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ORIGINAL ARTICLE

Virtual reality game-based therapy for treatment of postural and co-ordination abnormalities secondary to TBI: A pilot study

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Abstract

Primary objective: The study objective was to test the efficacy of game-based virtual reality (VR) therapy as a mean of correcting postural and co-ordination abnormalities in individuals with traumatic brain injury (TBI). Therapy was done with interactive customized VR games and scenarios, utilizing an Xbox Kinect sensor.
Research design: The study was a pilot project using the structure of a phase II clinical trial.
Methods and procedures: Fifteen participants with mild-to-moderate chronic TBI-related balance and motor co-ordination impairments participated in 15 sessions, each lasting ~50–55 minutes, scheduled 2–3 times a week over 5–6 consecutive weeks. Participants were evaluated at baseline, immediately after the final session and in a 1-month follow-up with a battery of clinical tests (measuring postural stability, gait and co-ordination) and movement performance parameters. Movement parameters included arm–leg co-ordination, dynamic stability and arm precision, calculated from kinematic data recorded with Xbox Kinect sensor.
Results: Following therapy, most participants improved their static and dynamic postural stability, gait and arm movements. These effects persisted over the retention interval.
Conclusions: Results will be used to improve the VR program, with the goal of producing a cost-effective, accessible and easy to individualize therapeutic approach. The pilot data will be used for designing a larger scale clinical trial.

Keywords

Brain injury, clinical trial, motor recovery, postural control, rehabilitation, virtual reality

History

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Introduction

Individuals with TBI are considered to be one of the largest groups of people with disability worldwide [1]. The motor and functional abnormalities seen post-TBI do not have a typical condition-specific pattern. Instead they vary considerably from person to person. However, at least 30% of individuals with even mild TBI do present with impaired balance and motor co-ordination, with this proportion being higher as severity of brain injury increases [2–4]. The neural mechanisms underlying these impairments may include direct and indirect injury to the motor cortices, cerebellum and cortico-cerebellar loops, brainstem and basal ganglia and vestibular and somatosensory sensory systems [5–7]. With so many possible combinations, these impairments can affect postural stability in standing and walking, bi-manual and arm-postural interaction during functional activities, manual precision and agility, co-ordination of eye and head motions and the ability for gaze fixation and tracking of a moving target [8–10]. As a result of these complex impairments, quality-of-life after TBI is reduced and individuals are limited in their ability to participate in vocational, recreational and family activities [11].

Although the need to improve posture and co-ordination is recognized, there is limited understanding of optimal therapeutic approaches to address these issues in individuals with TBI [12]. The complexity and wide variation in clinical manifestations makes the formation of groups for research difficult. Logically, physical rehabilitation approaches should force multiple body segments to work in a co-ordinated manner, as this ability is often lacking post-TBI. However, typical rehabilitation programmes focus on separate programmes for restoring gait or posture or arm function. The lack of activities and programmes with a focus on restoration of whole body functioning and the complexity of these movements ultimately limits the extent of improvement that people with TBI reach in their activities of daily living and the related return to a productive and meaningful life.

Also, individuals sustaining TBI are typically young, injured between the ages of 15–24 [13]. They may be reluctant to adhere to the repetitive, un-engaging exercise sequences seen in the traditional therapeutic programmes which are still used for management of post-injury related movement abnormalities. These exercises, while physiologically sound, are intrinsically dull and can seem 'pointless' to the clients leading to poor compliance [14]. Clearly there is a need for

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development of evidence-based accessible therapies incorporating engaging state-of-the-art technologies for patients with co-ordination and postural abnormalities due to TBI.

To address this need, this study developed a game-based virtual reality (VR) therapy specific to the treatment of co-ordination and postural abnormalities following TBI. Instead of the usual sequence of simple exercises, the VR program includes custom-designed immersive video games and scenarios, in which a client's representative (avatar) interacts with a virtual environment via a relatively inexpensive portable motion tracking sensor (Xbox 360 Kinect). This VR therapy is different from the frequently used 'off-the-shelf' games (e.g. by Nintendo Wii or Sony EyeToy), which have also been considered for alternative rehabilitation exercises [15–18]. Since 'off-the-shelf' games are designed for healthy people without movement impairments, they are typically unable to scale the skill level to one that allows continued success and motivation for the population with moderate-to-severe post-TBI impairments. Another concern is that they may not enforce the precise motor performance needed for a specific therapeutic purpose. For example, the Sony EyeToy system allows virtual targets to be intercepted with any part of the body when a therapist might want a specific part such as the hand to be used. Also, the use of a hand-held controller (e.g. Wii) to carry out a gaming task is not equivalent to a movement performed with a body part in the real physical world. The controller is a hand-held tool, rather than part of the body controlled centrally, and as a result distorts movement kinematics [19].

The VR therapy uses an avatar who takes the participant through a session that simulates the sequencing, dosage and content of a comprehensive physical rehabilitation programme for treatment of co-ordination and postural abnormalities in persons with TBI. This is a relatively novel approach to the use of VR applications. Therapy is presented using a complex game-based series of activities, with content progressing logically from simple single-limb guided movements to complex whole body task-oriented actions. This is different from most of the studies of VR rehabilitation which have used single gaming applications rather than structured, carefully sequenced and complete therapies. These experiments, including this work, found VR applications effective for retraining cognitive and functional abilities [20–22], balance and mobility [23–25] and whole body co-ordination [26]. The goal of the current study was to test effect of VR therapy for treatment of postural and co-ordination deficits in a small group of persons with chronic TBI-related impairments. Preliminary results on the first cohort of study participants have been presented as a pilot study [27].

Methods

Participants

Fifteen individuals (10 male, five female) with chronic TBI (1–14 years post-injury) and with mean ± SD of age of 30.6 ± 8.5 years participated. Clinical and demographic data are presented in Table I. A sample size of 15 participants was calculated using data from the sub-set tested in the pilot study [26, 27] as sufficient to have 80% power at the $p = 0.5$ level. Severity of brain injury was determined based on duration of loss of consciousness (LOS) [2]. According to this classification, loss of consciousness for 30 minutes or less indicates mild TBI; >30 minutes and <24 hours moderate TBI and more than 24 hours severe TBI. Most participants (12) presented with mild (#1–5, Table I) to moderate (#7–13) TBI. Two had experienced severe TBI (#14, #15, Table I). In participant #7 the duration of loss of consciousness was not available.

All participants were able to stand unsupported for at least 2 minutes. Most demonstrated full or nearly full upper extremity range of motion, none had severely increased muscle tone and all had normal or corrected visual acuity. Living arrangements varied from independent to sheltered with full-time attendant care. Two participants (#9, #10) had mild hemiparesis and spasticity on their dominant body side. One participant (#7) had a visual field cut compensated with prism glasses. All participants had mild-to-moderate impairments of gait, postural control and upper extremity movements, with clinical test scores ranging from: (a) 34–53 points on the Berg Balance Scale (BBS) [28] where a score of 45 or less indicates an increased fall risk; (b) 10–28 points on the Functional Gait Assessment Test (FGA) [29], where 22 points or less indicates an increased fall risk; and (c) 2–21 points on the Klockgether Ataxia Scale [30] in which 35 points

Table I. Demographic data and clinical scores of patients with TBI.

#	Gender	Age (years)	TBI onset (years)	LOC	BBS (points)	FGA (points)	Ataxia (points)	FRT (inches)
S1	F	30	2.5	<30 min	44	22	4	10.5
s2	F	44	14	<30 min	46	20	6	12
s3	M	21	2	<30 min	52	28	6	13.5
s4	F	21	1.5	<30 min	52	27	2	15.5
s5	M	26	4	<30 min	53	28	2	15
s6	M	20	1	Unknown	53	27	2	15.5
s7	M	39	6	>30 min and <24 h	46	14	7	14.5
s8	M	38	1.5	>30 min and <24 h	46	22	4	14
s9*	M	26	5	>30 min and <24 h	42	18	2	15
s10	M	39	11	>30 min and <24 h	45	21	3	10
s11*	F	21	17	>30 min and <24 h	44	21	8	9.5
s12*	M	33	14	>30 min and <24 h	43	16	11	11
s13*	F	45	1	>30 min and <24 h	43	13	9	12.5
s14*	M	28	7	>24 h	34	10	21	10
s15*	M	28	4	>24 h	42	18	19	9

*Indicates that the participant was guarded during VR game performance.

identifies severe ataxia. Participants were able to reach forward without taking a step between 9–15.5 inches, measured with the Functional Reach Test (FRT) [31]. It is important to note that severity of brain injury and severity of impairments in different domains (cognitive, behavioural and motor) do not always correlate. This was noted in several of the participants.

However, none of the participants displayed cognitive or behavioural impairments sufficient to restrict therapeutic practice [32]. All participants exceeded 21 points on the 30-point Saint Louis University Mental Status Examination (SLUMS), indicating presence of no or mild cognitive disorders [33]. All participants and guardians, when indicated, signed an informed consent form prepared in accordance with the Helsinki Declaration and reviewed by the local Institutional Review Board.

All participants had previously completed several courses of conventional rehabilitation before involvement in VR practice and been discharged from formal rehabilitation services. After the initial injury they had been in acute care hospitalization from 1–6 weeks, followed by 2–8 weeks of sub-acute in-patient care and from 3–50 weeks of out-patient therapy. Each had received neuropsychology services, recreation therapy, speech and language therapy, physical and occupational therapy. Most therapies were provided in individual treatment sessions, scheduled 3–4 times per week. Physical therapy had addressed range of motion, muscle strength, balance, co-ordination and endurance. As clients either reached therapeutic goals or improvement ceased they had been discharged from formal rehabilitation, with occasional re-referrals. At the time of the study all participants had been discharged from conventional physical therapy for having reached a performance plateau.

VR therapy

The VR therapy consisted of a series of immersive VR games and scenarios for re-training whole body co-ordination, including arm co-ordination, posture and gait. The games were delivered with the Kinect Motion sensor (Microsoft, Inc., Santa-Barbara) and projected onto an 82-inch screen (1080p Mitsubishi DLP® TV bundle, RealD Beverly Hills, CA, Figure 1).

The therapy began with a 1 minute introduction by an animated human character—Personal Instructional Avatar (PIA). PIA explained the procedure and described the exercise approach. The introduction was followed by two conceptually different types of games, referred to as 'virtual teacher' and 'virtual challenger', with examples illustrated in Figure 2(a–c) and summarized in Table II. Sixteen 2-minute 'virtual teacher' exercises were demonstrated by PIA, who asked the participant to copy her movements. All actions were performed in sitting, with or without the use of an object (stick), with the aim of re-training intra- and inter-limb co-ordination, agility, balance and eye tracking abilities.

The 'virtual challenger' exercises differed from the 'virtual teacher' exercises by having an avatar representing, but not superimposed on the participant's movement. Each of the exercises had a goal and allowed flexible options for individual movement strategies to achieve the goal. Four

Figure 1. Experimental set-up with participant standing in front of the screen and playing game Skateboard.

custom-designed VR games/scenarios were used, with each short game round lasting 1 minute, then being repeated or modified according to the individual participant's needs. All games had been previously tested in individuals with chronic TBI. They included games entitled: Octopus, Courtyard, Boat and Skateboard [26, 27, 34]. Each game allowed advancement through several difficulty levels (e.g. increased speed, frequency of obstacles and distance to an object to intercept). The game tasks were accompanied by music and organized by the therapist so that the participant could not begin the next game until the previous one was completed. Successful performance of each game was rewarded by a number of points that accumulated throughout the entire gaming session with the goal of collecting as many points as possible. Furthermore, each scenario and game had particular criteria for success, used as an outcome parameter for the data analysis (see sub-section data collection and analysis).

The games and scenarios were developed with the use of WorldViz software (WorldViz LLC, Santa Barbara, CA) with computer graphics performed with Alias' Maya package for 3D animation (Maya®, Version 7.0.1; Autodesk, Inc., San Rafael, CA). The gaming system included a Dell Alienware M18 (quad-core 2.2 GHz Intel Core i7-2670QM processor) with a graphics accelerator (nVIDIA GeForce GTX 560 M) integrated with the Kinect Motion sensor (Microsoft, Inc.).

Training protocol

This pilot study was designed as a phase II clinical trial testing effect of VR therapy. This design does not require a control group. Although the experimental set-up allowed in-home delivery, the therapy was tested in a supervised clinical setting (Figure 1) to establish safety policies and criteria prior to further implementation. Therapy included

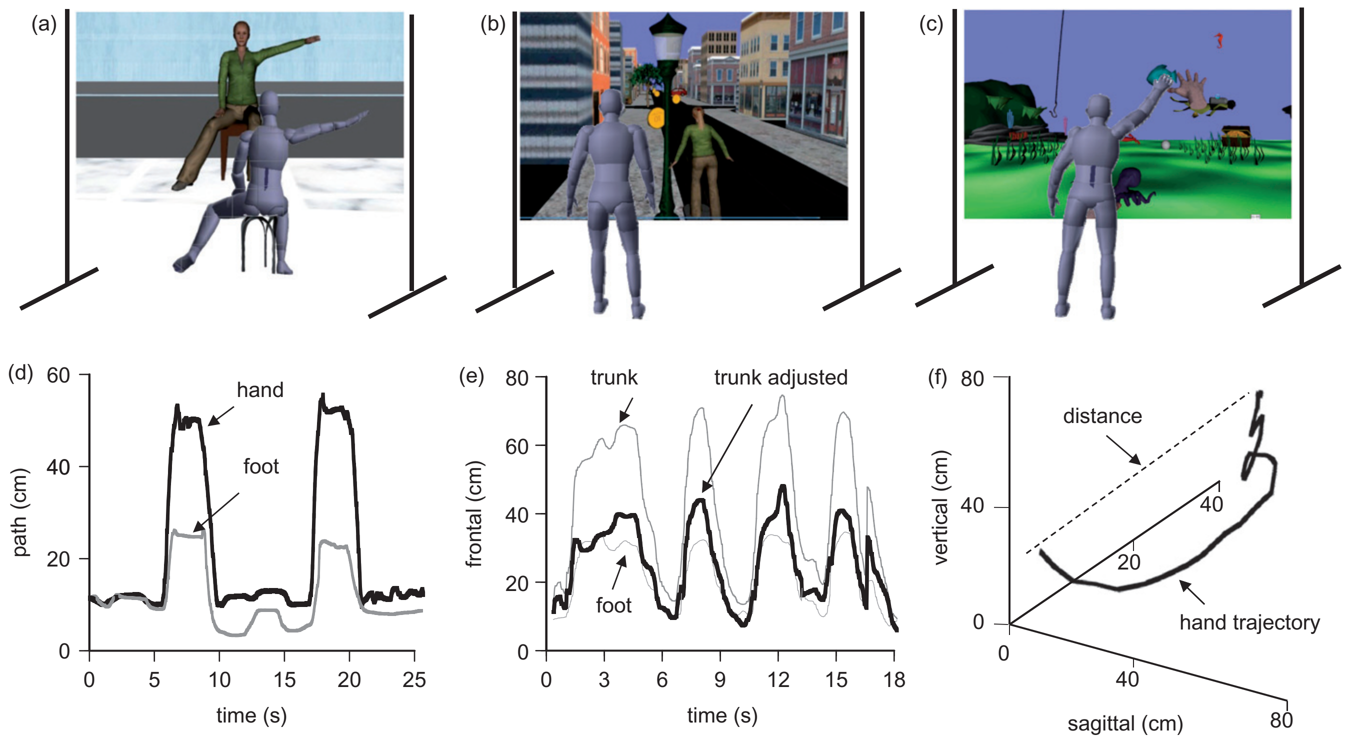

Figure 2. Three VR tasks performed by a participant during the Virtual Teacher Exercise (a), Skateboard, (b) Courtyard and (c) Octopus. Graphs illustrate trajectories of the body segment(s) of one representative participant, used for movement analysis. Co-ordination (d) was analysed as a cross-correlation of the dominant hand (black line) and the contralateral foot (gray line) path; dynamic stability (e) was calculated as RMS of adjusted trunk displacements (thick black line) in frontal plane; and arm movement curvature (f) was a ratio of the dominant hand path (black line) to the shortest distance (dashed line) between the initial and final hand position.

15 sessions, each ∼50–55 minutes in duration, scheduled 2–3 times a week over 5–6 consecutive weeks.

For the purpose of efficacy testing, an attempt was made to keep the sequence and timing of the training protocol as standardized as possible for all individuals. Some individual adjustments were unavoidable, based on client presentation and response to training. Fourteen participants performed games and exercises in a block practice format, beginning with virtual teacher exercises without an object, followed by virtual teacher exercises using a stick and then by sets of Skateboard (1–10 trials), Courtyard (2–5 trials), Octopus (1–10 trials) and Boat (1–3 trials) games. Game selection was based on participant impairment and adjusted as needed. One participant (#8, Table I) benefitted more from variable practice, as determined by his response to initial training sessions. This participant became flustered and had performance problems if the same game was repeated more than twice in a row, but was comfortable with sessions that mixed up the sequence. For that participant virtual teacher exercises were interspersed with game sets. Participants #9 and #10 had mild arm paresis and spasticity. To allow for maximum range of motion in the affected arm, upper extremity stretching and passive range of motion was done prior to the start of therapy. No other significant individual adjustments were made.

During the first session, the physical therapist evaluated the participant's capacity and tolerance for the exercises, selected suitable virtual challenge games and established the baseline for practice duration and difficulty level. Criterion for selection of the baseline was a participant's ability to successfully perform the exercise without physical assistance, engagement with the activity and impairments. For example, 'Boat' challenged visual-spatial orientation while 'Octopus' required bimanual co-ordination. Tiring after one round indicated a need to keep practice duration low, speed was adjusted to ensure success. Faded feedback on performance was used. During the first therapeutic session, the therapist guided the participant through the entire practice, sometimes demonstrating performance and providing supplementary instruction for the exercises. The typical feedback on virtual teacher performance included verbal instructions to 'copy PIA's actions as closely as you can'. During the Skateboard game, participants were instructed to 'lean your body to move and duck, and to capture coins; try not to take a step'; and in the Octopus game they were asked to 'catch the bubbles and bring your arm down after popping each bubble' and 'reach-to-pop the next bubble without taking a step' and 'catch the red bubbles with both hands and the white ones with one hand'. In subsequent sessions feedback frequency was gradually reduced, with minimum to no feedback by the end of the sessions.

Since some of the VR games were designed to be performed while standing, a risk of falling could not be excluded. To prevent falling, participants with signs of instability and risk of falling were guarded by the therapist. Guarding included the session supervisor standing close to the participant during the VR therapy sections performed in standing, in order to protect against falling. Participants with higher balance practiced without guarding, but the therapist was close enough to intervene if needed. A safety harness and suspension system was available but not needed for study participants.

Table II. Abbreviated content of VR therapy*.

Instructions	Therapeutic goals
Sample Virtual Teacher (VT) exercises while sitting on a chair with or without the use of an object (maximum 20 min; each done as continuous movements for set time period)	
Introduction by PIA	*To improve*:
1. Stretch one arm and opposite leg out to the side, repeat on other leg	• multi-segmental co-ordination
2. Bend to the floor on the right, sit up, repeat on the left	• sitting balance
3. Bend and straighten opposite arms and legs	• body awareness
4. Put one hand behind head and straighten opposite leg	• range of upper extremity movement
5. Copy a 'Macarena' type arm movement dance, while bending and straightening legs	• agility • eye-hand and eye-head co-ordination
8 Do actions like a reverse 'Jumping Jack' exercise	• To reduce intention tremor
9. Swing stick to one side while opposite leg stretches out to the other side	
6. Slide the stick first under one knee then the other	
7. With the stick at eye level focus on the coloured dot, follow it with eyes only as the stick moves up and down and side to side	
8. Put the stick behind head from one side and then the other while moving legs alternately out to the opposite side	
9. Lean back and forth, left and right while turning the stick to give support on the floor	
10. Imitate kayaking when holding a stick, while alternating bending the legs at the knee	
Virtual Challenger (VC) Games/Exercises while standing erect with feet 4–inches apart (1 min each; 25–30 repetitions maximum)	
1. *Courtyard*: Raise arm and reach to touch the furthest flower you can in the hedge; repeated at different visual perspectives for each arm	*To improve*: • static balance during standing
2. *Skateboard*: Lean and duck to collect coins and miss obstacles; speed and sensitivity can be varied	• dynamic balance while performing functional arm movement and obstacle avoidance
3. *Boat*: View is one of standing on a moving boat and looking at a shoreline; challenge is to adjust to visual motion; advance by progressively challenging real world balance	• arm-postural co-ordination • precision of arm pointing movement • arm range of motion
4. *Octopus*: Catch bubbles spat out by an octopus; one hand or two had catch depending on colour; advance by challenging real world balance or increasing bubble frequency and visual distractors	• agility and endurance • eye-hand co-ordination • stepping pattern when applicable *To reduce*: • head and visual motion sensitivity

*Not all VR exercises are presented in the table.

Data collection and analysis

The effects of VR therapy on impairment and functional activity (ICF model, WHO) were evaluated by comparing clinical (primary) and movement performance (secondary) outcome parameters before and after practice. Participants were evaluated with a battery of clinical tests up to 4-times: twice at baseline (PRE-TEST$_0$ (done with initial sub-set) and PRE-TEST) with ~2-week intervals between tests; immediately after the therapy (POST-TEST); and 1 month after completion of the training (RETENTION). All assessments were performed by one of two experienced physical therapists. During the PRE-TEST assessments, one physical therapist administered each standardized test, while the second observed and scored each measurement simultaneously. The physical therapists then clarified any inconsistencies in interpretation of observations in an effort to improve inter-rater reliability. The POST-TEST and RETENTION evaluations were then performed by either therapist based on availability.

Clinical parameters (primary) included the scores of four valid and reliable tests, regularly used in this patient population and described in the subjects sub-section (BBS; FGA; Ataxia Scale; FRT). *Movement performance* parameters (secondary) were calculated from the raw data captured with the Xbox Kinect Motion Sensor at a sample rate of 30 Hz. The Kinect Sensor allows recording displacement of the main segments of a participant's body (head, hands, arms, forearms, trunk, thighs, shanks and feet) in a 3D plane. Three VR tasks were selected to compute the following movement performance parameters: (1) arm and leg co-ordination; (2) dynamic stability; and (3) arm movement curvature. Figure 2(a–c) illustrates a single episode of each of three VR tasks, with a hypothetical position of a participant's body. The graphs beneath the figures represent trajectories of the body segment(s) used for analysis from one representative participant (Figure 2d–f).

The co-ordination was analysed as the strength of arm–leg coupling during performance of the virtual teacher exercise that required simultaneous displacement of the contralateral arm and leg in the diagonal plane (Figure 2a and d). The hand (dominant, black lines) and foot (gray lines) paths were plotted and used for computing the cross-correlation coefficient at 0 time lag, with coefficients of $p < 0.25$ indicating no coupling between segments. The path included displacements in sagittal, frontal and vertical planes. Cross-correlation coefficients were averaged across five repetitions of the same movements.

Dynamic stability was analysed during performance of 1 minute Skateboard game (Figure 2b and e). During this game participants were instructed to collect gold coins and avoid hitting or falling into other objects (e.g. tree, bench, car, sign, manhole) by leaning to the left or right and trying to not take a step. A dynamic stability index was calculated as root mean square (RMS) of adjusted trunk displacements in frontal plane. The adjusted trunk displacement (thick black line, Figure 2e) was obtained by subtracting the dominant foot displacement (lower-amplitude thin line) from an absolute displacement of trunk (higher-amplitude thin line). The stability index was averaged across five gaming trials.

Arm movement curvature, which is an indirect measure of movement precision for open-ended reaching tasks, was analysed during reaching to intercept a moving target (bubble) in the game Octopus (Figure 2c). Once launched, the bubbles randomly followed one of five trajectories, approaching the participant strictly in the sagittal or diagonal plane and on the left or right side [26]. In the current version of the game, the target is to be intercepted with either one or two hands, depending on the bubble colour (white or red). Movement curvature was analysed during unimanual movements only, as a ratio of the dominant hand path (black line, Figure 2f) to the shortest distance (dashed line) between the initial hand position and the position at which the target trajectory was intercepted. The arm movement curvature was computed during three reaches toward the targets moving in the sagittal, diagonal and side plane and then averaged across three consecutive gaming trials.

Statistical analysis

Normality of data distribution was verified with the Kolmogorov-Smirnov test ($p > 0.5$). The means of the clinical and movement performance outcomes were compared using a one-way ANOVA, repeated three times, including the PRE-TEST, POST-TEST and RETENTION assessments, with HSD post-hoc test. Paired *t*-test was used for comparing the same outcomes between the PRE-TEST$_0$ and PRE-TEST to ensure stability of clinical and movement presentation. In the case of significant difference between the pre-tests ($p < 0.05$), the means were averaged across both conditions to be used for further ANOVA repeated measure comparisons.

Results

General description

All participants successfully completed 15 sessions of VR therapy. Most indicated a strong level of satisfaction with the gaming component of the therapy and moderate satisfaction with the virtual teacher exercises. One participant found the games less motivating than the others—this participant had among the mildest impairments and perhaps needed more challenging activities. Participants reported they were able to comprehend the game performance and ‘began having fun’ by the forth to fifth session. None of the participants was able to perform a complete sequence of all activities during the first session, typically starting with approximately half the desired numbers of repetitions and not doing all games. The amount of practice was progressively increased through the 15-session training time. At the end, all participants were able to perform the whole 55-minute therapy, thereby confirming that the therapy was challenging enough for individuals with mild-to-moderate manifestations of TBI and that they were able to progress and improve their tolerance and scores over the course of therapy.

Clinical outcomes

All participants had been discharged from conventional physical therapy varying periods of time ago as having reached a plateau with stability of impairments and functional deficits. This was confirmed with the sub-set with repeated pre-tests on the battery of clinical tests where no significant difference was found between PRE-TEST$_0$ and PRE-TEST assessments on any of the tests ($p > 0.05$). Upon completion of the therapy participants improved scores on all four tests to a different extent, as illustrated in Figure 3. Specifically, BBS scores increased by 4.5 from the mean $\pm$ SD of 45.6 ± 5.15 to 50.2 ± 4.4 points ($F_{2,42} = 4.02$, $p < 0.01$) and FGA scores improved by 4.6 points from 20.3 ± 5.6 to 24.9 ± 4.6 points ($F_{2,24} = 3.66$, $p < 0.05$). The greatest changes were observed in FRT. Participants increased mean reaching distance by 2.3 inches from 12.5 ± 2.3 to 14.8 ± 2.3 inches ($F_{2,24} = 4.9$, $p < 0.01$). These effects were fully or partially maintained over the retention interval ($p > 0.05$). Practice also resulted in reduction of ataxia symptoms. Although scores improved by 1.7 points from 7.0 ± 6.2 to 5.3 ± 4.8 points, this difference did not reach significance level ($p > 0.05$).

Movement performance outcomes

In contrast to the stability of initial clinical scores, not all movement performance characteristics remained unchanged between the PRE-TEST$_0$ and PRE-TEST measures. Arm movement precision in the Octopus game improved significantly after a 2-week interval. The means of the index of curvature were averaged across pre-tests and used for ANOVA comparisons. The levels of co-ordination and dynamic stability remained stable throughout PRE-TEST$_0$ and PRE-TEST measures.

Overall, the therapy practice resulted in significant improvements of two out of three movement performance characteristics, as evident from Figure 4. A 20% increase in the arm–leg co-ordination coefficients, from the mean $\pm$ SD of 0.59 ± 0.22 to 0.71 ± 0.17, did not reach significance level ($p > 0.05$). Participants increased dynamic stability by 25% from 0.16 ± 0.03 to 0.20 ± 0.04 metres ($F_{2,24} = 4.82$, $p < 0.01$) and improved arm movement curvature by 21% from 2.10 ± 0.38 to 1.66 ± 0.44 ($F_{2,24} = 4.02$, $p < 0.05$). Improved dynamic stability and arm precision remained unchanged over the retention interval ($p > 0.05$).

Discussion

This study presents a novel and comprehensive VR approach to recovery of postural and co-ordination abnormalities after TBI. Participants with chronic impairments post-TBI and who had been discharged from formal physical therapy improved their postural stability, gait and arm movement after 15 practice sessions. They also demonstrated a trend towards improved motor co-ordination. Changes on most of the clinical scales were considered clinically meaningful and most of the movement outcomes significant. This supports the conclusion that VR therapy effect can be demonstrated in

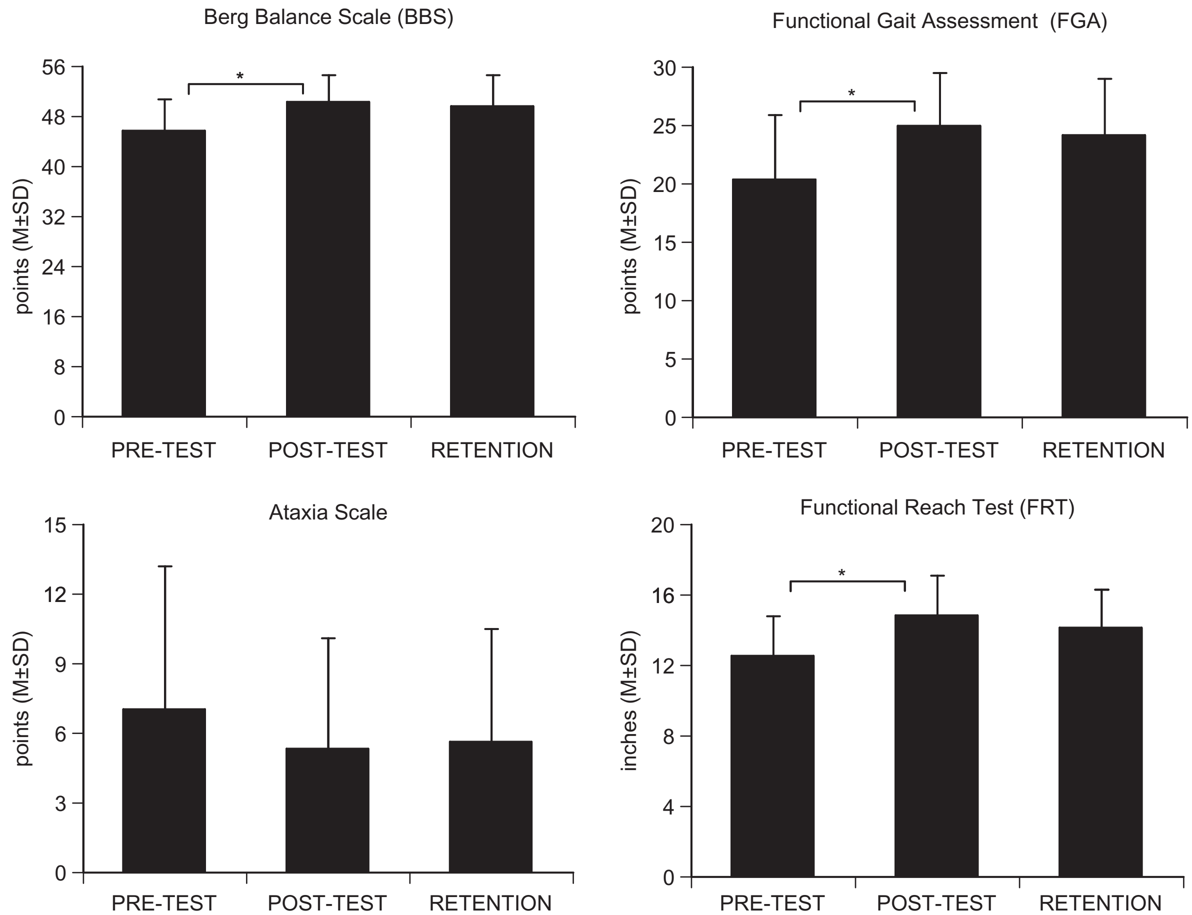

Figure 3. Means and standard deviations of BBS scores, FGA scores, Ataxia Scale scores and FRT distance during PRE-TEST, POST-TEST and RETENTION assessments. *Identifies significant difference between the tests.

individuals with chronic functional and motor abnormalities following TBI.

Most participants improved on three out of four of the clinical scales used for evaluation of posture, gait and motor co-ordination. Changes were significant and exceeded minimal detectable changes (MDC), established for the tests. An increase in the BBS score by 4.5 points can be considered clinically important. Different sources have reported that the MDC can range from 2.5 points in patients with chronic stroke [35] to 5 points in patients with stroke whose initial scores were between 35–44 points on the BBS [36]. The highest MDC established for patients with TBI was 3.83 points [37], confirming the clinical relevance of the results. Results seen in the FGA (improvements of 4.6 points) are consistent with other studies which have shown that the MDC varies with client diagnosis, with MDCs ranging from 4.2 points in a stroke population to 8 points for persons with vestibular disorders [35]. The greatest clinical evaluation changes seen in this sample were observed in the FRT scores which increased by 2.3 inches. This exceeds the 1.48 inch (3.7 cm) MDC established for patients with acute stroke [39]. However, the published standards for these scales were established for patients with stroke and vestibular disorders and information on MDC for these scales after TBI is lacking. The Ataxia Scale used is not yet widely adopted in clinical practice and MDC values for it are unavailable. Thus, it is unclear whether this 1.4 improvement on this scale is clinically meaningful.

Positive changes were also observed in the secondary outcomes of movement performance parameters of arm movement and dynamic stability as described above. In qualitative terms, participants reported feeling some performance improvements by the 4th–5th therapeutic session. These rapid self-reported improvements were probably associated with the participants learning which motor actions would lead to successful performance of the task, with these changes becoming clinically significant as measured by outcome scales by the end of the sessions. This is indirect evidence that the mechanisms of motor learning are still available after brain injury that has affected multiple brain structures. This observation is important for rehabilitation of injured individuals, as the re-learning of functional and motor skills is one of a limited set of mechanisms of recovery available to individuals in the chronic stage of the condition [40].

Improvements in primary and secondary outcomes were anticipated and may be related to several key features of practicing in a virtual environment. Numerous authors have found that virtual reality allows practice in a realistic, safe and motivating environment. While utilizing movements similar to those made in the equivalent physical world [41, 42], VR tasks can be designed with elements critical for motor performance restoration. It is possible to alter timing of actions and adjust the precision of required virtual interactions in a way that cannot be replicated in the real world [43], to give real-time performance feedback [23, 44] and to

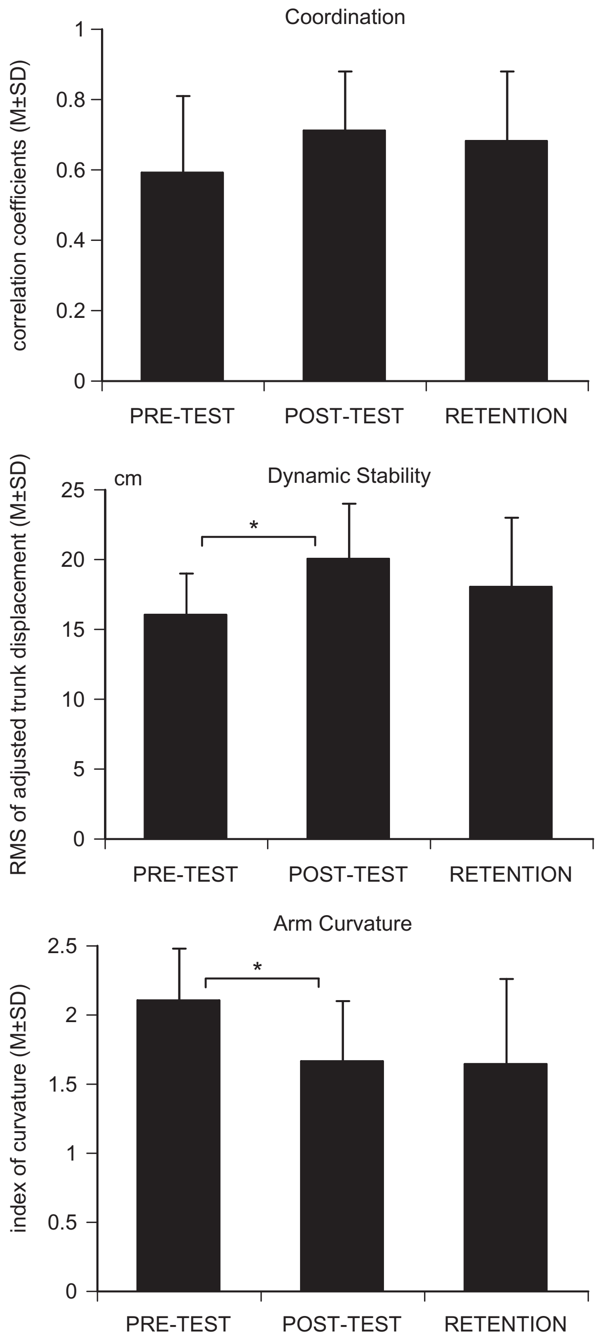

Figure 4. Means and standard deviations of the cross-correlation coefficients, characterizing arm–leg co-ordination, dynamic stability and arm movement curvature during PRE-TEST, POST-TEST and RETENTION assessments. *Identifies significant difference between the tests.

enhance participants' personal motivation thanks to the VR games offering competition paired with the ability to scale difficulty to enable success [45]. Practicing similar tasks in the real-world in a regular therapeutic setting can frustrate clients if their impairments make success in these activities too difficult and can lower motivation and adherence to practice [46, 47]. VR game-based therapy offers a variety of safe scenarios in which mistakes do not have a cost or risk for the participant (e.g. skateboarding, hitting an obstacle, tripping) and performance success criteria can be adjusted to match the individual's ability. It was found that initial success was very encouraging to the participants and increased compliance and enjoyment.

The well-known Frenkel exercise routine for ataxia [48] was used as the conceptual basis for designing the program. This is a well-established exercise sequence that has a long history of use with patients with co-ordination and postural deficits. This study elaborated on the basic format in light of fundamental principles of motor learning. For example, sessions began with the virtual teacher exercises in sitting, using maximally guided movement. Participants were to match their movements to PIA's as closely as possible. As the program advanced, participants moved on to less guided and more flexible actions in standing. The virtual games which closed the sessions allowed considerable variation in movement strategies needed for task completion. This design ensures that the therapy sessions progress logically from simple actions to more complex and variable ones.

The participants reported that the presence of the virtual instructor PIA was another beneficial aspect of VR therapy. Several participants stated that her presence made them feel more involved, as if they were having 'real therapy under supervision of an actual therapist'. This component was noted more by the older participants in the study. Younger participants, perhaps more accustomed to computer games, enjoyed more of the playing games with their own avatar interacting with the environment and without PIA's presence. They also felt they were participating in 'normal' activities with the games, as computer gaming is now perceived to be a typical recreational activity. Avatars and interactions can be adjusted in future application development so this aspect can be better tailored to the individual's background and interests.

Another possibility is to administer VR therapy remotely, via telerehabilitation. Many individuals with TBI live in rural and under-served areas. They may lack transportation services or be dependent on caregivers for travel and so have problems attending therapy. If these restrictions limit therapy sessions, for example to weekly, bi-weekly or even less often, then the person may have insufficient practice for motor recovery via re-education or re-learning. Basic principles of neuroplasticity suggest that in order to generate permanent changes in neural connections which lead to changes in motor behaviour, a stimulus (practice) should be repeated within a time window of long-term potentiation. Some sources suggest this window is only 2–3 days [49]. Practicing at longer intervals may be less effective or ineffective. With the option of supervised in-home via freeware videoconferencing, VR therapy has the potential to be accessible at a time and place convenient for the user while maintaining specialist expertise and feedback. This can reduce the need for travel between clients' homes and a rehabilitation facility, a benefit for those in rural areas or other under-served areas, especially important given the shortage of medical care providers in rural areas [50]. This program was designed with this possibility in mind and future studies may investigate this option.

Considering possibilities such as telerehabilitation and the extension of customizable VR therapy to individuals with more profound impairments raises the issue of ensuring safety. Some of the VR games are designed to challenge balance and require movements in standing, raising the possibility of falls. The present study has documented which participants required guarding during game practice, using clinical judgement and observation paired with reports of prior falls and clinical scores. It was found (Table I) that those participants who had lower scores on either the BBS (≤44 points) or the FGA (≤22 points) needed guarding. These point numbers correspond to the published cut-off scores that indicate increased risk of falling. Extension into the home for such individuals should explore means of ensuring safety such as training caregivers for guarding or using a mechanical support system with a safety harness.

Limitations

Although this study has demonstrated effect of the VR therapy with chronic mild-to-moderate TBI, there are some limitations. The current version of the program allows adjustment to accommodate a limited range of deficits matching the participants with mild-to-moderate impairments, but it is not able to scale performance requirements to meet the needs of the entire spectrum of movement disorders that will be seen in rehabilitation. It will not at present accommodate individuals with severe or profound abnormalities in muscle tone and strength. It is noted that this limited adaptability is shared by commonly used conventional neurorehabilitation techniques, none of which can accommodate all clients' problems. For example, Proprioceptive Neurofacilitation [51] and Neurodevelopmental Treatment [52] techniques are unsuited for management of co-ordination and fine motor control. The task-oriented approach [40] is not widely used for patients with minimal motor activity and severe motor impairments. Constraint-Induced Therapy [53, 54] primarily focuses on restoration of upper extremity function, while ignoring whole body co-ordination and movement. This VR therapy is not an exception to this, but can be seen as an option with its own client niche. VR does have the potential for other programmes which can benefit different populations. Another limitation is that all exercises were standardized for the purpose of this particular experiment. It is hoped to be able to make future programs more flexible and capable of additional adaptation to individual needs. Finally the participant pool was represented by a small and relatively heterogeneous group of individuals, each with unique sensorimotor and cognitive deficits. As the authors deliberately chose to study persons with a history of TBI, this is an unavoidable feature of the population from which this sample was drawn. This does not allow generalizing the current findings to a larger population of individuals with TBI. All these limitations are acknowledged and there is a plan on extension of the research. The pilot data from this study will be used for designing a larger scale clinical trial, in which more complete information on severity and neuropathology of participants' TBI-related impairments may be more available.

Declaration of interest

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