Ball Throwing Games in Virtual Reality for Motor Rehabilitation

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Abstract

Rehabilitation of motor impairment is a long and intensive process that should be challenging, task specific and motivating. Hence, researchers and clinicians are increasingly considering the use of virtual reality (VR) technology. This paper presents an interactive VR environment, which replicates a successful rehabilitation therapy through ball throwing games. In the developed VR system patients interact with a virtual therapist by throwing and catching of a virtual juggling ball. The VR system employs a novel learning-based framework for online synthesis of realistic complex body movements, which are reactive in real-time to the environmental parameters, to generate a therapist-like response of the avatar. The functionality of the VR system was validated using healthy subjects in two experiments replicating the rehabilitation procedure. The results suggest that healthy subjects adapt without difficulty to the virtual environment and that a high level of immersion was achieved.

Keywords: Motor rehabilitation, virtual reality, computer animation, movement synthesis, machine learning

1. Introduction

Rehabilitation of motor impairment is a long and intensive process. Current clinical and motor learning studies suggest that rehabilitation procedures should be challenging, intensive, task-specific and motivating. One such therapeutic training program that offers a goal-directed functional task that is familiar and motivating, yet challenging and intensive, is through games involving throwing and catching balls. It has been shown that this task is not only motivating, demanding and induces brain plasticity (Draganski et al., 2004; Sampaio-Baptista et al., 2015), but since it requires the coordination of arm movement and postural control, it also improves coordination and balance (Rodrigues et al., 2016). Furthermore, studies exploiting observation and response to natural ball movement demonstrated improvements to arm movements and trunk-arm coordination of Parkinson's patients (Majsak et al., 2008; Ma et al., 2012). Therefore, juggling tasks appear to be an appropriate training procedure to improve patients' motor function.

Accurate repetitions of these coordinative tasks are key points for successful physiotherapeutic treatment. However, these tasks are often strenuous for the patient and the rehabilitation efficiency depends on the subject's motivation. Hence, with the advance of technology over the last decades, researchers and clinicians are increasingly considering the use of virtual reality (VR) technology for motor impairment rehabilitation. Numerous studies provide evidence of learning of motor skills in virtual environments (VEs) (e.g. Holden, 2001) as well as their transfer to real world situations (e.g. Rose et al., 1998). Moreover, using virtual moving targets was found to be as effective as using real moving targets in arm movement rehabilitation (Wang et al., 2011). Other studies of ball games in VR setups were shown to be effective for the rehabilitation of patients suffering from Parkinson's disease (Su et al., 2014), stroke (Trojan et al., 2013) or hemiparesis (Viau et al., 2004). Additionally, using VR offers several advantages over physical reality. For example, a precise manipulation of ball properties and kinematics otherwise not achievable in physical reality is possible in VE (Zaal & Michaels, 2003). The intensity of the therapy could be adapted to the patients' needs and simultaneously recognise and encourage correct movements that can improve motor function whilst discouraging incorrect movements, which would otherwise lead to a deterioration of the motor behaviour (e.g. Barzilay & Wolf, 2013). Furthermore, the recent decrease in the cost, increased portability and wider

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availability of VR technologies makes it more attractive for motor rehabilitation, since these trends allow patients to carry out supervised rehabilitation exercises remotely, e.g. from home.

In this report, a novel approach to rehabilitation of motor impairments utilising VR is introduced. During a rehabilitation session the patient experiences the VE through head-mounted display (HMD) and the patient's kinematics are tracked real-time via a motion capture (MoCap) system. The novelty of this system lies in the virtual therapist movement generation, which is achieved through synthesis of real pre-recorded therapist motion. The developed VR system was tested on healthy subjects in series of pilot experiments, demonstrating its possibilities in therapeutic rehabilitation training.

2. Coordinative physiotherapy task and protocol

The developed Virtual Environment (VE) aims at rehabilitation therapy of motor impairment through ball throwing games. This clinical rehabilitation process arises from a well-established coordinative physiotherapy procedure with ataxia patients - a behavioural, active, self-determined and evidence-based training process (Brötz, 2015). Several studies have demonstrated the short- and long-term effectiveness of this procedure for improving coordination and balance as well as individual goal attainment of patients with ataxia (e.g. Ilg et al., 2010). The essential idea governing the coordinative physiotherapy implements repeated training of demanding tasks on coordination, throughout which the patients are asked to give up the typical fixations of their trunk and extremities, and instead accept the uncontrolled, swaying movements. Such relaxation in fixations tends to result in motor learning and improved movement control. From the repertoire of coordinative physiotherapy tasks, this study addresses the interactive task of ball juggling. Here, the patient and therapist collaboratively exchange a ball using underhand throws and as such avoid a direct contact, thus lessening the possible negative effect introduced by haptic devices in the VR scenario.

An important feature of this therapy is that the complexity can be scaled by using up to three balls, by varying the catching technique (under- and over-hand) and by the order of throwing and catching when using multiple balls. Throughout the rehabilitation procedure, the therapist assesses the patient's performance and adjusts the throws to vary the difficulty of the task for the patient and to match the difficulty level of the task optimally to the motor skills and motivation of the patient.

The presented work addresses the basic form of the rehabilitation procedure, and is aimed towards patients with mid to high motor impairment. The task is illustrated in Figure 1. During the rehabilitation process the therapist and patient stand opposite each other approximately 1.5-2 m apart and throw a single juggling ball (7.5 cm diameter, 200g) back and forth. First, the therapist throws the ball to the patient. The patient catches the ball and throws it back to the therapist. The exchange then continues until the ball is dropped, at which point the task is restarted by a new throw of the therapist. The distance between the therapist and patient can be adjusted according to the motor capabilities of the patient. The rehabilitation training assumes underhand throws and catching the ball with palm of the hand facing upwards. Furthermore, the therapist and the patient aim to throw the ball such that the catching of the ball by the other party is as easy as possible. This involves throwing the juggling ball to the height that is slightly above the head height (~2m), which results in the ball arriving to the catcher's hand almost vertically, i.e. perpendicular to the ground. The therapist also ensures that the throw is as accurate as possible to ensure that patient is able to catch the ball well. For patients with higher skills the throwing style can be modified in order to make the task harder, e.g. by introducing variability to the throwing target and the height of throws.

3. The virtual reality framework

An interactive VR environment was developed, which directly implements the physiotherapy process. Many simple VR applications in clinical and rehabilitation studies are restricted to basic control of primitive objects in plain environments. In more complex rehabilitation games, the avatars are animated by sequencing of pre-recorded motion, which often appear unnatural. In contrast, here the goal was to develop a realistic VR environment where patients directly interact with the virtual ball and environment as in the real world.

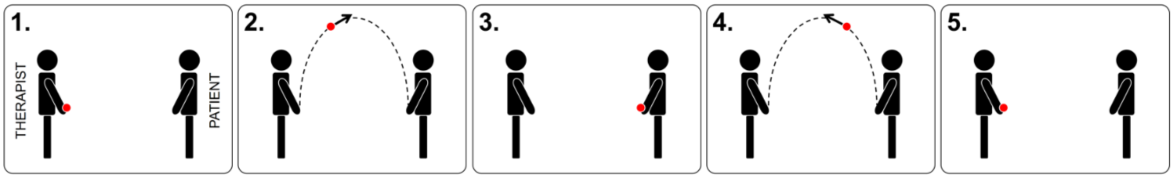

Figure 1. Coordinative physiotherapy task.

3.1. System architecture

The overview of the developed VR system is displayed in Figure 2. The top section presents the subject as an integral part of a real-time feedback loop. In this feedback loop, the subject's motion and action is measured through a set of input devices, whose data is processed in real-time and returned to a HMD that returns visual feedback to the subject. Ten-camera MoCap system (Vicon, Vicon Motion Systems, Oxford, United Kingdom) was used to capture the subject's motion at 120Hz acquisition frequency, where each subject was equipped with a set of reflective markers (14 cm diameter) placed according to a modified Plug-in-Gait marker set (Figure 2). The MoCap data were reconstructed using dedicated software (Vicon Nexus 2.6.1). The action of hand closing and opening was monitored using a custom-made two-state switch device (Figure 2) that was securely attached to the right hand of the subject. As an added feature, this device also provided haptic feedback when the subject interacted with the virtual ball. Visual feedback was displayed to the subject via an nVisor SX60 HMD (NVIS Inc, Reston, USA) at a resolution of 1280x1024, 60 fps and 60° field-of-view.

A significant section of the VR system comprises the purpose-specific real-time process manager software, developed using C# 7.0, responsible for continuous operation of the VE. The primary function of this software is to manage all the processes related to the VE with the following components:

- *Subject avatar controller*, which processes the MoCap data and translates the captured subject's movement directly onto the avatar. The communication with the Vicon MoCap system was realised using the Vicon DataStream SDK 1.7.1 that supplied a real-time stream of marker positions as well as the open/close state of the subject's hand from the haptic device. The properties of individual joints for the subject controlled avatar were then evaluated by calculating the joint centre positions from the relevant group of markers and the rotation angles utilising the respective root joint positions.

- *Real-time physics engine*, which provides real-time simulation of object dynamics and oversees the collisions amongst the objects and avatars, creating realistic object interaction. To manage the object collisions in the VE the custom-developed physics engine fitted the virtual room, environment objects, therapist and patient avatars, and the virtual ball with appropriate cuboid, spherical and cylindrical colliders. Every frame the avatar and environment colliders were tested for intersections with the virtual ball and appropriate physical response was applied to the virtual ball accordingly.

- *Therapist avatar controller*, which is responsible for human-like movement of the therapist avatar. Section 3.2 provides a detailed description on how this is achieved.

- *Data storage*, which maintains the important VR session data and stores it for later analysis.

- *Renderer communication client/server*, which provides a continuous data stream between the process manager and the renderer. The data sent via custom-designed TCP/IP server to the VE renderer is composed of information on the joint positions and angles for both therapist and patient avatars as well as the current position of the virtual ball.

- *Scene renderer*, which provides an environment that allows users to see and interact with scenarios in the VE and is realised using the Unity3D (v 2017.1) game development platform. The rendered VE consists of a furnished room resembling a therapist's rehabilitation office, an avatar representing the therapist, an avatar controlled by the patient and a juggling ball (Figure 2). Great effort was made to design the VE in order to enhance the effect of immersion and to be stimulating, but not distracting, to the user. The avatar poses and ball positions in the environment were updated at 60 fps.

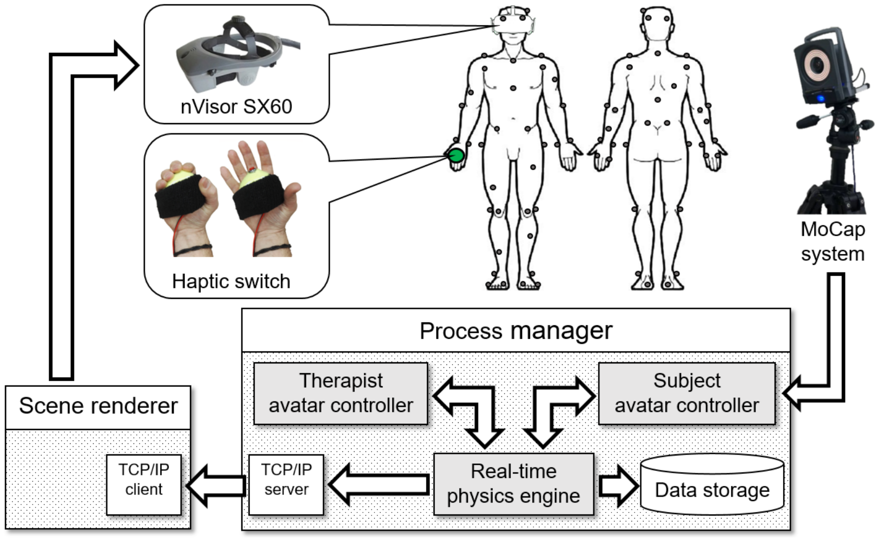

Figure 2. System architecture.

3.2. Animating the therapist avatar

The objective, when animating the therapist avatar, was to achieve therapist-like performance in catching and throwing. To that end, previously developed real-time synthesis model for complex full-body coordination patterns was utilised, where the controller is based on flexible task-dependent kinematic motion primitives extracted from recorded therapist motion.

For the first stage of the kinematic modelling of arm-and-upper-body throwing and catching movements a dataset of therapist's under-hand throws and catches during the physiotherapy task described in section 2 was recorded. Therapist and a healthy subject were equipped with reflective markers according to the modified Plug-in-Gait marker placement (Figure 2) and their movement was recorded using the ten-camera Vicon MoCap system. The task was to perform alternating throws and catches while standing face-to-face at a comfortable distance (approx. 1.65m).

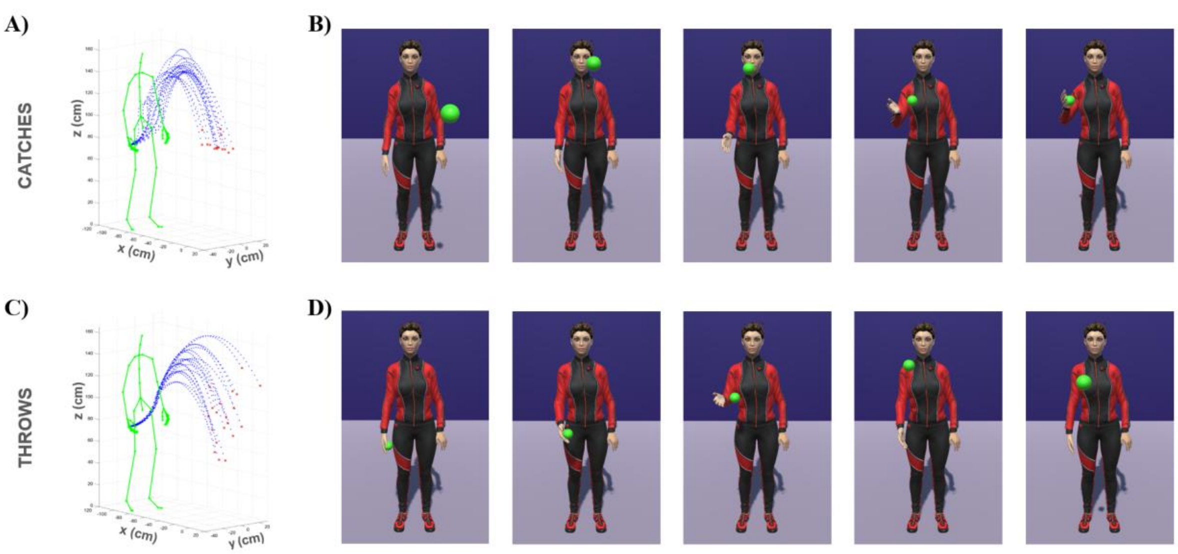

Figure 3: Captured and synthesised catching and throwing motion of the therapist. A) and C) depict resulting dataset of captured motion for ball catching (red crosses represent the starting points of ball trajectories) and ball throwing (red crosses represent goal points of the ball trajectories) respectively. The adjacent panels show screenshots of a synthesised catch (B) and a synthesised throw (D) ordered temporally from left to right.

The captured data of the therapist were segmented into throwing and catching episodes separately, including the ball fly phase, and then retargeted to a human avatar of identical size using MotionBuilder (Autodesk). The data were exported as local joint positions and angles for the human skeleton of the avatar and were first pre-processed in Matlab (Mathworks) by interpolation techniques enforcing the periodicity of each throw, starting and ending at the same "parking" arm posture, while the other body angles including torso were kept constant equal to the averaged freestanding posture. The second step of pre-processing was time warping of the arm trajectories, so that the total duration of the motion starting and ending at the same "parking" arm posture was equal to 1 sec. In this time warping, the ball free flying phase duration is preserved and the hand velocity at the moment of ball release and catch remains intact. Due to the pre-processing of the arm-trajectories, the hand position and orientation at the critical moment of ball touch or release are changed. Accordingly the instantaneous ball velocity at these moments was recomputed, and the whole ball trajectory was re-simulated, but for the same free flying phase time using a physics model for the ball. The resulting datasets for all retargeted trajectories are depicted in Figure 3AC.

Kinematic primitives were learned by anechoic demixing of the joint angle trajectories exploiting an algorithm by Chiovetto et al. (2016). The re-synthesis of the motion involves the linear blending of the anechoic source weights, while keeping their delays constant (Mukovskiy et al., 2015). To infer the source weights online the following task parameters were used: the azimuth and elevation angles and the absolute velocity of the ball at the moment of expected catch, the distance, the height difference and the time-in-the-air of the ball free flying phase. The inference is performed using Locally Weighted Linear Regression. The synthesis of the catching motion is similar, where the task parameters are the ball parameters at the moment of the ball release. The real-time motion synthesis architecture was implemented in C# 7.0 and integrated into the real-time process manager software described in Section 3.1. Figure 3BD illustrates resulting catching and throwing actions by the virtual therapist in the VE.

3.3. System validation

The level of immersion is very important, since the system is intended for use by patients. Hence, system functionality and immersion was validated through a set of pilot experiments evaluating the performance of catching and/or throwing actions. Two experiments were performed by healthy subjects.

3.3.1. Open loop interaction: catching

The first validation experiment tested the subjects' quality of immersion through their ability to catch virtual balls thrown to them by the therapist avatar. Ten healthy adults (four female and six male) aged 25.7±5.0 took part in the experiment. The subjects were equipped with HMD, haptic device and a set of reflective markers.

The subjects familiarised themselves with the VE for two minutes prior the actual experimental session. They were presented with the virtual room, a stationary virtual therapist and a virtual ball, and were allowed to explore the VE. Interaction with the ball using the haptic device was also possible. If the ball was within a specified proximity of the hand and hand-closed event was triggered, the ball was attached to the palm of the virtual hand and remained attached until hand-open event was detected. Otherwise the ball behaved under normal physics. After familiarisation one minute resting was allowed before starting the experiment. During the experiment, the subjects were asked to catch the ball thrown to them by the virtual therapist. Following every successful catch subjects could clearly see the ball in their virtual hand. The experiment consisted of 60 different throws and was split into three sessions each containing 20 throws. The 60 throws were randomly selected from the throwing training set. Each throw was a result of direct one-to-one mapping between the movement of the actual therapist and the learned avatar motion.

Out of the 60 throws by the virtual therapist, 53.3±2.3 thrown balls were caught on average, which corresponds to a 88.8±3.8% success rate. A further analysis of the trajectories of the virtual ball and subject controlled hand during unsuccessful catching attempts revealed that the virtual ball was always correctly intercepted, i.e. the ball and hand trajectories intersected, however, the subjects did not close the hand in time to successfully complete the catching action. By design, if a hand-close event was detected before the ball hit the hand, the attempt was classified as a successful catch. The virtual ball impact points on the subject hand during successful catches were found to be on average 49.0±27.9 mm from the centre of the virtual palm. The distribution of the impact points centred in the middle of the virtual palm (-1.4±36.8 mm, -2.6±42.6 mm), however there was greater variability towards the thumb and index finger side of the hand (Figure 4A).

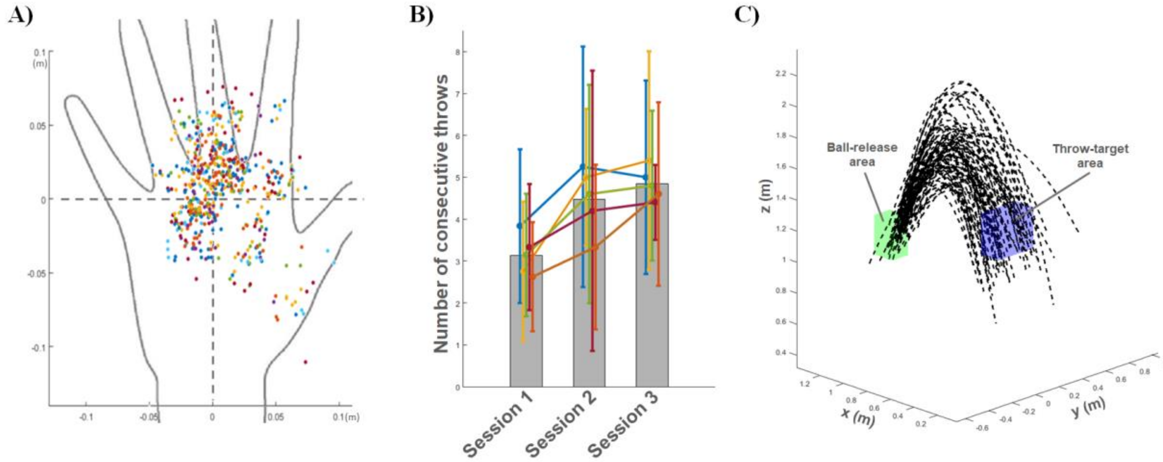

Figure 4. A) The distribution of virtual ball impact points on the palm of a subject controlled hand during catching. Each colour represents a set of catches by single subject. B) The mean number of consecutive throws by subject and virtual therapist for each one-minute session. The coloured data represents the mean performance per subject and grey bar represents the overall mean performance. C) A sample of throwing trajectories successfully intercepted by the virtual therapist. The green and blue areas correspond to the ball-release and throw-target areas from the experiment.

3.3.2. Closed loop interaction: catching and throwing

In order to validate the functionality of the virtual therapist's control algorithm, a second experiment was conducted that evaluated the subjects' performance in the physiotherapy catching-throwing task. Five healthy adults (one female and four male) aged 27.8±6.2 participated in the experiment. Similar to the previous experiment, the subjects were equipped with an HMD, haptic device and a set of reflective markers.

The subjects were already familiar with the VE from the previous experiment, however they underwent a 5-minute familiarisation to the newly introduced VE features of ball-release and throw-target areas. These areas were displayed as semi-transparent 3D boxes and their dimensions were determined by the training set of throw releases and catches used in designing the controller for the virtual therapist. The width, depth and height of the release and target areas were 0.133×0.1545×0.225m and 0.3×0.267×0.15m respectively. During the familiarisation period, the subjects were allowed to throw the ball freely as well as practice more targeted throws from the ball-release box towards the throw-target box. The virtual therapist did not react to the throws during this period. The experiment was split into three one-minute sessions. The subjects were asked to throw the virtual ball to the virtual therapist and then catch it, when thrown back at them. A successful throw was one, where the ball flight phase commenced within the ball-release area and its projected trajectory intersected the throw target area. Both areas remained visible throughout the experiment. If the ball was not released within the specified area and/or part of its trajectory did not intersect the target area, the virtual therapist did not react to the throw. At the start of each session or following each unsuccessful catch or throw, the virtual ball appeared in front of the subject, remaining stationary mid-air until retrieved by the subject.

Table 1 shows the results of each session for each subject. The average number of consecutive throws by either subject or virtual therapist between all subjects was 3.1±0.4, 4.5±0.7, 4.8±0.3 for sessions 1, 2 and 3 respectively (Figure 4B) and the highest number of continuous interactive throws was 9. The analysis of the throws successfully caught by the therapist avatar located the average throw-release at (0.01±0.022m, 1.21±0.054m, 1.08±0.095m), which was located within the ball-release area (Figure 4C). The release velocity of the ball was 3.5±0.4 ms^{-1} and the apex of the ball trajectory was at 1.7±0.17m w.r.t. the ground.

Subject	Session 1	Session 2	Session 3
1	1, 5, 5, 5, 2, 5	5, 2, 9, 5	7, 3, 3, 7
2	1, 3, 3, 1, 3, 1, 5, 5	5, 7, 3, 5	7, 5, 1, 7 ,7
3	3, 5, 3, 3, 1, 2, 5	5, 3, 3, 3, 9	3, 7, 5, 3, 6
4	3, 1, 5, 3, 5, 3	5, 1, 9, 1, 5	5, 3, 5, 4, 5
5	3, 1, 2, 3, 1, 5, 3, 3	3, 5, 5, 1, 1, 5	7, 3, 3, 7, 3

Table 1. Number of consecutive throws by subject and virtual therapist per catching and throwing session.

4. Discussion

The presented work introduced a VR system suitable for motor impairment rehabilitation, which implements virtual ball catching and throwing based on an established clinical procedure of a collaborative ball juggling game. The system was evaluated with healthy participants in two experiments with encouraging results.

The first experiment evaluated the subjects' ability to catch the ball in the VE. Although subjects were not always successful at catching the virtual ball, the results indicate that they were able to adapt well to the task. More importantly, the subjects were able to judge the distances within the VE correctly, which is evidenced by the high number of successful catches, but also by the overlapping ball and hand trajectories during the unsuccessful attempts. This suggests that high level of immersion was achieved.

The actual rehabilitation task was recreated in the second experiment. However, since this task was performed by healthy subjects, additional restrictions of specific ball-release and throw-target areas were imposed on the ball throwing technique. The results indicate that although the subjects were not able to exchange the ball with the avatar continuously, they managed up to nine consecutive throwing exchanges. The level of accuracy of the throws also indicates, that the subjects were able to control the virtual object well using the developed haptic device. Overall, in a short time period the subjects adapted well to the virtual environment and the presented task, which is evidenced by the learning effect manifested by inter-session increase in the number of successful ball exchanges. These results, considering the limitations imposed on the subject throws, support the suggestion from the first experiment that high level of immersion was achieved.

Despite the proven functionality of the developed VR system, more thorough testing of the system is required for application in the rehabilitation of patients with motor impairments. The intended target group of patients consists of ataxia and stroke patients with different severity of motor impairment and so far it is unclear how well these patients will accept the developed VE. Hence, future evaluations are required in order to identify patients' responses to the VE and the avatar.

Due to the fast advancement of VR systems and associated hardware, perhaps the most potential for improvement of the developed system lies in hardware upgrades ensuring that its portability and affordability remains up-to-date. Current system was developed with proof of concept in mind, thus focusing less on portability and more on accuracy of patient motion capture. However, low-cost and portable MoCap systems with comparable accuracy exist, which could substitute the one used in the developed VR (Müller et al., 2017). Such a system could improve the portability and also the usability by reducing the preparation time prior to a training session. Furthermore, the patient's immersion could be improved by replacing current HMD with one that provides higher resolution and FOV (e.g. Oculus Rift or HTC Vive). Alternatively, an augmented reality HMD could be used, which would allow for more natural interaction with the virtual therapist and improve the level of immersion by eliminating the need to generate the virtual room and body. Finally, the utilised haptic device provides only limited detection of finger movement, because it consists of hand-open or hand-closed states only. Monitoring the finger movement and simultaneously providing haptic feedback is essential during the presented rehabilitation task, hence the current haptic device could be substituted with a data glove that provides both capture of the finger movement as well as haptic feedback.

In order for the rehabilitation to be effective, it is essential to introduce processes, which will manage online evaluation of the patients' performance, and employ an adjustment mechanism for the throwing style and task-difficulty based on patient's improvement in skill and motivation. Future versions of the VR system will implement the above mentioned changes to hardware, software and subject populations.

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6. References

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: changes in grey matter induced by training. Nature, 427(6972), 311-312.

Sampaio-Baptista, C., Filippini, N., Stagg, C. J., Near, J., Scholz, J., & Johansen-Berg, H. (2015). Changes in functional connectivity and GABA levels with long-term motor learning. Neuroimage, 106, 15-20.

Rodrigues, S. T., Polastri, P. F., Gotardi, G. C., Aguiar, S. A., Mesaros, M. R., Pestana, M. B., & Barbieri, F. A. (2016). Postural control during cascade ball juggling: Effects of expertise and base of support. Perceptual and motor skills, 123(1), 279-294.

Majsak, M. J., Kaminski, T., Gentile, A. M., & Gordon, A. M. (2008). Effects of a moving target versus a temporal constraint on reach and grasp in patients with Parkinson's disease. Exp. Neurol, 210(2), 479-488.

Ma, H. I., Hwang, W. J., Wang, C. Y., Fang, J. J., Leong, I. F., & Wang, T. Y. (2012). Trunk–arm coordination in reaching for moving targets in people with Parkinson's disease: Comparison between virtual and physical reality. Human movement science, 31(5), 1340-1352.

Holden, M. K. (2001). Neurorehabilitation using "learning by imitation" in virtual environments. Usability evaluation and interface design: Cognitive engineering, intelligent agents and virtual reality, 1, 624-628.

Rose, F. D., Attree, E. A., Brooks, B. M., Parslow, D. M., Penn, P. R., & Ambihaipahan, N. (1998). Transfer of training from virtual to real environments. In 2nd European Conference on Disability, Virtual Reality and Associated Technologies.

Wang, C. Y., Hwang, W. J., Fang, J. J., Sheu, C. F., Leong, I. F., & Ma, H. I. (2011). Comparison of virtual reality versus physical reality on movement characteristics of persons with Parkinson's disease: effects of moving targets. Arch Phys Med Rehabil, 92(8), 1238-1245.

Su, K. J., Hwang, W. J., Wu, C. Y., Fang, J. J., Leong, I. F., & Ma, H. I. (2014). Increasing speed to improve arm movement and standing postural control in Parkinson's disease patients when catching virtual moving balls. Gait & posture, 39(1), 65-69.

Trojan, J., Diers, M., Fuchs, X., Bach, F., Bekrater-Bodmann, R., Foell, J., ... & Flor, H. (2014). An augmented reality home-training system based on the mirror training and imagery approach. Behavior research methods, 46(3), 634-640.

Viau, A., Feldman, A. G., McFadyen, B. J., & Levin, M. F. (2004). Reaching in reality and VR: a comparison of movement kinematics in healthy subjects and in adults with hemiparesis. J Neuroeng Rehabil, 1(1), 11.

Zaal, F. T., & Michaels, C. F. (2003). The information for catching fly balls: judging and intercepting virtual balls in a CAVE. Journal of Experimental Psychology: Human Perception and Performance, 29(3), 537.

Barzilay, O., & Wolf, A. (2013). Adaptive rehabilitation games. J Electromyogr Kinesiol, 23(1), 182-189.

Brötz, D. (2011). Koordinative Physiotherapie verbessert Feinmotorik bei zerebellärer Ataxie–Bewegungskontrolle der Hand. physiopraxis, 9(03), 26-30.

Ilg, W., Brötz, D., Burkard, S., Giese, M. A., Schöls, L., & Synofzik, M. (2010). Long-term effects of coordinative training in degenerative cerebellar disease. Movement Disorders, 25(13), 2239-2246.

Chiovetto, E., d'Avella, A., & Giese, M. (2016). A Unifying Framework for the Identification of Motor Primitives. arXiv preprint arXiv:1603.06879.

Mukovskiy, A., Land, W. M., Schack, T., & Giese, M. A. (2015). Modeling of predictive human movement coordination patterns for applications in computer graphics.

Müller, B., Ilg, W., Giese, M. A., & Ludolph, N. (2017). Improved Kinect sensor based motion capturing system for gait assessment. bioRxiv, 098863.