

Virtual reality system for the enhancement of mobility in patients with chronic back pain

B Bolte¹, M de Lussanet², M Lappe²

^{1,2}Institute of Psychology, ²Otto Creutzfeldt Center for Cognitive and Behavioral Neuroscience,
University of Münster,
Fliehdnerstr. 21, 48149 Münster, GERMANY

b.bolte@uni-muenster.de, lussanet@uni-muenster.de, mlappe@uni-muenster.de

ABSTRACT

Back pain is among the most common health problems in the western world. While surgery can reduce pain and disability for patients with symptoms specific to spinal degeneration, for chronic back pain (CBP) patients exist a variety of therapeutic interventions, which are, unfortunately, not very effective. In addition, CBP patients tend to develop a fear of movement (kinesiophobia) and stiffness of the trunk that probably lead to further problems due to reduced physical activity. To address these problems, we propose a virtual reality system using head-mounted displays for the enhancement of mobility in CBP patients. We manipulate the visual feedback to change the motor behavior of participants by applying gains to alter the weight with which neck, back and hip rotations contribute to the orientation of the virtual camera. Users will not notice the manipulation if the gains are sufficiently small. In an evaluation study we showed that our approach has the potential to increase back movement amplitudes in control and CBP participants. Although we have used a specific task, the big advantage of our method is that any task involving body rotations can be used, thereby providing the opportunity to tailor the task to a patient's specific preference or need.

1. INTRODUCTION

Back pain is among the most common health problems in the western world with a lifetime prevalence of 84% (Balagué et al, 2012), and constitutes a major burden in the public health system. For example, costs associated with back pain in Germany were estimated to be in the range of 49 billion Euros in 2008 representing 2.2% of the German gross domestic product (Wenig et al, 2009). Thus, the burden from back pain is immense both for patients and the society. For patients diagnosed with disc degeneration in the spine, surgery can reduce pain and disability (Phillips et al, 2013) but in many patients the symptoms are not specific to spinal degeneration (Fishbain et al, 2014). These chronic back pain (CBP) patients are treated with a number of therapeutic interventions including education about the problem, the participation in daily physical activities, the use of non-steroidal anti-inflammatory drugs, the short-term use of weak opioids, exercise therapy, and spinal manipulations (Dagenais et al, 2010). Multimodal interventions are usually more efficient than monotherapy (Huge et al, 2006, Jensen et al, 2009, Koes et al, 2006, Raspe, 2012). Unfortunately, these back pain treatments are not very effective (Balagué et al, 2012).

CBP patients tend to develop a fear of movement (kinesiophobia) (Swinkels-Meewisse et al, 2003), which in turn is thought to lead to reduced physical activity and increased risk of re-injury (Roelofs et al, 2007). In addition, changes of the motor system are often found in CBP patients such as stiffness of the trunk, which can be related (Karayannis et al, 2013) or uncorrelated (Lamoth et al, 2006) to fear of movement. It is highly desirable to find methods to counteract the changes of the motor system and increase the motility of the back in patients with CBP. Unfortunately, because of pain and/or kinesiophobia it is often difficult to motivate these patients to move. Virtual Reality (VR) systems can be used to distract from pain and anxiety (Hoffman et al, 2001) and motivate patients to move by engaging them in virtual movement games (Sarig-Bahat et al, 2010).

In the present work we describe a VR system that itself exploits the motor adaptation process to induce enhanced movement of the back without the patient being aware of it. Our approach is based on the fact that VR setups, e.g. using head-mounted displays (HMDs), allow us to change motor behavior of users by decoupling the visual feedback from other sensory feedback during movements. This approach has been used for example in

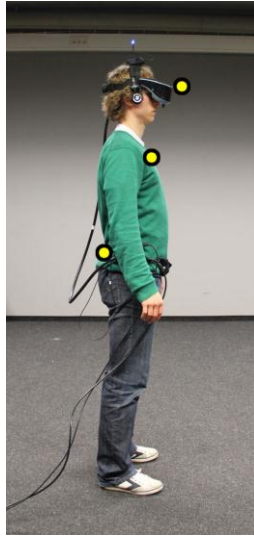


Figure 1. *Illustration of the instrumentation. The participant is wearing the head-mounted display with a fixed infrared marker. Yellow circles indicate the positions of the orientation trackers.*

redirected walking, in which users are led on physical paths that differ from their virtual path (Razzaque, 2005, Bruder et al, 2013), and in the analysis of sensorimotor adaptation of arm movements to perturbed visual feedback of a target (van Beers, 2009, van den Dobbelsteen et al, 2003). For redirected walking, curvature gains are applied, i.e. the virtual camera is slightly rotated and translated with every step of the participant, so that participants physically walk on a curved trajectory while virtually walking straight. If the gain is small enough, users will neither notice the manipulation of the visual feedback nor the adaptation of their motor behavior. Sensitivity to gain manipulations can be investigated using psychophysical experiments to determine gain thresholds for unnoticeable manipulation (Steinicke et al, 2010).

Our goal was to transfer the concept of gain-based visual feedback modification to induce enhanced back rotation amplitudes in CBP patients. We applied gains to change the weight with which neck, back and hip rotations contribute to the orientation of the virtual camera. By changing the weight of the individual rotations, we expected that patients should compensate by also changing the amount of individual rotations. Specifically, by penalizing neck and hip rotations, we expected patients to perform proportionally more back rotations. As this method does not require a particular task in the VE but instead changes the motor behavior by altering the visual feedback during natural movements, it is very versatile. Participants can thus move freely without fixation of any body parts, and patients do not have to be aware that they are actually training.

In order to evaluate the change of motor behavior due to the visual gain manipulation, we designed an experiment in which participants have to move a ring using body rotations (without moving their feet) to catch a flying basketball. We compared the involved proportion of back rotations between a control and a CBP group for two conditions: (1) without gains and (2) with gains to penalize neck and hip rotations.

2. VISUAL-GAIN-BASED CHANGE OF MOTOR BEHAVIOR

In order to render the virtual scene for visual feedback presentation on the HMD, the position and orientation of the virtual camera must be determined. Often, the position and orientation of the head is mapped directly to the virtual camera. We instead want to calculate the head orientation hierarchically based on the orientation of the feet and joints to which we are then able to apply gains.

The yaw orientation with respect to the negative gravity vector (i.e. the orientation in the transverse plane) and relative to a calibrated zero point was determined for the head $\alpha_h \in \mathbb{R}$, upper trunk $\alpha_u \in \mathbb{R}$ and hip (or coxa) $\alpha_c \in \mathbb{R}$ in world coordinate space. Figure 1 shows the placement of the head, upper trunk and hip orientation sensors used for the evaluation of the method.

Based on these orientations the relative rotation of the legs $\theta_h \in \mathbb{R}$ is the orientation of the hip with respect to the world coordinate space, the rotation of the back $\theta_b \in \mathbb{R}$ is the orientation of the upper trunk with respect to the orientation of the hip, and the rotation of the neck $\theta_n \in \mathbb{R}$ is the orientation of the head with respect to the orientation of the upper trunk:

$$\theta_h = \alpha_c, \theta_b = \alpha_u - \alpha_c, \theta_n = \alpha_h - \alpha_u \quad (1)$$

To determine the yaw orientation of the virtual camera, all rotations were multiplied with gains $g_h, g_b, g_n \in \mathbb{R}$ to introduce a discrepancy between the contribution of hip, back and neck rotations to the orientation of the virtual camera compared to the real world. We calculated the yaw orientation of the virtual camera hierarchically based on the hip, back and neck orientation as follows:

$$\alpha = g_h \theta_h + g_b \theta_b + g_n \theta_n \in \mathbb{R}, \quad (2)$$

which is equal to the head yaw orientation if the gains g_h, g_b, g_n are set to 1:

$$\alpha = \theta_h + \theta_b + \theta_n = \alpha_c + (\alpha_u - \alpha_c) + (\alpha_h - \alpha_u) = \alpha_h \quad (3)$$

The remaining pitch $\beta \in \mathbb{R}$ and roll $\gamma \in \mathbb{R}$ Euler rotation angles were set to the corresponding angles of the head orientation tracker.

Gains below 1 introduce a penalty and gains above 1 introduce an advantage to the individual rotations. For instance, if we choose a gain of $g_n = 0.5$ to penalize neck rotations while not modifying the other rotations ($g_h = g_b = 1$), only half of the rotation amplitude contributes to the yaw orientation of the virtual camera. Assuming that participants would use 45 degrees of neck rotation for a neck gain of $g_n = 1$ to achieve a final yaw orientation, only 22.5 degrees contribute to the virtual camera if the neck rotation is penalized by $g_n = 0.5$. Participants can either compensate the missing 22.5 degrees by performing an additional 45 degrees neck rotation, by using 22.5 degrees of additional back or hip rotations, or any combination thereof. We expected that participants would compensate with more additional rotations of the not penalized rotations compared to the penalized rotations to keep the amount of compensational rotations low. But for participants with CBP the magnitude of compensational back rotations might be severely reduced compared to the participants without CBP, which we evaluated in the following study of motor adaptation caused by our gain-based change of the visual feedback.

3. EVALUATION OF MOTOR ADAPTATION

3.1 Participants

We had a *chronic back pain group* (PG) consisting of 17 participants (6 males, 11 females, age: 16–63, $M = 42.1$, $SD = 14.8$), which had CBP for at least 6 months but were able to stand and walk on their own. The pain was mostly localized in the lower back region. Participants had an average body mass index (BMI) of $M = 23.65$ ($SD = 3.18$). Fifteen participants of the chronic back pain group previously participated in studies concerning CBP, but not involving movement studies in VR.

Our *control group* (CG) consisted of 18 participants (5 males, 13 females, age: 20–30, $M = 23.4$, $SD = 2.5$), which had no CBP history. Participants had an average BMI of $M = 22.06$ ($SD = 1.54$). Sixteen participants of the control group were students (mainly Psychology). We discarded the data of one participant as the data set indicated that the participant always rotated the back in the opposite direction of the target, which might be caused by an improper attachment of the orientation trackers.

All participants had normal or corrected to normal vision and were naïve to the experimental manipulation of the visual feedback. Prior to the beginning of participant data collection, the experiment was approved by the local ethical committee.

3.2 Instrumentation

Three InertiaCube 3 orientation trackers from InterSense ($\leq 1^\circ$ accuracy, 4ms latency, 180Hz update rate) determined the orientation of the hip, upper trunk and head in world coordinate space (see Figure 1). The tracker for the head orientation was attached to an extension board mounted on the displays of the HMD. The tracker for the upper trunk orientation was placed with medical tape on the skin at the sternal notch. The tracker for the hip orientation was placed with medical tape on the skin at the superior end of the sacral crest. We put a fresh cotton pad between tracker and skin for each participant. To increase the accuracy of the orientation tracker, we disabled all data filtering, which also slightly increased data jittering.

An active infrared marker was attached to the head-mounted display (see Figure 1). The Precision Position Tracking (PPT) X4 system from WorldViz ($< 1\text{mm}$ precision, $< 1\text{cm}$ accuracy, $< 20\text{ms}$ latency, 60Hz update rate) tracked the marker to determine the participant's position in world coordinate space.

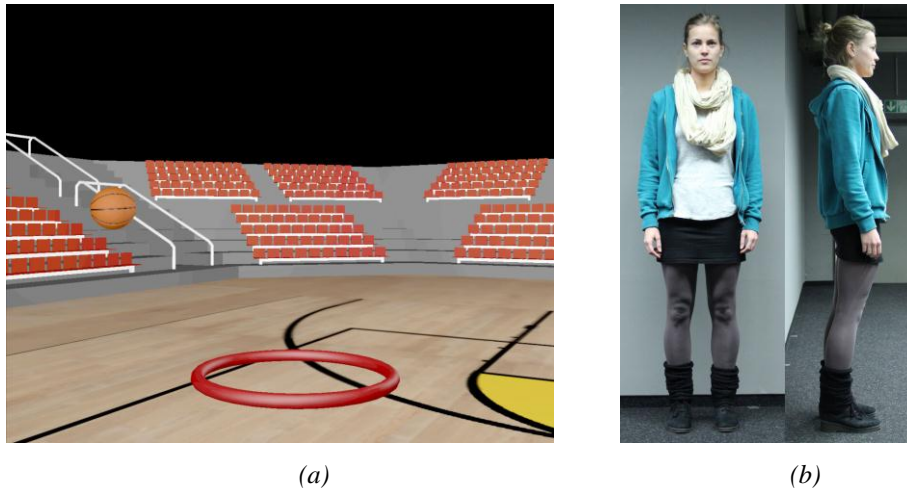


Figure 2. Illustration of (a) the virtual basketball arena and (b) the calibration pose.

We used a computer with 3.4GHz Intel Core i7 processor (16GB main memory) and Nvidia GeForce GTX 680 graphics card in surround screen mode for three displays with a total resolution of 3840×1024 pixels. The virtual scene was stereoscopically rendered using the Ogre3D rendering engine (<http://www.ogre3d.org/>) and our own software. We displayed the rendered images on the Sensics zSight head-mounted display (60° vertical field of view, 2560×1024 pixels resolution, 60Hz update rate). The refresh rate for rendering was synchronized with the refresh rate of the displays. On the third display we rendered the view of both eyes and additional debug information to monitor the progress of the experiment.

3.3 Virtual Environment

The virtual environment consisted of a virtual basketball arena with a width of 20 meters, a depth of 40 meters, and a height of 7 meters (see Figure 2(a)). Participants were located in the center of the basketball arena. The red ring was positioned 0.35 meters below the eye level and 1.5 meters directly in front of the participant, i.e. the ring rotated on a circle with 1.5 meters radius around the participant and the rotation angle was equal to the rotation angle of the virtual camera. The radius of the ball was 0.12 meters and 0.2 meters for the ring.

We simulated the ballistic trajectory of a basketball during passing with a constant speed towards the participant of $s = 8.33$ meters per second (approximately 30km/h), but adjusted the duration of the ball flight to $\Delta_t = 3$ seconds so that participants had enough time to comfortably catch the basketball with the ring. The start position of the basketball was determined on a circle with radius 6.5 meters around the participant with a distance of $\Delta_z = 5$ meters from the ring. The ball start and end position was 0.35 meters below the eye level of participants, i. e. a height offset of $\Delta_y = 0$ meters. We simulated the trajectory assuming gravity $g = 9.31$ meters per square second in a physical vacuum. Without loss of generality, we can calculate the trajectory in the yz -plane in model coordinate space, where the y -axis represents the height offset and the z -axis represents the distance between basketball and ring. Arbitrary ballistic trajectories for a given target angle and height above the floor were achieved using an appropriate transformation of the ball position from model to world coordinate space. Thus, the position of the basketball $p(t) \in \mathbb{R}^3$ at a certain point in time $t \in \mathbb{R}$ is given by $p(t) = \frac{(\lambda t)^2}{2} a + \lambda t v + p_0$ with the basketball start position $p_0 = (0, 0, \Delta_z)^*$, constant velocity $v = (0, g\Delta_z/2s, -s)^*$, constant acceleration $a = (0, -g, 0)^*$ and time scaling factor $\lambda = \Delta_z/s\Delta_t$, where the star notation $(\cdot)^*$ denotes the transposed vector.

3.4 Procedure

We welcomed the participants and gave a short introduction to the experimental procedure. Afterwards, we obtained written consent and participants filled out pre-questionnaires.

We measured the eye level of the participants and individual interpupillary distance for the stereoscopical rendering. Afterwards, we attached the orientation trackers on the participants and participants put on the HMD. The laboratory room was completely darkened during the experiment. Participants received on-screen instruction about the task in a slide show.

To calibrate the system, participants stood straight and still to assume a calibration pose as illustrated in Figure 2(b). While participants were in the calibration pose, the experimenter set the yaw orientation of all

orientation trackers to 0 degrees and set the current head position as reference to calculate the relative movement for the rendering.

Participants performed a dynamic virtual basketball catching task within a basketball arena in which they had to align a virtual ring with the trajectory of a flying basketball to catch the ball. To localize the ball and align the ring, participants had 3 seconds. Participants used only body rotations to move the ring and were instructed that they must not move their feet. At the end of each trial, participants received feedback about their success or failure using a text overlay for 2 seconds. Then, the next trial started.

The experiment was divided into a training block and two experimental blocks: (1) baseline block without visual feedback manipulation ($g_h = g_b = g_n = 1$), (2) test block with visual feedback manipulation ($g_h = g_n = 0.5, g_b = 1$) in which the neck and hip rotations were penalized. The gains for the visual feedback manipulation were based on results of preliminary testing. Each experimental block consisted of 100 trials with basketballs coming from a 45 degrees angle alternately from the left and the right. Between the experimental blocks was a short break in which a video was shown on the HMD to mask the transition between the blocks.

The training block consisted of 10 trials in which the basketball was coming from 0 degrees to 90 degrees alternately from the left and the right. In each training trial the angle of the basketball was increased by 10 degrees. We checked the 90 degrees angle to ensure that participants were able to perform the second block of the experiment in which larger rotations were required to compensate for the neck and hip rotation penalty.

At the end, the experimenter took off all devices. Then, participants filled out post-questionnaires, were informally interviewed and debriefed. The total time per participant including instructions, training, experiment, breaks, questionnaires and debriefing took 60 minutes while the actual experiment took approximately 12 minutes.

3.5 Recorded Measures

We recorded the tracked position and orientation data with a sampling rate of 60Hz. In particular, we recorded the hip, back and neck orientation at the end of each trial for further analysis. Additionally, we noted whether the ball was successfully caught during the trial.

Participants filled out the German version of the Tampa Scale of Kinesiophobia (TSK-DE) to investigate their pain related fear of movement/(re)injury (Kori et al, 1990, Vlaeyen et al, 1995, Nigbur et al, 2009). As the evaluation experiment involves relatively fast rotational movements and the visual feedback differed from the real movement in the test block, we wanted to record the level of simulator sickness caused by the experiment. Therefore, participants filled out Kennedy's simulator sickness questionnaire (SSQ) immediately before and after the experiment (Kennedy et al, 1993). In addition, participants filled out the Slater-Usuh-Steed (SUS) presence questionnaire (Usuh et al, 1999), and a questionnaire collecting anthropologic data and informal responses after the experiment.

3.6 Data Analysis

For statistical analysis, we used the R software (version 3.0.2) from R Foundation for Statistical Computing (R Core Team, 2013). Significance was determined at the level of $p \leq 0.05$ for all comparisons. We tested the assumption that the data is normally distributed with the Shapiro-Wilk test. The age of the participants and the TSK-DE scores were compared between groups using the Welch two sample t-test, and the pre and post SSQ scores were tested for significant differences using the paired t-test. All questionnaires were additionally analyzed using non-parametric tests (Wilcoxon Rank Sum and Signed Rank Tests).

For the analysis of changes in motor behavior concerning back rotations of participants induced by our approach, we calculated the proportion of the back rotation on the total body rotation $p_b = \theta_b / (\theta_h + \theta_b + \theta_n)$, where $\theta_h, \theta_b, \theta_n$ are the hip, back and neck rotations at the end of the trial. As penalizing some of the body rotations of participants inevitably lead to an increase of the amount of body rotations including the back rotation of participants, we analyzed the proportion of the back rotation on the total body rotation. The repeated measures of each experimental block were averaged to provide one proportion of back movement for each block and each participant. All trials in which the basketball was not caught, i.e. the participant had not performed the intended rotation, were discarded (67 of 6800 trials, < 1%). We used Levene's Test to analyze variance homogeneity between the groups. In a 2 (group: CG, PG) \times 2 (block: baseline, test) mixed model analysis of variance (ANOVA) we tested for differences between groups and between experimental blocks. For significant effects, we performed post-hoc pairwise comparisons using paired and Welch two sample t-tests.

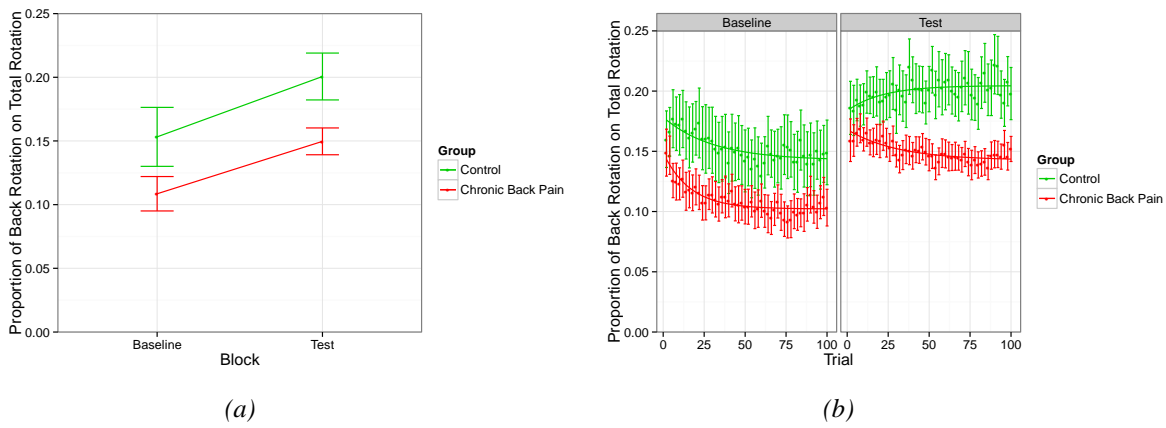


Figure 3. Result plots for the proportion of back rotations on the total body rotation at the end of each trial. The error bars indicate ± 1 standard error of the mean. (a) Mean proportion of back rotation for both groups and both experimental blocks. Chronic back pain participants use on average less back rotation compared to the control participants. The proportion of back rotations was increased during the test block for both groups. (b) Time course of the proportion of back rotation for both groups and both experimental blocks. The solid lines show the fitted exponential functions $(a - b)e^{-t/\tau} + b$. While the motor adaptation of participants is similar for both groups in the baseline block, it differs during the test block. Control group participants increased their proportion of back rotation over time until an asymptotic limit was reached in the test block. Otherwise, participants decreased their proportion of back rotation over time.

In addition, we investigated the time course of motor behavior adaptation induced by our approach in order to measure the stability of the effect over time. Therefore, we fitted the exponential function $(a - b)e^{-t/\tau} + b$ to the proportion of back rotation using a non-linear least squares fit. The time constant $\tau \in \mathbb{R}$ reflects the speed of adaptation from an initial towards an asymptotic proportion of back rotations $b \in \mathbb{R}$, the time in trials is denoted by $t \in \mathbb{R}$, and $a \in \mathbb{R}$ is the intercept at time $t = 0$. We combined the rotation directions for each participant by averaging every two consecutive trials, as the basketball came alternately from the left and right side. Then, the proportion of back rotation was averaged over all participants for each trial.

3.7 Results

Figure 3(a) shows a comparison of the mean proportion of back rotation on the total body rotation of participants between the baseline block (without visual feedback manipulation) and the test block (with visual feedback manipulation) for both groups. Participants of the control group showed a significantly higher variability of the proportion of back rotation compared to the participants with CBP in the test block, $F(1,32) = 4.24$, $p < 0.05$, and a trend for higher variability in the baseline block, $F(1,32) = 3.91$, $p = 0.057$. There was no interaction effect between the factors group and block, $F(1,32) = 0.11$, $p = 0.74$. We found that both the group, $F(1,32) = 4.63$, $p < 0.05$, and the block, $F(1,32) = 21.52$, $p < 0.001$ had a significant effect on the proportion of back rotation. Post-hoc analysis revealed that the average proportion of back rotations was greater in the test block (CG: $M = 0.20$, $SE = 0.02$, PG: $M = 0.15$, $SE = 0.01$) compared to the baseline block (CG: $M = 0.15$, $SE = 0.02$, PG: $M = 0.11$, $SE = 0.01$) for both the control group, $t(16) = -2.93$, $p < 0.01$, $r = 0.59$, and the CBP group, $t(16) = -4.07$, $p < 0.001$, $r = 0.71$. In addition, the average proportion of back rotations was significantly greater for the control group ($M = 0.20$, $SE = 0.02$) compared to the CBP group ($M = 0.15$, $SE = 0.01$) in the test block, $t(25.45) = 2.40$, $p < 0.05$, $r = 0.43$, but differed not significantly between the groups (CG: $M = 0.15$, $SE = 0.02$, PG: $M = 0.11$, $SE = 0.01$) in the baseline block, $t(25.76) = 1.66$, $p = 0.11$, $r = 0.31$. As the age of participants differed significantly between the control and CBP group, $t(16.92) = -5.09$, $p < 0.001$, $r = 0.78$, we compared the control group to a subset of the CBP group with an age range similar to the control group (3 males, 3 females, age: 16–31, $M = 24.2$, $SD = 6.4$) to investigate whether the group difference was mainly driven by age. These comparisons also revealed that the average proportion of back rotations was significantly greater for the control group ($M = 0.20$, $SE = 0.02$) compared to the subset of the CBP group ($M = 0.15$, $SE = 0.01$) in the test block, $t(20.87) = 2.34$, $p < 0.05$, $r = 0.46$, but differed not significantly between the control group ($M = 0.15$, $SE = 0.02$) and the subset of the CBP group ($M = 0.12$, $SE = 0.02$) in the baseline block, $t(18.60) = 1.05$, $p = 0.31$, $r = 0.24$.

Figure 3(b) shows the time course of the mean proportion of back rotation on the total body rotation for both groups and both experimental blocks. The solid lines show the fitted exponential functions $(a - b)e^{-t/\tau} + b$ for each combination of group and experimental block. In the baseline block, the motor adaptation of participants

seemed to be similar for both groups. The average proportion of back rotation decreased over time (time constants: CG $\tau = 30.4072$, PG: $\tau = 16.4344$) from an initial proportion of back rotations (intercepts: CG: $a = 0.1783$, PG: $a = 0.1487$) towards the asymptotic limit (CG: $b = 0.1425$, PG: $b = 0.1022$). In contrast to the baseline block, the motor adaptation of participants differed between the groups in the test block. For the control group, the average proportion of back rotations increased over time (time constant: $\tau = 21.4383$, intercept: $a = 0.1837$) towards the asymptotic limit ($b = 0.2046$), but decreased over time (time constant: $\tau = 30.9652$, intercept: $a = 0.1682$) towards the asymptote ($b = 0.1425$) for the CBP group. The difference between intercept and asymptote was similar between the groups (CG: 0.0209, PG: 0.0257) in the test block and decreased in the CBP group from the baseline block (0.0465) to the test block (0.0257) by 44.7%. In the CBP group the time constant increased from the baseline block ($\tau = 16.4344$) to the test block ($\tau = 30.9652$) by 88.4%.

We found no difference for pain related fear of movement using the TSK-DE questionnaires between the control group (CG) ($M = 28.20$, $SE = 1.37$) and the chronic back pain group (PG) ($M = 32.38$, $SE = 1.93$), $t(26.71) = -1.76$, $p = 0.09$, $r = .32$ (3 participants were excluded due to missing answers in the questionnaire). The simulator sickness caused by the experiment differed between the groups. In the CBP group, there was no significant difference between the mean SSQ score before the experiment ($M = 29.7$, $SE = 6.90$) and after the experiment ($M = 36.3$, $SE = 8.05$), $t(16) = -1.11$, $p = 0.28$, $r = 0.27$, whereas the SSQ score significantly increased from $M = 8.14$, $SE = 1.58$ before the experiment to $M = 30.8$, $SE = 9.03$ after the experiment for the control group, $t(16) = -2.81$, $p < 0.05$, $r = 0.58$. Participants rated their sense of presence in the virtual basketball game with an average score of $M = 3.60$, $SE = 0.27$. We found that on average participants of the control group rated their sense of presence ($M = 4.16$, $SE = 0.36$) significantly greater than the participants of the CBP group ($M = 3.05$, $SE = 0.36$), $t(32.00) = 2.18$, $p < 0.05$, $r = 0.36$.

4. DISCUSSION

The results of our evaluation show that our approach to manipulate the visual feedback using gains to penalize specific components of the body rotations is a viable way to change the motor behavior. Participants of the control group made proportionally more back rotations and showed a higher variability of back rotations compared to the CBP patients. We expected this difference between the control and CBP participants due to the often-found stiffness of the trunk in CBP patients as stated in the introduction. Although the control participants were considerably younger than the CBP patients, we found no evidence that the difference in back rotations between groups was mainly driven by the age of participants. It is interesting to note that in the test block the CBP group showed nearly the same average proportion of back rotations compared to the control group in the baseline block, which suggests that CBP participants used less back rotations in the baseline block even though they were generally able to use the same amount compared to control participants. More importantly, despite the differences between the groups, both groups increased the back rotation in the test block by an equal amount compared to the baseline block and therefore showed the same response to the visual feedback manipulation. On average participants proportion of back rotations on the total body rotation was increased by 4.7% for the control group and 4.1% for the CBP group to accomplish the goal of catching the ball, when the hip and neck rotations were penalized with a gain of 0.5.

For the motor adaptation over time, we expected that participants learn the benefit of back rotations compared to the other rotations in the test block. Indeed, we found that the control group increased the proportion of back rotations during the test block. The CBP group slightly decreased the proportion of back rotations, but less and slower than in the baseline condition. A likely interpretation is that CBP patients chose a strategy in-between the benefit of using more back rotations compared to the other rotations and the CBP-typical minimization of back movements.

The CBP group was not kinesiophobic according to a cut-off score of 37 (Vlaeyen et al, 1995). This shows that our sample of CBP patients represents a different selection from the population than in typical studies for validating kinesiophobic measures. However, the mean TSK score for the CBP group was comparable to symptomatic groups of other pain related movement studies in virtual reality environments (Sarig-Bahat et al, 2010). Since the CBP patients made less back rotations our study supports the results by Lamoth et al. (2006) who found that the kinematic changes during walking were not correlated with fear avoidance measures.

Some participants had problems with the VR hardware and reported that the HMD pressed on the forehead after time. However, in the CBP group no simulator sickness was caused by the visual feedback manipulation of the experiment. Although we found that in the control group simulator sickness was increased after the experiment, the effect was mainly driven by three participants with a large deviation of the pre- and post-SSQ score difference to the other participants of the group. This was also manifested in a non-normal and skewed distribution of the data, which is problematic for the statistical tests. The difference between pre- and post-SSQ score is comparable to findings of visual feedback manipulation in redirected walking experiments (Steinicke et

al, 2010). Therefore, we assume that some participants are vulnerable to simulator sickness in general and the experiment did not caused unexceptional simulator sickness.

While the evaluation has shown the potential of the approach to alter the motor behavior of participants, in a next step the clinical applicability of the approach must be tested. In particular, it would be of interest to investigate if CBP patients also use more back movements in real life after taking part in the virtual reality session. Another interesting question is if training during repeated usage of the approach reduces the pain intensity and thus improves the quality of life of these patients. One may also expect that patients are more willing to use playfully virtual training compared to plainly performing the involved movement exercises, but this remains to be tested. Although we have used a specific task (ball catching) to evaluate our system, one must keep in mind that the big advantage of our method is that no particular task is required to induce the increase of back rotations. Instead any task involving body rotations can be used, thereby providing the opportunity to tailor the task to a patient's specific preference or need. Likewise, although our system is developed for patients with problems of the lower back, similar approaches could be used for other movements and problems, such as neck or shoulder pain.

Acknowledgements: Authors of this work are supported by the Deutsche Forschungsgemeinschaft (DFG 29160962) and Bundesministerium für Bildung und Forschung (BMBF 01EC1003A). We thank Lina Valtin and Sascha Kuck for their help with conducting the experiment.

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