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The Influence of Visual Feedback on the Mental Representation of Gait in Patients with THR: A New Approach for an Experimental Rehabilitation Strategy

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Abstract Due to total hip replacement (THR), patients reveal abnormal gait patterns which post-operative do often not return to "normal". The restoration towards normal gait reduces stress on the adjacent joints which consequently reduces risk of osteoarthrosis development. Motor-performance is related to the structure of the movement in long-term memory, thus it seems to be essential to imprint correct gait patterns in there. Mental representation structures can develop over the course of training and visual feedback presumably helps regaining a better representation of gait in long-term memory. The purpose of this study is to evaluate the effect of visual feedback on mental representation in patients with THR. In a randomized controlled trial, 20 women (57 ± 6 years) with THR have been enrolled. Subjects were randomly assigned to a control group (CG) or intervention group (IG). Additionally to inpatient treatment, all subjects participated in a standardized gait training including either an intervention based on verbal information from a physiotherapist (CG) or an intervention based on real-time visual feedback (IG). Mental representation was measured in pre-test and post-test using the structure-dimensional analysis. Results indicate significant improvements in mental representation of gait in the post-test only in IG, suggesting that beneficial effects were provoked by visual feedback.

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Introduction

As a consequence of the history of disease or pain occurring in patients suffering from hip arthrosis, gait patterns show non-physiological asymmetries, muscular imbalances and insufficiencies as well as increased stress of the hip and knee joint (Whittle 2003). These "abnormal" gait patterns frequently do not return to "normal" gait patterns after THR (Beaulieu et al. 2010; Foucher and Wimmer 2012). These patients also show Trendelenburg gait (Pai 1996; Sander et al. 2011), asynchronous pelvic oscillation (Lugade et al. 2010) as well as asynchronous or increased oscillations of trunk movements (Perron et al. 2000; Vogt 2003). Over 20 years ago, Shih et al. (1994) already postulated that one essential purpose of THR should be the restoration of a normal gait. This presumably reduces stress on the adjacent joints which consequently reduces the risk of development of osteoarthrosis. Another important issue is that regaining normal gait might also reduce the wear on the implant (Foucher et al. 2009; Hurwitz et al. 1999; Husted et al. 1996; Sayeed et al. 2009; Shakoor et al. 2002). Hence, new and effective approaches aimed at helping patients to improve gait performance are of utmost importance.

In motor control and motor learning, the existence of movement related feedback is fundamental. There are multiple sources of task-intrinsic feedback (e.g. visual, auditory, proprioceptive feedback). Furthermore, feedback provided by external sources (as further referred to augmented feedback) might enhance or provide additional information to task-intrinsic feedback. This leads to a

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simpler or faster learning of motor tasks. Augmented feedback contains two categories which are knowledge of results (KR; e.g. information about achieving a goal) and knowledge of performance (KP; e.g. information about movement characteristics). However, KP is particularly valuable when kinematic movement tasks have to be performed according to specified movement characteristics (e.g. angles in hip joint, etc.) and when specific movement components, which require complex coordination, must be corrected (Magill 2010).

Gait retraining aimed to regain normal gait patterns is a motor learning task which is popular when aiming to improve gait characteristics in THR patients. In order to provide augmented feedback, physiotherapists usually use verbal, tactile, and visual feedback (e.g. a mirror). However, according to a systematic review (Tate and Milner 2010), there is some evidence that gait retraining using kinetic, temporo-spatial, and kinematic feedback leads to moderate, positive short-term intervention effects and to greater rehabilitation success than conventional therapy methods. Thus, implementing a feedback system in order to correct gait pattern in patients with THR, which we already evaluated in a pilot study in subjects with and without gait disorders (Hamacher et al. 2012), might be more beneficial. In THR patients, the addressed feedback system successfully helps correcting abnormal pelvis and trunk movements in the frontal plane (e.g. Trendelenburg and Duchenne gait; Schega et al. 2011). Furthermore, the verified improvement of motor action (e.g. kinematics of pelvis and trunk), might imply simultaneous improvements in the motor program.

According to Schacks' (2004) theory of the cognitive architecture of complex movements, there is a functional construction of actions with different levels of action organization: (1) level of sensorimotor control, (2) level of sensorimotor representation, (3) level of mental representation, and (4) level of mental control. The main function of level 1 (sensorimotor control) is the regulation of functional units using afferent feedback, effectors and the perceptual effect representations (from level 2). Thus, the need of level 2 is obvious. The perceptual effect representation incorporates action-specific information (e.g. spatio-temporal adjustments). In level 3, the motor program is built. Therefore, the action is structured into representation units, the so-called basic action concepts (BACs). These BACs combine functional and sensory features and represent functional and perceptive properties which had been transferred from the anticipated action goal (level 4: mental control; Schack and Ritter 2009). Thus, if an improvement in kinematic outcomes is found this is a result of the adapted perceptual effect representation and probably from a changed BAC structure in level 3 (mental representation).

In order to evaluate the effect of visual feedback in THR patients on the mental representation of gait-relevant BACs in long-term memory, we applied the structure-dimensional analysis (SDA). The SDA is a method to explore the mental structure of specific knowledge which has been developed by Lander and Lange (1992). This method has already successfully been applied in several studies (Lander and Lange 1992) and in 2004, it has been modified into the SDA-M (Schack 2004; Schack and Mechsner 2006). The additional "m" symbolizes the relation to motor skills. This modified method has already successfully been used in classical dance, Volleyball and Judo (Bläsing et al. 2009; Schack 2004; Velentzas et al. 2010; Weigelt et al. 2011) and showed that experts present motor knowledge in a more structured way than beginners. According to Schack and co-workers, the SDA-M method data processing implies four major steps (Schack 2004; Schack and Mechsner 2006). The first step contains the Split-Procedure to get sum-matrices which imply proximity data of the BACs. Therefore, relevant BACs have to be extrapolated and can afterwards be represented in written or graphical format. For each possible combination of two BACs, the patients had to decide whether they think the two BACs are associated with one another or not. This information is used in a distance scaling process of BACSs resulting in a distance matrix which is described in detail, elsewhere (e.g. Heinen 2005). The second step includes the structural analysis via a hierarchical cluster analysis based on the proximity data (distance matrices). The output is a dendrogram showing individual clusters of BACs. In order to decide whether two BACs are linked or not, a specific critical distance value can be applied. The third step involves a dimensional analysis of the determined clusters with the help of factor analysis. The last step depicts an intra- and inter-individual invariance analysis (between two cluster solutions) using an invariance value λ (Schack 2004).

Since we already found an improvement in pelvis and trunk kinematics (Schega et al. 2011) and based on the knowledge that using augmented feedback in gait retraining might lead to a better outcome compared to a conventional intervention (Tate and Milner 2010), we hypothesized that the proposed feedback system will lead to an improved structure of BACs in long-term memory.

The purpose of this study is to evaluate the effect of a gait retraining program, which provides concurrent visual feedback, on the mental representation in patients with THR which we aim to compare with a conventional gait retraining program based on verbal information.

Methods

Study Design

In a randomized controlled trial 20 women (57 ± 6 years) with unilateral THR were randomly assigned either to a control group (CG, n = 10, age: 59 ± 4 years, BMI 28.7 ± 4.2, intake 14 ± 4.0 days after surgery) or an intervention group (IG, n = 10, age: 56 ± 7 years, BMI 27.8 ± 7.1, intake: 16.6 ± 3.8 days after surgery). Further joint diseases or implants as well as any kind of postoperative complication lead to exclusion. Additional to the inpatient treatment, all patients participated in a standardized gait training program (3 weeks, 20 min/day). Corrections of gait pattern have been given by either verbal information (CG) or using visual real-time feedback (IG). In order to identify differences between the intervention strategies, pre- and post-tests have been performed. Tests and interventions were undertaken in a clinical setting at an orthopedic rehabilitation clinic.

Prior to the pre-test, goals, contents and methods of the study were explained to the subjects, confirming their voluntary participation. The study has been approved by the local Ethics Committee and complies with the principles of the Declaration of Helsinki.

Intervention and Application of Visual Feedback

In addition to the inpatient treatment, all patients passed a standardized gait retraining program which successively increased its level of difficulty (3 weeks, 20 min/day). In the first week, the patients just walked with forearm crutches up and down a level hallway. During the second week, an obstacle course (sidestep movements, stair treads, different surfaces, teeter board and others) was performed using forearm crutches. During the third week, walkway training without forearm crutches was conducted. During the gait retraining corrections of gait patterns were either given by an officially recognized, state-approved physiotherapist (CG) or with help of a visual real-time feedback (IG). The primary goal was to achieve balanced gait patterns in the frontal plane. Therefore, actual three-dimensional movement trajectories of the pelvis and trunk inclination in the frontal plane were captured by inertial sensors with implemented magnetometers (MVN, XSens) and visually represented by means of a three-dimensional (3d) model in real-time as green axes via a head-mounted display (see further descriptions below). This means that via the 3d model, the subjects saw their own movements in real time. Subjects were briefed to walk in a way that the supplied axes of the model would oscillate symmetrically within the visually provided red limits (reflecting a range of motion of ±6° and ±4° in the frontal plane for trunk and pelvis respectively). The limits are based upon reference data that were previously captured in healthy women (Hamacher et al. 2012). Also, a third axis on the head was presented. Participants were asked to avoid viewing down which would be coupled with a downward tilt of the head in the sagittal plane. The data was processed by means of an Ultra Mobile PC (UMPC) and the visualization was presented using a Head-Mounted Display (HMD, Nikon Media Port UP300x).

Data Processing

To utilize the SDA-M procedure, gait specific BACs had to be extrapolated. Referring to Perry's gait model which divides the gait cycle into periods (stance and swing), phases (initial contact, loading response, mid stance, terminal stance, pre swing, initial swing, mid swing and terminal swing) and tasks (weight acceptance, swing limb support and swing limb advancement) (Perry and Burnfield 2010), the following BACs were deduced: ground contact of right foot and left foot (BAC 1 and BAC 2, initial contact and loading response), extension of right hip and knee and left hip and knee (Bac 3 and BAC 4, mid stance and terminal stance), offtake of right foot and left foot (BAC 5 and BAC 6, pre-swing and initial swing), forward swing of right foot and left foot (BAC 7 and BAC 8, mid swing), extension of right knee and flexion of right hip (BAC 9, terminal swing) and extension of left knee and flexion of left hip (BAC 10, terminal swing). In addition the following BACs have been deduced: looking down (BAC 11), tilt of hip in the frontal plane (BAC 12) and tilt of torso in the frontal plane (BAC 13).

The Split-procedure was performed in pre-test and the post-test using this BACs and the software WinSplit II (Heinen 2005). A significance level of $\alpha = 0.05$ was chosen. Consequently, the value of the critical distance is $d_{crit} = 3.434$ (Heinen 2005). As Perry's gait model (Perry and Burnfield, 2010) was used to determine relevant BACs, that model was consequently also applied to create a reference structure using the SDA-M procedure. Since the group analysis according to Schack (2010) and Heinen (2005) depends on the number of BACs in each cluster, inductive statistics might yield additional valuable insights. Therefore, an invariance value λ was calculated for each patient in pre-test and post-test which represents the structural invariance of the individual BAC-structure of the patient compared to the reference structure based on Perry's gait model. The formula used has been described in Heinen's work (2005). After examining the data for normal distribution (Kolmogorov–Smirnov test), differences of pre-test versus post-test for each group (t test, dependent groups) and CG versus IG for pre-test and post-test (t-test, independent groups) were tested. A significance level of $\alpha = 0.05$ was set.

Results

Figure 1 shows the dendogram according to Perry's gait model. The BACs were within two symmetrical clusters

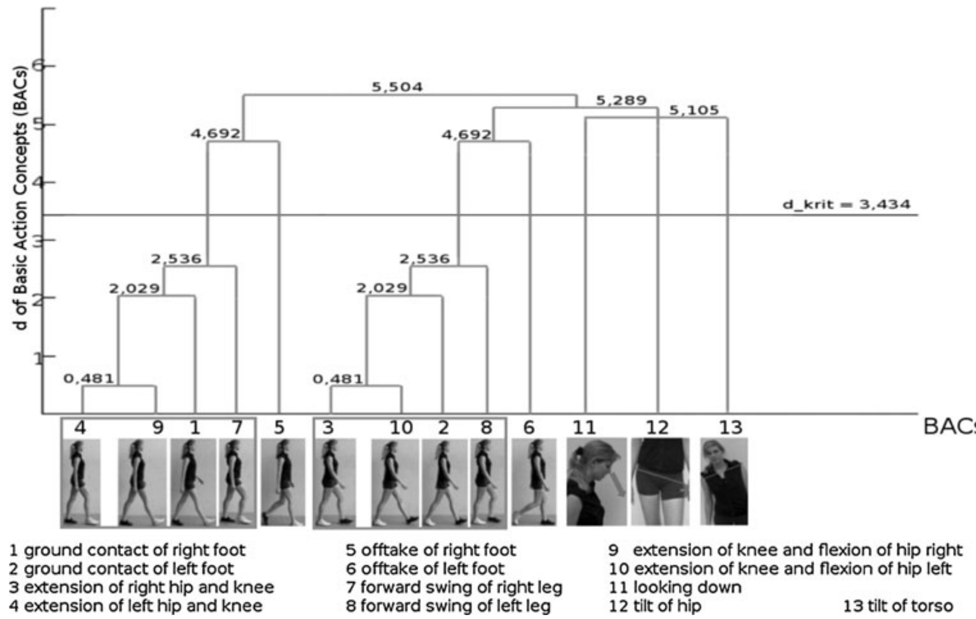

Fig. 1 The dendrogram based on Perry's gait model (d: distance). The result depicts two symmetrical cluster: 4–9–1–7 (extension of left hip and knee–extension of knee and flexion of hip right–ground contact of right foot–forward swing of right leg) and 3–10–2–8 (extension of right hip and knee–extension of knee and flexion of hip left–ground contact of left foot–forward swing of left leg). Furthermore the Basic Action Concept (BAC) 5 (offtake of right foot), 6 (offtake of left foot), 11 (looking down), 12 (tilt of hip) and 13 (tilt of torso) were singles and not included in any cluster

4–9–1–7 (extension of left hip and knee–extension of knee and flexion of hip right–ground contact of right foot–forward swing of right leg) and 3–10–2–8 (extension of right hip and knee–extension of knee and flexion of hip left–ground contact of left foot–forward swing of left leg). The BACs 4–9 (extension of left hip and knee–extension of knee and flexion of hip right) and 3–10 (extension of right hip and knee–extension of knee and flexion of hip left) depicted the shortest distance. The BACs 5 (offtake of right foot), 6 (offtake of left foot), 11 (looking down), 12 (tilt of hip) and 13 (tilt of torso) were singles and not included in any cluster.

In CG, the data of all 10 participants were analyzed. In IG, only 9 participants finished the Split-procedure as one subject did not pass the post-test. In the pre-test of CG, the group dendrogram showed a cluster solution with the four clusters 4–7 (extension of left hip and knee–forward swing of right leg), 3–8 (extension of right hip and knee–forward swing of left leg), 1–9 (ground contact of right foot–extension of knee and flexion of hip right) and 2–10 (ground contact of left foot–extension of knee and flexion of hip left).

In the corresponding post-test of CG (Fig. 2), the two clusters 3–2–10–5 (extension of right hip and knee–ground contact of left foot–extension of knee and flexion of hip left–offtake of right foot) and 7–4–1–9–6 (forward swing of right leg–extension of left hip and knee–ground contact of right foot–extension of knee and flexion of hip right–offtake of left foot) were depicted.

In IG, the pre-test denoted a group dendrogram with the two clusters 7–4–1–9–5 (forward swing of right leg–extension of left hip and knee–ground contact of right foot–extension of knee and flexion of hip right–offtake of right foot) and 8–3–2–10 (forward swing of left leg–extension of right hip and knee–ground contact of left foot–extension of knee and flexion of hip left).

Analyzing the post-test of IG (Fig. 3), we revealed a cluster solution with the two clusters 8–3–2–10–5 (forward swing of left leg–extension of right hip and knee–ground contact of left foot–extension of knee and flexion of hip left–offtake of right foot) and 6–1–9–7–4 (offtake of left foot–ground contact of right foot–extension of knee and flexion of hip right–forward swing of right leg–extension of left hip and knee).

While a significant difference of the invariance value λ in IG ($\lambda = 0.76 \pm 0.15$) versus CG ($\lambda = 0.54 \pm 0.16$) in post-test ($p = 0.010$) was observed, we did not find that in the pre-test. Comparing pre-test (IG: $\lambda = 0.56 \pm 0.19$, CG: $\lambda = 0.52 \pm 0.20$) versus post-test, a significant improvement in IG ($p = 0.019$) was perceived (Fig. 4).

Discussion

The current study introduces an approach that helps patients to improve gait performance. As motor-performance is related to the structure of BACs of the movement in long-term memory (Schack 2004), imprinting correct gait patterns appears helpful. In order to gain further insights towards the possible capability of visual feedback helping representing the correct structure of gait in long-term memory, the current study aimed to evaluate the effect of a gait retraining program using a system which delivers concurrent visual feedback on the mental representation in patients with THR.

Our work confirmed the recent work of Thikey and co-workers (Thikey et al. 2012) who stated that augmented

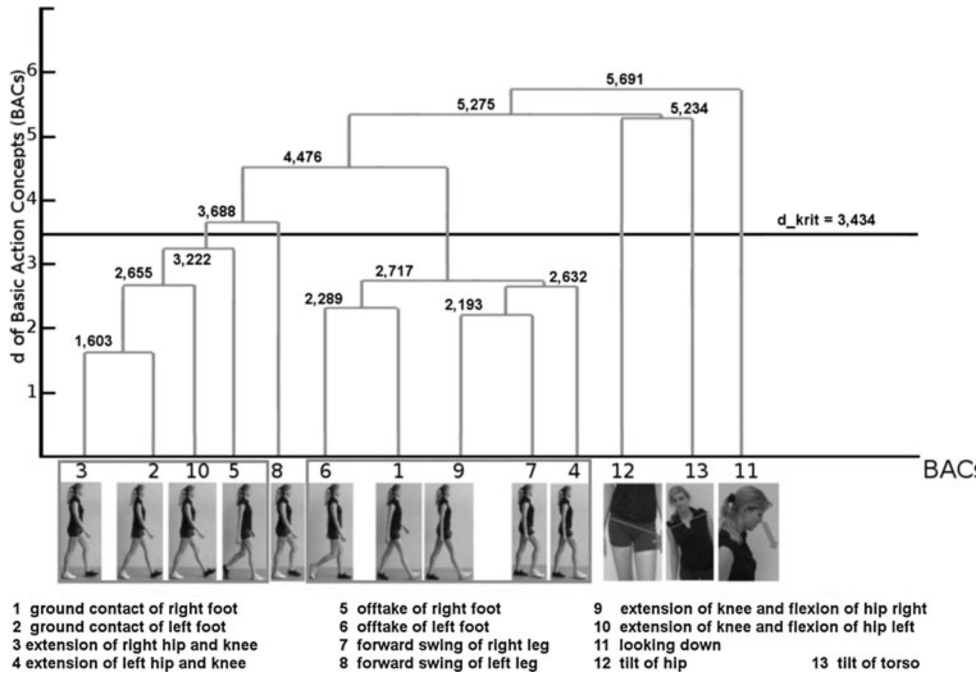

Fig. 2 The dendrogram shows the cluster solution of the control group in post-test

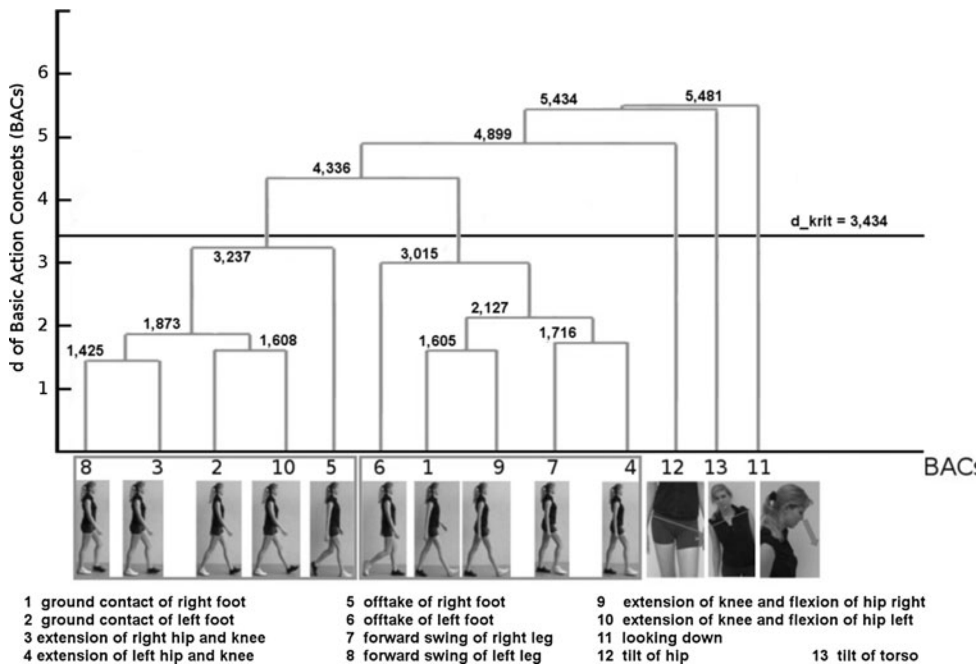

Fig. 3 The dendrogram shows the cluster solution of the intervention group in post-test

visual feedback of movement performance improves the rehabilitation process by helping subjects change their pathological gait pattern towards a healthy gait pattern. Further, the most important outcomes of this study are (1) that a more functional BAC structure has been found in IG in post-test as compared to CG and (2) that only IG improved over the course from the pre-test to post-test. In contrast to verbal information based gait training, visual feedback-based training leads to an improved BAC structure. Thus, the developed gait pattern using visual feedback (Schega et al. 2011) might not only be a result of an adapted perceptual effect representation (level 2) but also of a more functional BAC structure in mental representation (level 3). Since no improvement was found in CG, verbal instruction based interventions do not lead to improved BAC structures and should generally be extended to other sorts of feedback (e.g. visual feedback). The authors speculate that the provided real-time visual

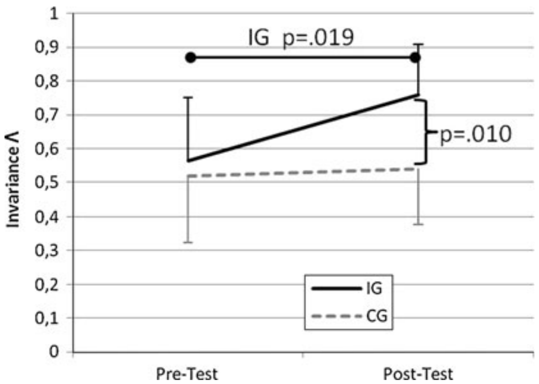

Fig. 4 Comparison of invariance values in IG versus CG in pre- and posttest. While there was no difference comparing the IG versus CG in pretest the IG improved their mental representation of gait ($p = 0.019$) resulting in a significant difference in posttest of IG versus CG ($p = 0.010$)

feedback in IG promoted the process which imprints the related correct gait patterns in long term memory and consequently supported the subjects to link the correct BACs. Among other reasons, this might explain why benefits among kinematic gait parameters of pelvis and trunk in the frontal plane have been observed in patients after THR that received gait re-training with visual feedback (Schega et al. 2011).

Thus, it can be concluded that an additional visual feedback-based intervention may lead to positive changes of gait-relevant movement representation in long-term memory which again is associated with movement performance. Since we did not find an improvement in CG, verbal instructions should be augmented with other feedback in general. In conclusion, visual feedback based therapy might be useful within the treatment of patients with THR considering the recovery of movement representing the above mentioned gait parameters. Here, functional adaptions could be provoked by concurrent visual feedback as BACs are attributed to provide the relevant reference structures for movement control (Schack 2004). A limitation of this study is the reduced external validity due to low group sizes and homogenous group characteristics. Therefore, our results should be verified in further studies. Furthermore, our visual feedback system provides a complete virtual character. However, it would be interesting to determine if partial information, which does not include the whole body, would lead to similar results. In that case, the required data for the feedback information could be collected with fewer sensors which would minimize temporal and monetary costs.

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