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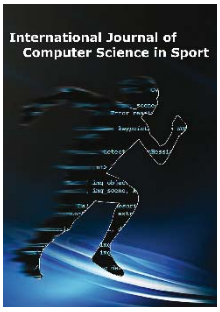

Gait Training In Orthopedic Rehabilitation After Joint Replacement - Back To Normal Gait With Sonification?

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Abstract

Even several years after total hip (THR) and total knee replacement (TKR) surgery patients frequently show deficient gait patterns leading to overloads and relieving postures on the contralateral side or in the spine. Gait training is, in these cases, an essential part of rehabilitation. The aim of this study was to compare different feedback methods during gait training after THR and TKR focusing, in particular, on auditory feedback via sonification. A total of 240 patients after THR and TKR were tested in a pre-post-test design during a 3-week rehabilitation period. Even though sonification did not show, statistically, a clear advantage over other feedback methods, it was well accepted by the patients and seemed to significantly change gait pattern during training. A sudden absence of sonification during training led to a rapid relapse into previous movement patterns, which highlights its effectiveness in breaking highly automated gait patterns. A frequent use of sonification during and after rehabilitation could, hence, reduce overloading after THR and TKR. This may soon be viable, since new technologies, such as inertial measurement units, allow for wearable joint angle measurement devices. Back to normal gait with sonification seems possible.

KEYWORDS: SONIFICATION, GAIT TRAINING, SEQUELAE, AUTOMATISMS, RELEARNING

INTRODUCTION

Orthopedic rehabilitation after endoprosthetic joint replacement is an important part of modern medical care. In Germany, about 235,000 total hip replacements (THR) and 175,000 total knee replacements (TKR) were performed in 2017 (Bleß & Kip, 2017; Beeres, 2018). In 2002, 381,000 primary TKR surgeries were carried out alone in the United States (Milner, 2009). In the USA, in 2010 there was a prevalence of 2.55 million THR and 4.7 million TKR (Kremers et al., 2015).

Main reason for THR or TKR is joint degeneration due to e.g. old age, overweight, malposition or injury. Main goals after joint replacement include restoring mobility, improving joint mobility and functional range of motion, as well as increasing strength and reducing pain (Schönle, 2004; Bochdansky, Laube, & Böckelberger, 2008; Jöllenbeck & Schönle, 2012). Recovery of gait function is one of the primary goals for patients, surgeons and physical therapists after THR and TKR (Casartelli, Item-Glatthorn, Bizzini, Leunig, & Maffiulett, 2013). A typical goal of rehabilitation after TKR is also to achieve at least 90 degrees of knee flexion (Milner, 2009).

THR surgery provides pain reduction for patients (Okoro, Lemmey, Maddison, & Andrew, 2012). After TKR surgery, patients can achieve improvements in all areas, pain, symptoms, function in ADL and function in sport and recreation (Naili et al., 2017). Improvements are shown post-operatively, and apparently a clinically unremarkable gait pattern seems to be present. However, literature shows that even several years after THR and TKR there are still significant deficits on the operated side. *Main deficits after THR include*: incomplete restore of physical function (Okoro et al., 2012); more atypical gait cycles in patients than in controls (Agostini et al., 2014); strength deficits and dynamic joint stiffness on the operated side (Agostini et al., 2014); pre- and post-op differences not only in the hip but also in the knee kinematics (Horstmann, Listringhaus, Haase, Grau, & Mündermann, 2013); significant ipsilateral quadriceps muscle atrophy up to 5 month post-op (Reardon, Galea, Dennett, Choong, & Byrne, 2001); pre-op atrophy of muscles acting about the arthritic hip continues for the first two years after THR (Rasch, Byström, Dalén, Martinez-Carranza, & Berg, 2009); *Main deficits after TKR include:* reduced or missing flexion-extension-movement (Jöllenbeck & Schönle, 2012) and reduced peak knee flexion during weight acceptance and less knee flexion excursion than in healthy controls of a similar age (Milner, 2009); presurgery gait patterns were retained up to 18 months after surgery (Milner, 2009); 6 years post-op, a disproportion of the extensor to the flexor force referring to the disadvantage of the flexors could be proven (Handel et al., 2005).

In order to avoid pain in walking, patients have developed individual compensation strategies pre-op over a period of several years. These are expressed in gait patterns characterized by clearly evasive movements, which are so highly automated that they still endure post-op. Possible consequences of these pre-op acquired compensation strategies include distinct side asymmetries in gait parameters (Jöllenbeck & Schönle, 2012; Jöllenbeck, 2015), increased wear of the endoprosthesis as well as the bilateral kinematic chain and damage to the spinal column (Jöllenbeck, 2015). Therefore, the restoration of a physiologically normal gait should play a key role in rehabilitation (Jöllenbeck & Schönle, 2012; Jöllenbeck, 2015). Currently, however, only weekly gait training takes place during rehabilitation. This is completely insufficient to break up existing automatisms and initiate new movement patterns. This task can only be solved with targeted and feedback-based gait training.

State of knowledge and strategy

Feedback training is mainly used in neurological rehabilitation. It is a useful tool for motor rehabilitation in Parkinsons´s disease (PD) (Kearney, Shellikeri, Martino, & Yunusova, 2018) and can be used as an effective rehabilitative strategy to improve gait and upright posture in people with PD (Baskaran, 2017). Individuals with deficits in the central nervous system (CNS) also benefit from treatment with feedback training (Aruin, Hanke, & Sharma, 2003).

In order to use feedback training in orthopedic rehabilitation, where not the CNS but skeletal and locomotor system are affected, it is important to consider the cause-effect mechanisms of the impaired gait in detail, identifying which of them need to be addressed in order to change the gait pattern permanently. In an earlier study the key parameters were identified, which need to be addressed after THR and TKR (Jöllenbeck & Schönle, 2012; Jöllenbeck, 2015).

A key target for intervention measures that aim at optimizing gait patters is the normalization of hip movement after THR and knee movement after TKR (Jöllenbeck et al., 2008; Jöllenbeck, 2015; Jöllenbeck & Schönle, 2012). After THR the entire flexion-extension movement in the hip joint must be addressed, taking into account the load-relevant phases. After TKR the deficient flexion-extension movement in the knee joint in the stance phase as the propulsion effective phase is primarily to be addressed, while the unloaded pre-swing phase characterized by clear knee flexion is of secondary importance (Jöllenbeck, Neuhaus, & Grebe, 2010; Jöllenbeck, 2015). However, restauration of normal gait requires a novel strategy oriented to the key parameters after THR and TKR.

Auditory feedback has been successfully used to train movements in sports, for example in rowing (Schaffert & Mattes, 2015). However, its potential as a means for physical therapy has yet to be explored. In particular, real-time sonification of measured data, though rarely tested, seems to be promising. In PD therapy (Gorgas et al., 2017), for instance, sonification of force data captured via insoles proved to be very effective. In this study, sonification of joint angles was tested as a method to control the deficient parameters of gait pattern in orthopedic rehabilitation. Two questions are addressed: 1) Can auditory feedback be used in rehabilitation after THR and TKR for relearning gait? 2) Are patients able to implement and understand the auditory feedback?

The basic framework design for this study was defined based on the findings of a pilot study on gait behavior during orthopedic rehabilitation after TKR (Jöllenbeck et al., 2008) (Fig. 2 following chapter). The project *back to normal gait* describes procedures with focus on the development of the gait behaviour of patients during the 3-week rehabilitation.

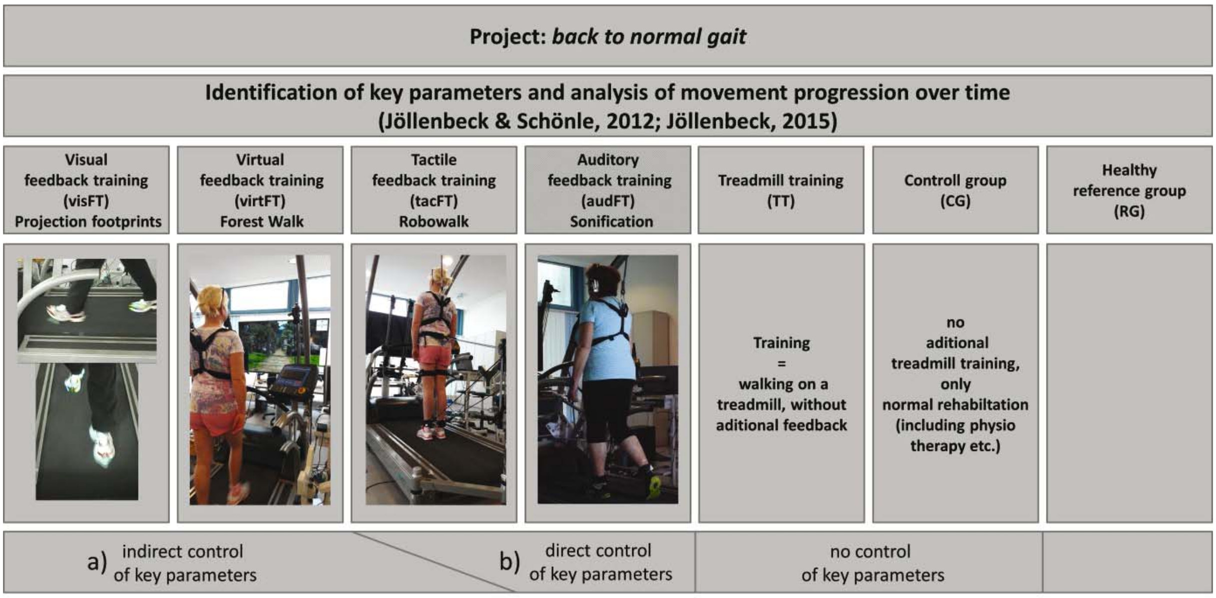

Fig. 1: Overview of the project *back to normal gait* including all groups and their control options

Two types of parameter control were tested and compared to each other (Fig. 1): (a) indirect control, where a change in the key parameters is targeted indirectly by adjusting the stride length, (b1) unspecific direct control, where joint motion during gait is directly influenced by pulling forces, and (b2) specific direct control, where a direct influence on the key parameters is attempted via sonification of the joint angles, played to the patient online. We hypothesized that training with sonification would be able to foster the reduction of asymmetries after joint replacement and, thus, an individually normal gait pattern could be learned more rapidly.

Methods

This was a randomized controlled clinical trial having one control and five training groups (Fig 1). 120 patients after THR (70 female, 50 male; 55.9 ± 6.8 years; 81.6 kg ± 15.4 kg; 173.9 ± 8.3 cm; BMI 26.9 ± 4.4) and 120 patients after TKR (81 female, 39 male; 58.2 ± 6.2 years; 89.1 kg ± 17.1 kg; 171.3 ± 9.9 cm; BMI 30.3 ± 5.1) were included in this study. Patients were recruited from the orthopedic rehabilitation center (Klinik Lindenplatz, Bad Sassendorf, Germany). Inclusion criteria were: receiving a THR or TKR; ability to walk on a treadmill without the use of walking aids; and ability to understand verbal and written information in German. Exclusion criteria were: another ipsi- or contralateral THR or TKR, any previous major orthopedic surgery in the lower limbs, any neurological disease, any other condition affecting walking ability, and an age older than 75 years. Additionally, an age-appropriate healthy reference group (RG) of 20 volunteers (10 female, 10 male; 55.9 ± 6.8 years; 70.0 kg ± 11.5 kg; 173.0 ± 6.9 cm; BMI 23.3 ± 2,8) without any orthopedic limitations was recorded. The RG was only collected for one measurement time. All patients and volunteers were between 45 - 75 years old.

All patients were measured at 14-day-interval at the beginning and end of their stay, taking into account the prescribed clinical procedures and length of stay. Pre-test was performed on day 3 or 4 and post-test on day 17 or 18 of rehabilitation. Interventions were scheduled as evenly as possible between pre- and post-test. The prescribed therapy plan of the patients was not to be impaired by the study participation. A patient and test person clarification as well as a questionnaire for anamnesis were obtained before pre-test. A positive ethics vote was given by the Medical Association of Westfalen-Lippe and the University of Münster.

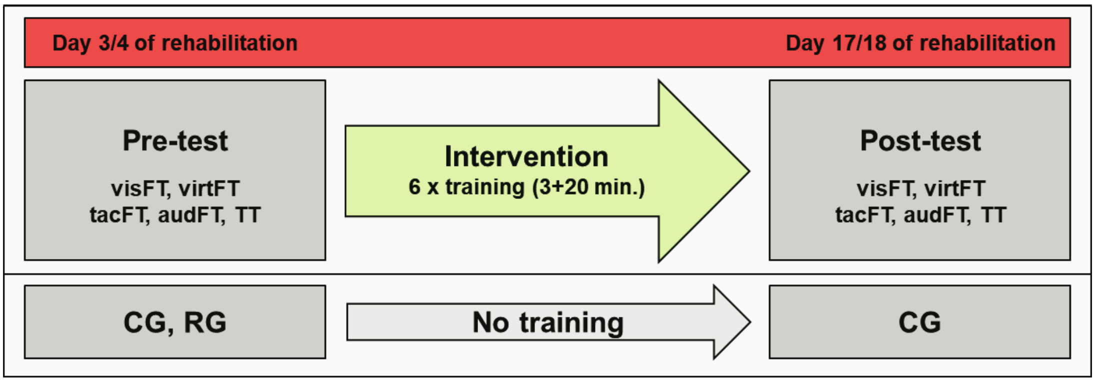

Fig. 2: Schematic study design: IGs - intervention groups, CG - control group, RG - reference group.

To determine kinetic and kinematic parameters of gait analysis at pre- and post-test, a set of instruments, consisting of a gait analysis measuring technique (©Zebris FDM; Zebris medical GmbH, Isny, Germany) integrated in the treadmill (©h/p/cosmos quasar med 4.0, h/p cosmos sports & medical GmbH, Nussdorf - Traunstein, Germany) including a pressure plate to record kinetic parameters (sensor area: 135,5 x 54,1cm; number of sensors: 10,240 ≙ 1,4 sensors/cm^2; sample rate = 120Hz), video recording (dorsal) and a 3D-ultrasound-motion-analysis-system

(©Zebris WinGait with CMS-HS, 100Hz) to record kinematic parameters with a total set of 15 active markers (bilateral fixation, 4 triple markers and one sacrum marker) was used.

Patients and volunteers were asked to walk on a treadmill with a self-selected walking velocity. After 3 minutes of getting used to the test conditions, they were asked to set first a comfortable walking pace and then a faster but confident walking pace. Within the 6 training units (intervention), patients should set a walking pace that can be kept up for 20 minutes. The measurements and interventions could be stopped at any time. The treadmill display was completely covered in order to guarantee an independent and stepless adjustment of speed. A visual analog scale was used at each appointment to document the general state of health and the sensation of pain. The results of the analyses were only communicated to the patients and volunteers after all measurements had been completed.

Visual feedback training (visFT)

During visual feedback training (©Zebris RehaWalk: projection footprints), a gait analysis was first used to determine the step lengths on both sides as well as the mean footprints. The shorter one was then adapted to the longer step lengths. In the feedback training that followed, the footprints were projected onto the treadmill using a projector with adjusted step lengths, i.e. the same on both sides. The patients were instructed to hit the footprints as accurately as possible.

Virtual feedback training (virtFT)

During the virtual feedback training (©Zebris RehaWalk: forest walk), the patients walked along a virtual two dimensional forest path that was displayed on a large monitor in front of the treadmill. The patients had to avoid or cross virtually arranged obstacles such as rocks, tree trunks, puddles etc. on a parkour or even cross wooden bridges.

Tactile feedback training (tacFT)

During tactile feedback training (©h/p/cosmos robowalk expander), the robowalk expander, which was attached with a total of 6 pulls, was configured in such a way that, depending on the stance or swing phase, the upper body was erected and stabilized over the pelvis with 2 pulls each from dorsal, the hip and knee extension or knee flexion were supported via the ankle joint, and the hip flexion was supported via the thigh.

Treadmill training (TT)

The treadmill training was performed without feedback, the patients should concentrate only on an even gait.

Auditory feedback training (audFT)

During auditory feedback the hip joint angles and the knee joint angles were measured on both legs with inertial measurement units at each side (IMUs: m400, menios GmbH, Ratingen, Germany). Three sensors were used in the case of a THR to measure the hip angles in the sagittal plane, one sensor at each thigh and one sensor at the sacrum. Four sensors were used, in the case of TKR to measure the knee angles in the sagittal plane, one sensor at each thigh and at each lower leg (ankle) (Fig.3).

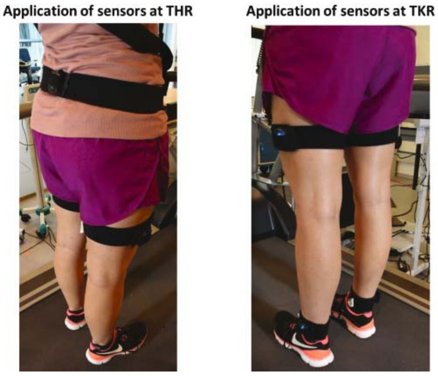

Fig. 3: Application of the IMU´s; 3 sensors at THR (left side); 4 sensors at TKR (right side).

Every measured joint angle was mapped, in real-time, to the frequency of a pure tone ("sonification", see Fig. 4), which allowed for each angle progression to be played as a "melody of movement" on the ipsilateral ear of the patient via headphones. In the case of a THR, the joint angles were sonified during the whole gait cycle. In the case of a TKR, the joint angles were sonified only during the stance phase of the corresponding feet, which means, only ± 15 degrees of the joint angle were sonified. As a further special feature, the feedback during the 20-minutes training was divided according to a simple fading principle, at first 6 minutes with, then 4 minutes without auditory feedback. After a short break of recalibration of sensors the patients had a training of 4 minutes with, then 6 minutes without feedback. The task was to adapt the melody of the operated (op) side to that of the non-operated (nop) side and to maintain the motion sequences even in the periods without feedback.

Sensor technology and software of auditory feedback

Real-time sonification of the joint movements, i.e. hip or knee angles, was performed using wireless inertial measurement units "m400" (menios GmbH, Ratingen, Germany) and the object-oriented multibody C++ library MobileBody© (ITBB GmbH, Neukirchen-Vluyn, Germany). Two sensors were placed at the proximal and distal segments of each joint, respectively. They were set to use a six-axes-fusion algorithm to compute their absolute orientation with respect to a common inertial reference frame, and to deliver it using Quaternions at a rate of 200 Hz and a constant latency of 16ms. These signals were processed online by the software in three steps: (1) Reduction of the drift error, (2) computation of the relative angular displacement between the sensors (which corresponds to the angular displacement between segments), and (3) generation of a pure tone as a function of the sagittal component of the angular displacement.

The reduction of the drift error was possible because the expected motion of the segments on the treadmill excludes large rotations about the vertical and the target angles (knee and hip flexion) are contained within the sagittal plane. Since a six-axes-fusion algorithm corrects all components of the drift error except the one parallel to the gravity vector, all vertical angular displacements with respect to a given reference configuration on the treadmill were considered errors and, hence, eliminated. The computation of the relative angular displacement between the segments was done using the rigid-body model of the human musculoskeletal system available in MobileBody©, which converts the relative Quaternions to the anatomical Euler-angles as described in the literature (Kadaba, Ramakrishnan, & Wootten, 1990). The generation of the pure tone was performed with the open-source C++ libraries openAL, which are integrated in the MobileBody© libraries. Each angle q was linearly mapped to a pure tone with frequency

,

$$f(t) = \sigma * A_0 * \sin(\left(1 + \frac{q}{D}\right) * 2\pi * f_0 * t) \qquad (1)$$

where t is the time, A_0 and f_0 are the base volume and base frequency of the pure tone, respectively, D is a proportionality constant, and σ is a blending factor with

$$\sigma = e^{-c*(q-q_{min})^2}, \text{ if } q < q_{min},$$

$$\sigma = e^{-c*(q-q_{max})^2}, \text{ if } q > q_{max},$$

$$\sigma = 1, \text{ otherwise.}$$

While the angle q is in the interval $q_{min} \leq q \leq q_{max}$ a pure tone is produced with a frequency which linearly depends on q. When it leaves the interval, the pure tone is muted. The muting is performed smoothly by the rules given by the blending factor σ. In the case of THR, q_{min} and q_{max} where set to -45° and 45°, respectively, in order to sonify the whole joint motion. In the case of TKR, q_{min} and q_{max} where set to -15° and 15°, respectively, in order to sonify the joint motion only in the stance phase. In both cases, f_0 was set to 440 Hz (concert pitch A) and D to 180°.

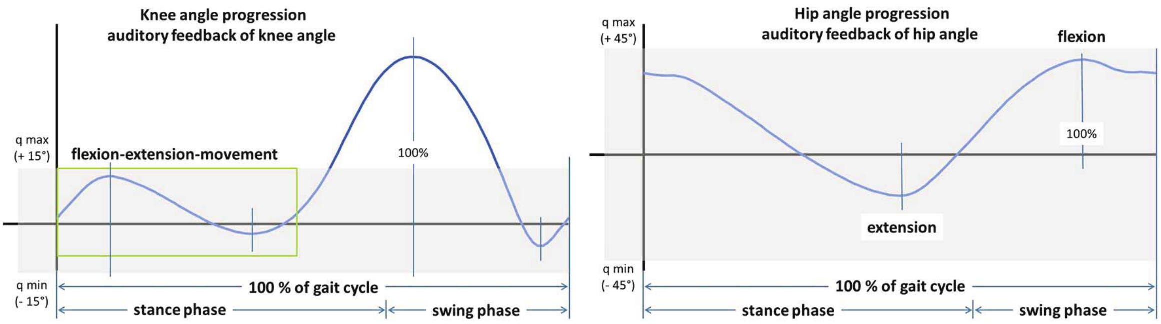

Fig. 4: Schematic illustration of knee (left) and hip angle progression (right) and its sonification during flexion-extension movement in the stance phase. The grey area shows the domains that were effectively mapped to sound.

Statistics

Statistical analyses were performed using IBM SPSS Statistics version 24. A significance level was set at p <0.05. A normality check was performed with the Kolmogorov-Smirnov test. To assess change in function of pre- and post-test, paired sample t-tests or Wilcoxon signed-rank tests were used, depending on the distribution of data. A factorial repeated measures ANOVA (TEST × GROUP) was used. Partial eta-squared (η) was used to calculate corresponding effect sizes. The resulting p values were Bonferroni adjusted.

Results

Based on paired t-tests, there were statistically significant improvements in all essential gait parameters such as gait speed (Fig. 5), stride lengths, stance phase etc. ($p < .001$) between pre- and post-test in all intervention groups (visFT, virtFT, tacFt, TT, audFT) and in the CG. At post-test, all parameters remain in deficit in comparison to the RG (Pietschmann & Jöllenbeck, T. & Geu Flores, F, 2017).

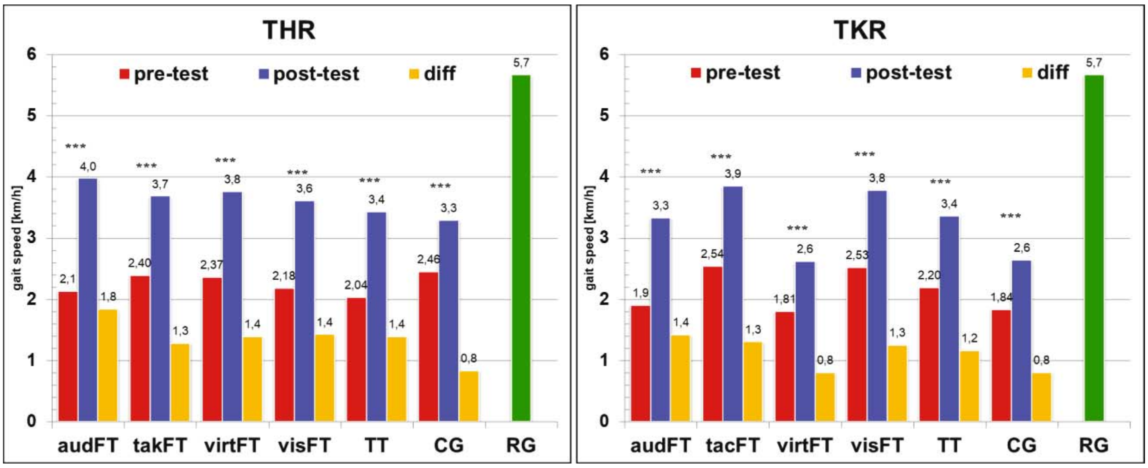

Fig. 5: Gait speed (km/h – mean values) at pre- and post-test and its change (diff) during rehabilitation in all IGs and in comparison to CG and RG.

The ANOVA showed a statistically significant interaction between TEST and GROUP of speed ($F(11,228) = 1.98$, $p = .031$, partial $\eta^2 = .087$), however there was no statistically significant interaction between TEST and GROUP of stride length (op-side) ($F(11,228) = 1.79$, $p = .055$, partial $\eta^2 = .080$); stride length (nop-side) ($F(11,228) = 1.39$, $p = .178$, partial $\eta^2 = .063$), stance phase (op-side) ($F(11,228) = 1.19$, $p = .291$, partial $\eta^2 = .055$) and stance phase (nop-side) ($F(11,228) = 1.31$, $p = .219$, partial $\eta^2 = .060$).

Results of the 3D-gait-analysis showed an improved range of motion in the hip joint after THR and in the knee joint after TKR at post-test compared to pre-test in all intervention groups. At the end of the 3-week rehabilitation, however, there were still significant differences in the angle progression and range of motion after THR (Fig. 6) and TKR (Fig. 7) to the RG.

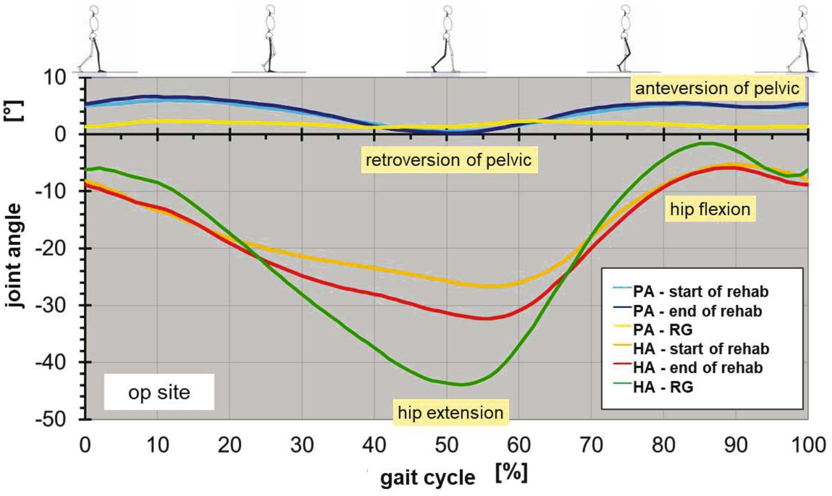

Fig. 6: Change in the hip (HAP) and pelvic angle (PAP) progression on the op side (mean value of all groups) during rehabilitation, HAP and PAP are shown offset for better representation.

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[1] Improved range of motion is only reported if significance ($p<.05$) is available.

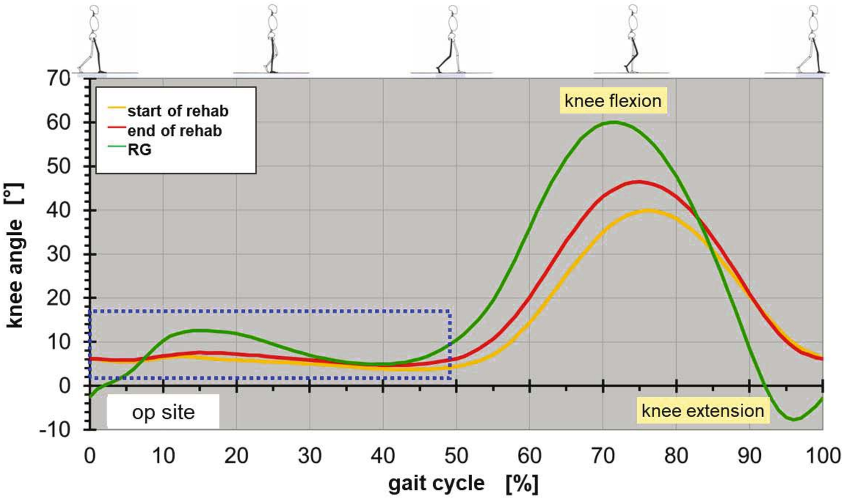

Fig. 7: Change in the knee angle progression on op side (mean value of all groups) during rehabilitation, RG (green), start of rehab (pre-test = yellow), end of rehab (post-test = red); reduced flexion-extension-movement (blue).

With regard to direct control of key parameters after THR the flexion-extension movement in the hip joint was also improved with tacFT and audFT, but deficits (Fig. 8) and asymmetries (Fig. 11) between the op and nop sides remain as well as deficits on both sides with respect to the RG. Identical results can also be seen in direct control of key parameters after TKR, the flexion-extension-movement of tacFT and audFT in the foot attachment and middle stance phase show only a slight improvement. Deficits (Fig. 8) just like asymmetries (Fig. 11) between op and nop side still remain, as well as deficits on both sides compared to the RG.

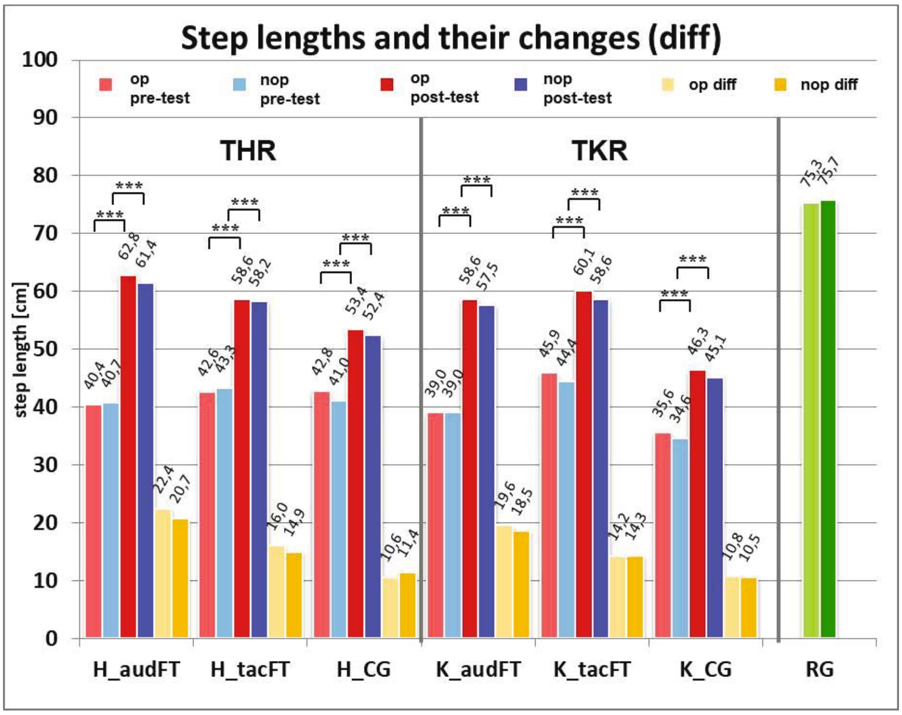

Fig. 8: Step lengths (mean values) of op-side (op) and nop-side (nop) and their changes (diff) during rehab in audFT and tacFT and in comparison to CG and RG, H (hip) – THR, K (knee) – TKR.

At the end of rehabilitation, the 3D gait analysis also showed that there are still significant differences in the movement progression between op and non-op side in all groups in comparison to RG (Fig.9 and 10, exemplary presentation of the audFT group at pre-test and post-test).

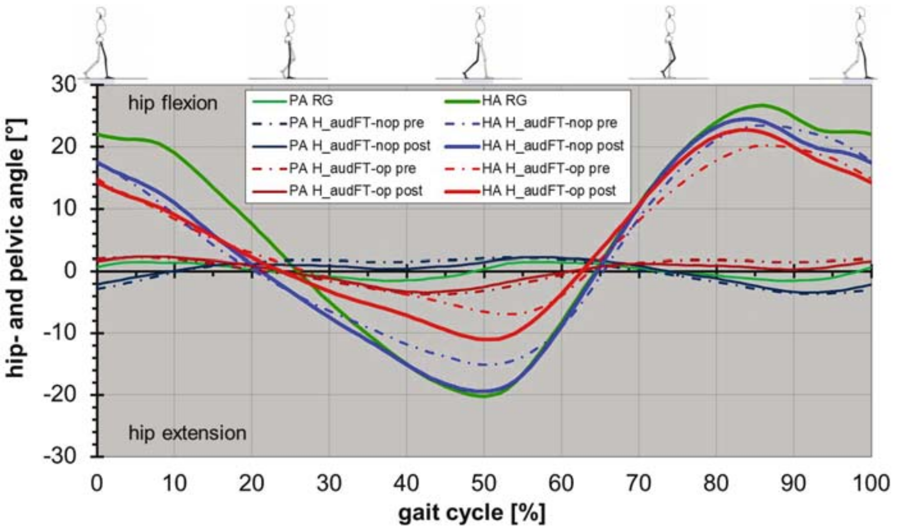

Fig. 9: Change in the course of movement from hip (HA) and pelvic angle (PA) after THR (H) during rehabilitation as an example with audFT in comparison to op and nop side and to RG.

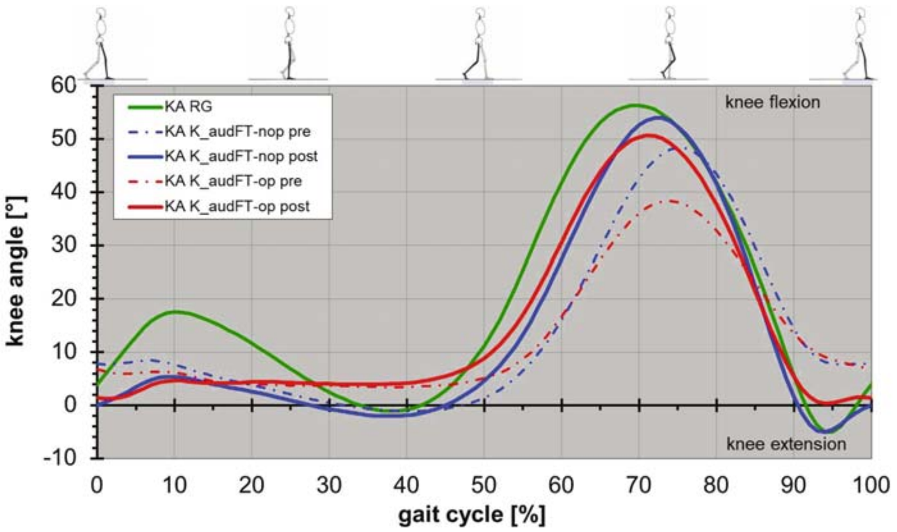

Fig. 10: Change in the knee angle movement course (KA) after TKR (T) during rehabilitation exemplary in audFT in comparison to op and nop side and to RG.

After THR, in the overall view of all IGs, audFT consistently showed the greatest improvements in speed, cadence, stride length and stance phase, at least in terms of amount. Similarly, audFT showed the greatest increases in the dynamic range of motion in the hip and knee joints (Fig. 11) and, unlike the other IGs, no further increase in the pelvic angle.

[2] Only the results of the rapid gait speed are presented consistently, because they best reflect the current performance of the patients.

[3] Improvements or differences are only reported if significance (p<.05) is available.

After TKR, audFT and tacFT show the greatest improvements in speed and cadence of all IGs in terms of value and audFT also in stride length. Similarly, audFT and tacFT show the greatest increases in the amount of movement in the knee joint (Fig. 11).

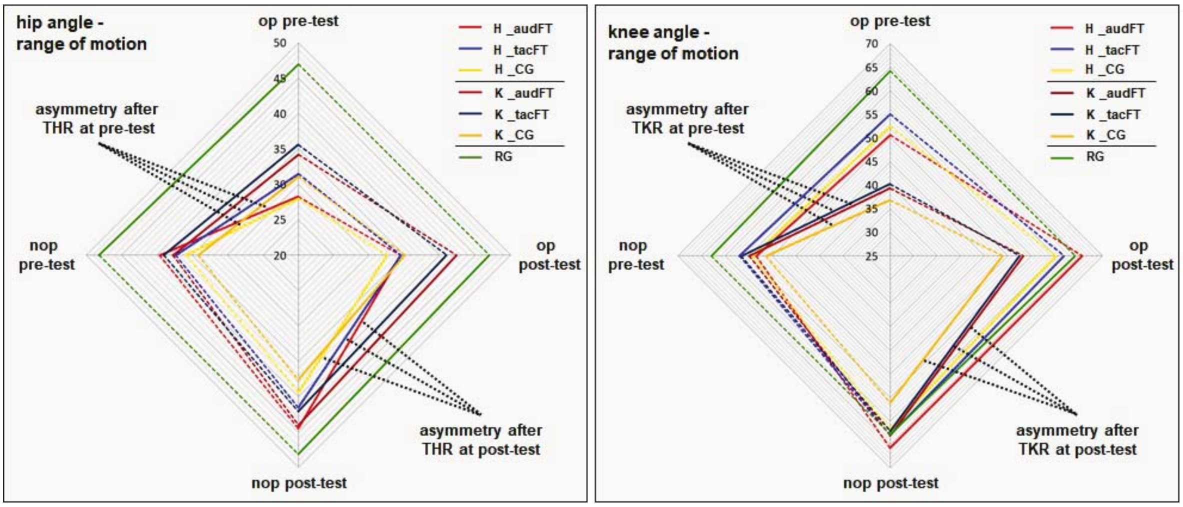

Fig. 11: Range of motion of hip (left) and knee angles (right) and their changes during rehabilitation in audFT and tacTF and in comparison to CG and RG (green line), H (hip) - THR, K (knee) - TKR.

An additional result was the observation (on the control monitor) of the rapid relapse into previous movement patterns in the absence of auditory feedback (Fig. 12). While in the first phases with feedback (duration of 6 min) the effort of the patients to approach the op side to the nop side was clearly visible, in phases without feedback (duration of 4 min) i.e. after switching off the sonification, the movement quickly returned to its original course.

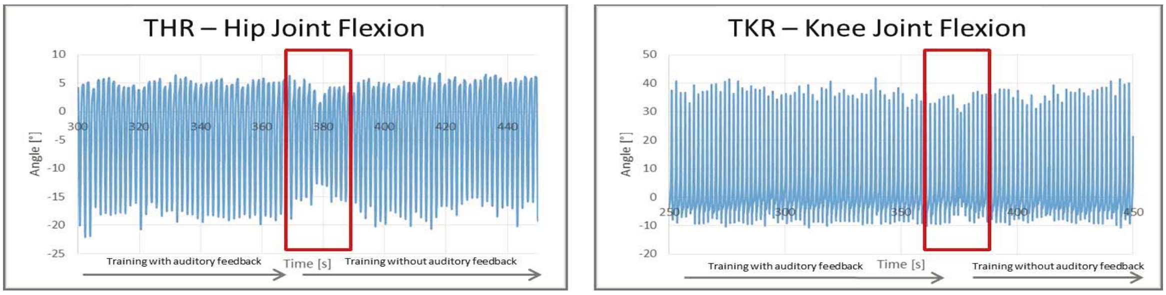

Fig. 12 Relapse into previous movement patter. Auditory feedback starts at 20 sec and ends at 380 sec (6 min); fading feedback

Discussion

In this study, a specific direct control of the key parameters was tested via sonification of the joint angles (audFT), and compared to unspecific direct control via tactile feedback (tacFT) and indirect control by means of visual feedback (visFT), virtual feedback (virtFT) and treadmill training (TT).

Results of all intervention groups, independent of direct or indirect control, largely coincide with those of the control groups. Improvements can essentially be attributed to the normal healing process during rehabilitation with improvements in joint mobility and increasing gait safety with simultaneous pain reduction (Jöllenbeck et al., 2008; Jöllenbeck et al., 2010; Jöllenbeck & Schönle, 2012; Pietschmann & Jöllenbeck, 2015a, 2015b).

In most cases, however, no interaction effects between the different intervention groups can be demonstrated. Thus, step length adjustments or conscious distractions alone do not seem sufficient to indirectly influence the key parameters. There are several possible explanations for this. In principle, the small differences between the op and nop sides (symmetry index <3%) previously determined in the control groups did not suggest any significant effects. In addition, visFT did not provide patients with direct feedback on how exactly the task was performed. In the case of virtFT, there was at least feedback on the success or failure in overcoming the obstacles, as well as a total score at the end. Both increased the challenging character but were not very helpful with regard to the goal.

Results of tacFT and audFT are largely the same as those of the other IGs and CG and do not provide any new insights at first glance. Without demonstrable interaction effects, an unspecific direct control (tacFT) or a specific direct control (audFT) of the key parameters seems to be less successful. Clear differences between op and nop side (symmetry index >14%) had suggested more effects. In contrast to tacFT, audFT has provided patients with direct control of the key parameters with each step for the first time. This may be the reason why the results of audFT tend to be slightly better than those of tacFT, but this remains purely speculative due to the lack of statistically reliable data at the present time.

The fact that audFT is effective in sport movements has already been demonstrated, for example in rowing (Schaffert, & Mattes, 2015). However, it cannot be assumed a priori that its effects on a learned sport motor-skill can also be expected on a highly automated and unconsciously executed movement pattern as the human gait. Nevertheless, the results provide reasons for cautious optimism and even suggest indications for further action. The online control of the movement process on the op and nop side with and without feedback, which is not visible to the patients, reveals that patients are very well able to consciously and controllably change their movement process by means of suitable assessment (feedback). But without feedback, the patients fall back very quickly into their previous highly automated and correspondingly stable movement. At this point, it cannot be ruled out that similar effects may have occurred in the other interventions without direct feedback. The rapid relapse into previous movement patterns is an essential explanation for the question why no interactions between the interventions or differences to CG or TT could be demonstrated on post-test. Rapid relapse into previous movement patterns in the absence of auditory feedback is an impressive demonstration of the importance of regular gait training, which must be carried out at least several times a day, far beyond the rehabilitation period, if the gait pattern is to be permanently and sustainably controlled and continuously improved.

Furthermore, the results of the 3D-gait-analysis showed that a reduced range of motion in the hip joint can be compensated by an increased range of motion in the pelvis and knee joint and vice versa. However, the range of motion in the hip and knee joints is reduced at the same time, which further increases the reduced movement in the kinematic chain. Without compensation for one-sided reduced movements on the op side, the resulting gait parameters are also affected. Thus, step lengths, stance phases and ground reaction forces are not the cause of the existing gait deficit, but its result.

Limitations

A basic problem is the frequency and duration of feedback and training. With a total of 6 training units of 20 minutes each, only 2 hours within 2 weeks, are not enough to break up a highly automated, but deficient movement unconsciously performed over much longer periods of time and to replace it with an optimized movement. This also explains why the usual therapeutic gait training courses cannot have a lasting effect.

Conclusion

In summary, improvements of essential gait parameters following a 3-week rehabilitation after THR and TKR could be acknowledged for all tested training methods. However, there are still clear asymmetries in essential parameters (when comparing the op with the nop side) and clear differences with respect to the RG. The restoration of an even and safe gait at the end of rehabilitation is clearly far from being achieved. The results reveal an urgent need for action beyond rehabilitation in order to normalize the gait pattern and avoid long-term consequential damage to the musculoskeletal system.

AudFT did not show, statistically, a clear advantage over other feedback methods. Nevertheless, our study confirms that sonification is very well accepted by the patients and that it does significantly change gait pattern during training.

Since training units during rehabilitation are not sufficient to break up a highly automated gait pattern that has been incorrectly practiced over several years, a self-contained daily training after rehabilitation should be provided. This may soon be viable through sonification, since new technologies, such as inertial measurement units, allow for wearable joint angle measurement devices that can easily be coupled with mobile audio players.

Future

A wearable, mobile set of instruments for audFT will be developed for it to be used easily after THR and TKR in a daily basis during and especially after rehabilitation. We are confident that the direct control of key parameters during longer periods of time will allow for deficient gait patterns to be broken.

Even though sonification via pure tones was well accepted by the patients, more complex rules mapping joint angles to sound will be investigated.

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