTF condition compared to the IMS condition, which increased from week 1 to week 2.

In this regard, it can be added here that the COV of stride length recorded under the 20 min training conditions was higher under both IMS and RTF conditions than under the test conditions presented in study 2. COV of stride length for training condition (study 1) (n = 10): week 1, RTF: 11.81% ± 8.81%; week 2, RTF: 17.26% ± 7.75%; week 1, IMS: 10.69% ± 6.84%; week 2, IMS: 11.86% ± 4.81%; COV of stride length for test condition (study 2) (n = 9): pre-test: 4.8% ± 2.6%; intermediate test: 5.1% ± 4.4%; post-test: 3.5% ± 1.7; re-test: 5.3% ± 3.8%. This clear difference is presumably due to the lower constraints during the TSs, contrary to a predefined, straight path during the test measurements.

Study 2: *Acoustic Feedback in Gait Rehabilitation — Pre-Post Effects in Patients With Unilateral Hip Arthroplasty*
In contrast to study 1, this study reported and evaluated the results of clinical tests and gait analysis at four measurement time points that were part of the investigation de-

scribed in study 1. Measurements were conducted before the first TS (pre-test), after the fifth TS (intermediate test), after the tenth TS (post-test), and two days after the post-test (re-test). The two groups, SG and CG, consisted of the same patients as in study 1, although, two additional patients had been included in each group, who were excluded from study 1 due to missing data (CG: *n* = 11, SG: *n* = 11). The following objective was addressed: "[T]o provide more detailed information on the effectiveness of gait sonification beyond the direct use", particularly with regard to gait symmetry and "to determine whether a possible effect on the gait pattern can still be observed 2 days after the end of the intervention (re-test)." (Reh et al., 2021). Indications for an impact of gait sonification on step length symmetry could be found, with improved step length symmetry in the post-test compared to the pre-test in the SG. Additionally, differences in hip joint RoM were evident between the two groups. In particular, an increase in RoM in the affected leg was observed in CG, but not in SG.

It is remarkable that the step length of the affected leg of the SG decreased from post-test to re-test but increased in the CG. A similar effect was observed for the RoM in the hip joint of the unaffected leg, which decreased from post-test to re-test in the SG but increased in the CG.

This indicates that the intervention did not result in a sustained effect. Furthermore, in relation to study 1, it should be noted that no differences in gait variability were observed between the two groups in the test results examined.

Study 3: *Loudness Affects Motion: Asymmetric Volume of Auditory Feedback Results in Asymmetric Gait in Healthy Young Adults*

In this study the influence of the parameter loudness during the use of gait sonification on the gait pattern of healthy study participants was investigated. Thirty-two persons participated in the one-time gait analysis (cross-sectional study design). The task was to walk blindfolded several times under different sonification conditions towards a previously visually perceived target. The sonification conditions differed with respect to loudness (resp. volume). Thus, a quiet, normal, and loud sonification was used in a habituation phase and a left quiet, right quiet, and equally loud (baseline) sonification was used in the asymmetry phase.

The study participants were divided into two groups, with group 1 (G1) receiving higher frequency sonification and group 2 (G2) receiving lower frequency sonification. The objective was to "investigate the influence of different volume and its interaction with pitch of real-time sonification of the ground contact on the gait pattern of healthy persons" (Reh et al., 2022).

An impact of the asymmetric volume on the duration of the ground contact time was shown for G1. Thus, a left-sided quiet sonification led to an increased ground contact time of the left foot and a right-sided quiet sonification led to an increased ground contact time of the right foot. In addition, an interaction effect of volume and frequency was evident in the habituation period, as greater step width was observed for G1 under the loud sonification condition and lower step width under the quiet sonification condition, while a reverse effect was observed for G2.

7.2 Classification of the Studies

Overall, the studies gathered in this work show that kinematic gait sonification which is based only on inertial sensor technology could be developed (cf. chapter 1, **(Q3)**) and used to modify the gait pattern of orthopedic patients and healthy individuals. Study 1 confirmed the feasibility of using gait sonification in a clinical setting **(Q4)**. Furthermore, effects on kinematic parameters such as step length, gait variability, and hip joint RoM were found in study 1 and 2 **(Q1)**.

Against the background that the effect of acoustic feedback and sonification on gait is not yet well understood, the observed results of the studies suggest the great potential of gait sonification for orthopedic rehabilitation. This raises the question of how the sonification method can be optimized and further developed to meet the needs of different patient groups.

A first indication in this regard was provided by study 3, which identified loudness as an acoustic parameter that affects temporal symmetries in gait, in concrete ground contact time **(Q2)**.

To identify further determinants, additional investigations will be needed to analyze the interaction of different sound parameters, their direct impact on gait, and different sound mapping strategies. The factors arising from this work that are relevant to the above aspects are explained in more detail below.

7.3 Development of an Action-Sound Mapping for Orthopedic Gait Rehabilitation

For movement sonification, the sound quality has a special relevance in two respects. First, the sound used should have a high informative content by varying in loudness, frequency, timbre, but also in its temporal structure. Second, a link to the movement should be as intuitive as possible. If the movement-sound mapping succeeds accordingly, it is assumed that the sonification can exert an unconscious effect on the movement (Effenberg, 2005; Dyer et al., 2017a).

In the studies discussed here, gait sonification was implemented by mapping ground contact and, in studies 1 and 2, additionally the angular speed of the knee extension to sound. This is a crucial difference to the study by Pietschmann et al. (2019), in which patients after THA were asked to actively align the hip joint angles of both legs using sonification. However, since the movement of the hip joint during natural gait hardly produces any sounds and therefore a link between action and sound seems counterintuitive, a different approach was chosen in the three studies in this thesis: The contact of the feet with the ground was sonified, as sounds usually occur here in everyday life and thus an action-sound coupling can be assumed. In addition, the angular speed of the knee extension was sonified. Also, knee extension does not commonly make any noise in everyday life. But in study 1 and 2 it was the aim to generate additional information on the speed of movement of the individual legs to enable a direct comparison. The focus was not to be on the affected hip joint, but on the basic execution of the gait movement. In this context, the underlying hypothesis was that multisensory integration contributes to relearning of the gait pattern (Effenberg, 2005), so that a conscious comparison of the hip joint movement is not necessary. The effect on the patients' gait pattern observed in study 2, which lasted at least for a short time, suggests a better efficacy of the distal approach compared to the Pietschmann et al. (2019) study, even though a targeted effect has not yet been achieved. However, based on the results of study 3, in which only the ground contact of both feet was sonified, the question arises whether further sound beyond the ground contact is helpful or rather disturbing.

To determine which sound design is most effective for patients after unilateral THA, the different approaches should be directly compared. In particular, a comparison of the distal approach (sonification of the ground contacts) with the sonification of the hip joint could help to clarify underlying principles. In addition, the effects observed in the third study on the gait pattern of healthy persons suggest that the use of asymmetric loudness of sonification can affect the symmetry of gait more targeted than has been achieved so far. It therefore seems necessary to investigate the effect of asymmetric loudness on the gait pattern of unilateral THA patients.

7.4 Enhancing Gait Feedback Research by Biomechanical and Neurophysiological Advancements

Human gait has been scientifically studied for a long time. In this context, osteoarthritis and subsequent joint replacement at knee or hip are also frequently the focus of investigations. For example, THA is known to have a positive impact on the patients' mobility and quality of life (Zhai et al., 2019). Nevertheless, gait pattern of THA patients often does not reach that of healthy persons even after one year (Bahl et al., 2018). It was even possible to determine reliable spatio-temporal parameters that are characteristic for gait pattern deviations due to hip osteoarthritis and THA. However, detailed kinematic analysis (Ismailidis et al., 2021; Porta et al., 2021), which allows assessment of intra- and intersegmental coordination, is relatively new. These new capabilities can, in all possibility, contribute greatly to making gait sonification more appropriate and effective for this patient group. It can also help to better track and manage gait improvements and rehabilitation trajectories. For example, Porta et al. (2021) reported a shift in stance phase durations and reduced plantar flexion at terminal stance in the ankle joint of the affected side in patients with hip osteoarthritis. Future research should investigate whether and for how long similar kinematics can also be observed with the use of an inertial sensor system in patients with THA. Gait sonification with asymmetric volume of ground contacts could then be used specifically for a relevant period of time to improve gait pattern. However, if similar kinematics are not evident in THA patients, the effect of asymmetric loudness of gait sonification should be investigated in patients with hip osteoarthritis prior to hip replacement.

It should also be noted that inertial sensor technology is predominantly used for feedback systems that have real-time capability. This technique is becoming more and more precise and user-friendly, so that the development of reliable and universally applicable algorithms is to be recommended to improve and facilitate biomechanical gait analysis. A first approach to this is provided in particular by study 2.

On the neurophysiological level, it should be considered that on one hand gait is a rhythmic movement (Hogan & Sternad, 2007; Wiegel et al., 2020), and on the other, that gait movement is highly automated (Clark, 2015; Bayot et al., 2018): Since temporal structures in particular can be perceived auditorily with high accuracy (Repp & Penel, 2002; Merchant et al., 2008) and a close neurophysiological link between auditory-temporal and motor regions in the brain is assumed (Chen et al., 2008; Morillon & Baillet, 2017; Cannon & Patel, 2021), it is likely that auditory feedback is superior to feedback of other sensory modalities for a rhythmic movement such as gait. However, the question arises to what extent external sensory stimuli are integrated and relevant for movement execution due to the high degree of automation of gait. If, for instance, a conscious adaptation of gait to sound parameters, e.g., rhythmic cues, is intended, it can be assumed that executive processes interfere with gait control. This may result in dual-task (Clark, 2015) or guidance effects (Dyer et al., 2017a), potentially reducing a sustained positive effect on gait. These factors should be considered when instructing study participants or patients.

In study 1, increased gait variability was observed during RTF compared to IMS. The patients were not instructed to align their gait tempo with the IMS. That increased gait variability did not occur under this condition is consistent with observations from other studies (Nowakowska-Lipiec et al., 2021). The cause of the increased gait variability during RTF, whether it is dual-task cost or a relearning process which is occurring, could not be clarified in the context of this study. Yet, the increase in variability from the first to the second week suggests that this reflects a conscious or unconscious attempt to change the gait pattern.

Based on this assumption, it must be challenged whether orthopedic patients benefit from additional IMS or whether pure real-time sonification is more effective. To investigate this, fMRI studies could be beneficial. For example, orthopedic patients could receive either RTF (group 1) or IMS (group 2) during regular gait training. Before and after training intervention, activity in the premotor cortex could be determined while listening to the auditory feedback to identify action-perception couplings that might have emerged (see also section 2.1.1, de Manzano et al., 2020). Also, fMRI could be used to measure an attenuation of activity in primary auditory cortex and an increase of activity in motor areas under the condition described above. This would suggest the emergence of a predictive sound model, suggesting increased relevance of sound to movement (see also section 2.1.2, Heins et al., 2020).

7.5 Limitations

This thesis highlights the applicability of gait sonification in orthopedic gait rehabilitation, provides preliminary evidence for an effect on the gait pattern of THA patients, and the potential of using asymmetric loudness to enhance targeting of the method. However, the experimental investigation of different action-sound mappings and movement tasks is beyond the scope of this thesis. Furthermore, only the effect of sonification on the movement pattern and not on body perception or neurophysiology was considered.

With respect to the individual studies, it should be emphasized for studies 1 and 2 that the intervention duration was short, with ten 20-minute TSs, and possibly for this reason no lasting effect occurred. In addition, the timing of the intervention probably affected the impact of gait sonification and the validity of the results, as the patients were still dependent on walking aids and had musculoskeletal limitations and pain.

Furthermore, in all three studies, the fact that no measurements of musculoskeletal and biomechanical gait parameters and a correspondingly balanced distribution of participants among the subgroups were performed before the start of the study, can be considered a limitation.

8

Conclusion

In the present thesis, three studies were presented which provide evidence for gait pattern adjustment using gait sonification in patients after unilateral THA and in healthy individuals. It was shown that gait sonification is applicable in clinical settings and is accepted by patients. The following three points are to be highlighted as key results:
(1) A distal mapping from movement to sound, as described in this thesis, seems to be more effective than a proximal mapping. **(2)** Modification of loudness of the feet's ground contacts can particularly affect the symmetry of the ground contact time in walking. **(3)** Increased gait variability with pure real-time feedback suggests that real-time feedback is more likely to trigger gait adaptation in THA patients than instructive feedback sequences.
The systematic investigation of underlying mechanisms of the above three key results represents a crucial component contributing to a more targeted impact of sonification on the gait pattern of THA patients in the future. Consequently, the results will facilitate the development of an efficient gait sonification method and thus improve orthopedic gait rehabilitation.
As a central prospective aim, the development of user-friendly systems for the application of gait sonification in home training via mobile phone or tablet seems to be of special importance. In this regard, the gait sonification method presented here is particularly suitable, as it does not require a treadmill, which increases its applicability and usability in everyday life. Thus, the method could be used beyond location-based rehabilitation in the long term to achieve increased and more sustained effectiveness.

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Curriculum Vitae

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04/2019 to 03/2020	Practical Class: Assistance and Safety in Sports
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04/2017 to 03/2019	Seminar: Introduction to Sports Science Research Methods
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Published Work

Publications Included:

Reh, J., Schmitz, G., Hwang, T.-H., & Effenberg, A. O. (2022). Loudness affects motion: Asymmetric volume of auditory feedback results in asymmetric gait in healthy young adults. *BMC Musculoskeletal Disorders*

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Further Publications:

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