Virtual Reality Game–based Therapy for Persons with TBI: A pilot study

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Abstract—The virtual reality (VR) therapy described below consists of a series of VR exercises, delivered with low-cost equipment. It replicates the conventional exercise and activity sequences recommended for restoring postural and coordination abnormalities after traumatic brain injuries (TBI). Efficacy was tested in a pilot group of 9 participants with TBI. They completed 15 sessions, each approximately 50 minutes duration. Most participants improved their postural stability, gait, and upper extremity movements. Exercise was done in a supervised environment to establish safety criteria. Results will be used to refine the current version of the therapy into a cost-effective, highly-accessible approach which can be delivered remotely via telerehabilitation.

Keywords—virtual reality; traumatic brain injury; therapy; Kinect

I. INTRODUCTION

TBI survivors constitute one of the largest groups of people with disability worldwide [1]. Unlike other neurologic disorders (e.g. stroke, Parkinson Disease), post-TBI motor and functional abnormalities vary substantially from person to person and rarely exhibit a common disease-specific pattern. However, regardless of the type, location, and severity of the brain injury, most persons with TBI-related disability do present with impaired postural control and motor coordination [2,3]. Several neural mechanisms underlie the development of these deficits. They include direct and indirect (e.g. compression, diffuse axonal injury) injury to the motor cortices, cerebellum and cortico-cerebellar loops, brainstem and basal ganglia, and vestibular and somatosensory sensory systems of the brain [4 – 6]. Presenting in a variety of different combinations, these postural and coordination deficits produce motor and functional abnormalities which include, but are not limited to: instability while standing and walking; impaired gait; disrupted arm-postural interaction during object-related actions; lack of bilateral arm/leg coupling; poor manual precision or dexterity; difficulties with coordinating eye and head movements; and problems with visual tracking or focusing on a target [7 – 9]. Furthermore, a brain injury does not need to be considered severe to affect functions such as postural stability, which is affected during walking even in individuals with mild brain injury or concussion [10]. These impairments reduce the quality of life in TBI survivors by limiting their ability to work, and to participate in social and family activities [11].

Despite the importance of restoring postural and coordination abilities, there is a general lack of understanding of what types of interventions are most suited to patients with TBI [12]. The TBI population has not been a primary target for evidence-based research, perhaps due to the complexity of TBI-related impairments which makes it difficult to form a relatively homogeneous experimental group. It is intuitively clear that most physical therapy approaches should include tasks that force multiple body segments to work in a coordinated manner. However, conventional rehabilitation often ignores the variability and complexity of whole body movement coordination, and instead focuses on separate programs for restoration of gait, posture, and arm function. The lack of therapies that focus on whole body functioning ultimately limits functional improvement in activities of daily living and related return to a productive and meaningful life.

Another problem is that receiving physical therapy services or accessing specialists becomes particularly difficult or impossible for those individuals with TBI living in rural and underserved areas. A lack of transportation and dependence on caregivers limits attendance at available therapeutic sessions. Limited therapy sessions, such as scheduling weekly or bi-weekly, may not offer sufficient practice for recovery via reeducation of relearning. Basic principles of neuroplasticity suggest that in order to generate permanent changes in neural connections, leading to long term changes in motor behavior, a stimulus (practice) should be repeated within the time window of long-term potentiation, which is considered by some researchers to be within 2-3 days [13]. Practicing at longer intervals may be less effective or even completely ineffective.

Finally, the majority of TBI survivors are relatively young individuals [14]. They are reluctant to continue repetitive, boring, exercise sequences based on the “old-fashioned” therapeutic programs that are still frequently used in ataxia treatment. These exercises, while physiologically sound, are un-motivating and likely to seem “useless” to the clients, with consequent poor compliance [15]. In summary, limited access to rehabilitation, particularly in rural areas and a lack of scientifically proven and motivating therapeutic approaches creates a clear need for development of evidence-based accessible therapies incorporating state-of-the-art technologies for patients with coordination and postural abnormalities due to TBI.

To address this need we designed and developed a virtual reality (VR) game-based therapy program, specific to the treatment of coordination and postural abnormalities following

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Instead of regular exercises, the therapy includes custom-designed immersive video games and scenarios, in which a patient’s representative (avatar) interacts with a virtual environment via a relatively inexpensive portable motion tracking sensor (Xbox 360 Kinect). In this regard, the VR therapy deviates from frequently used “off-the-shelf” games (e.g. by Nintendo Wii, Xbox Kinect, or Sony EyeToy), which have also been considered as effective alternative rehabilitation exercises [16 – 18]. The “off-the-shelf” games are designed for healthy individuals and usually lack the ability to scale skill levels for the population with severe disabilities. They also may not require the precise motor performance with the specific body segment that a therapist may want for a particular motor activity. For example, VR environment targets in Sony EyeToy systems can be intercepted with any part of the body rather than a specific part such as the hand. Also, a gaming task performed using a hand-held controller (e.g. Wii) is not equivalent to a movement performed in the real physical environment. The controller is a hand-held tool, rather than part of the body controlled centrally, and as a result distorts movement kinematics [19].

Our VR therapy is provided by a virtual instructor and simulates sequencing, dosage, and content of a comprehensive physical therapy program for treatment of coordination and postural abnormalities in persons with TBI. This is a relatively novel approach in VR applications, which presents a complex game-based solution, with a content progressing logically from simple single-limb guided movements to complex whole body task-oriented actions. To date most studies of VR rehabilitation have reported on the results of using single gaming applications rather than well-structured and complete therapies. These experiments, including our work, found VR applications effective for retraining cognitive and functional abilities [20 – 22]; Christiansen et al, 1998), balance and mobility [23 – 25], and whole body coordination [26]. The goal of the current study was to test efficacy of VR therapy in restoring motor and functional deficits in a small group of persons with TBI.

II. METHODS

A. Study Design

This was a pilot study testing efficacy of VR therapy. Although the experimental setup allowed for in-home delivery, the paper reports on pilot testing in a supervised laboratory setting (Fig.1) to establish safety procedures and criteria prior to further testing in other settings. Therapy included 15 sessions, each approximately 50-55 minutes in duration, scheduled 2-4 times a week over 5 – 7 consecutive weeks.

B. Therapeutic Content

The therapy includes a series of immersive VR games and scenarios for retraining whole body coordination, including arm coordination, posture and gait. Therapy begins with a 1-min introduction by a Personal Instructional Avatar (PIA). PIA explains the procedure and describes the exercise approach. The introduction is followed by two conceptually different types of games, referred to as “virtual teacher” and “virtual challenger.” Examples of these activities are briefly summarized and illustrated in Table 1. In the complete program, 16 2-min “virtual teacher” exercises are demonstrated by PIA, who asks the participant to copy her movements. In this version, actions are performed in sitting, with or without the use of an object (stick), with the aim of re-training intra- and inter-limb coordination, manual dexterity, balance, and eye-head coordination.

The “virtual challenger” exercises differ from the “virtual teacher” ones by having an avatar representing the participant’s movement. Each exercise has a goal and has flexible options for individual movement strategies to achieve the goal. Four custom-designed VR games/scenarios are available used, each in repeatable sessions of 1 min. The games include: Octopus, Courtyard, Boat, and Skateboard.

The Octopus and Courtyard games are designed to train dynamic balance and arm-postural coordination while reaching to intercept a moving target (a bubble in Octopus) or to “touch” a stationary target (a flower in Courtyard). The interception could be done with either or both hands. The Boat scenario challenges postural stability under sensory conflict conditions generated by a moving visual stimulus (simulating a boat moving in waves against a stationary land mass). Skateboard addresses static and dynamic postural control, agility and stepping pattern in patients with TBI. The gaming scenario shows the avatar on a skateboard moving along the street. The goal of Skateboard is to avoid stumbling or striking obstacles by shifting body weight to the left or right, forward or backward, ducking under, and stepping (if feasible for the participant).
**TABLE I. Examples of VR therapy activities**

<table>
<thead>
<tr>
<th>VR exercises/games</th>
<th>Instructions</th>
<th>Therapeutic Goals</th>
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</thead>
<tbody>
<tr>
<td><strong>Exercises while sitting on a chair with or without the use of an object (maximum 20 min)</strong></td>
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<tr>
<td><strong>Introduction by PIA</strong></td>
<td>VT 1. Simultaneously stretch out left arm and right leg on opposite diagonals, return; repeat with the other leg and arm&lt;br&gt;VT 2. Bend to the right, touch the floor, return; repeat on the left side&lt;br&gt;VT 3. Simultaneously bend left arm/right leg; repeat on the other side&lt;br&gt;VT 4. Simultaneously place the left hand behind the head and the right leg out to the side, return; repeat on the other side&lt;br&gt;VT 5. Place the stick on the right lap, while stretching the left leg out to the side, return; repeat on the other side&lt;br&gt;VT 6. Bend forward, pass the stick under the knee, return, repeat with the right knee&lt;br&gt;VT 7. Raise the stick to the eye level, focus on the dot on the center of the stick, move the stick slowly left-right and up-down, while following with eyes only&lt;br&gt;VT 8. Holding the stick with both hands, move it behind one shoulder, return; do on other side, then coordinate this with leg diagonal movement to the opposite side&lt;br&gt;VT 9. Lean back and forth, left and right while using the stick as support against the floor&lt;br&gt;VT 10. Rise from the chair while holding a stick in front of you</td>
<td>To improve: &lt;br&gt;1) multi-segmental coordination&lt;br&gt;2) sitting balance&lt;br&gt;3) body awareness&lt;br&gt;4) range of upper extremity movement&lt;br&gt;5) agility&lt;br&gt;6) eye-hand and eye-head coordination&lt;br&gt;7) reduce intention tremor</td>
</tr>
<tr>
<td>virtual teacher 1</td>
<td>VC Court: Raise arm to shoulder level and point to the furthest flower that can be reached without taking a step, repeat with the other arm, and under other visual angular perspectives; advance by narrowing the base of support&lt;br&gt;VC Skateboard: Body shift left-right, and duck to avoid obstacles and collect coins, advance by altering speed or sensitivity&lt;br&gt;VC Boat: Stand still and try not to move, ignoring the sensory perturbation caused by a boat moving on the screen, advance by standing in tandem&lt;br&gt;VC Octopus: Raise or lower arm(s) to catch flying bubbles without taking a step; catch with either or both hands depending on the color; bubbles will approach from different directions, advance by narrowing the base of support or standing in tandem, or adjusting speed</td>
<td>To improve: &lt;br&gt;1) static balance during double and single stance&lt;br&gt;2) dynamic balance while performing functional arm movement, obstacle avoidance, body-weight shift, ducking and jumping is possible&lt;br&gt;3) arm-postural coordination&lt;br&gt;4) precision of arm pointing movement&lt;br&gt;5) arm range of motion&lt;br&gt;6) agility&lt;br&gt;7) endurance&lt;br&gt;8) eye-hand coordination&lt;br&gt;9) stepping pattern when applicable&lt;br&gt;10) To reduce head and visual motion sensitivity</td>
</tr>
<tr>
<td><strong>Exercises while standing erect with feet 4 to 6 inches apart (1 min each; 25-30 repetitions maximum)</strong></td>
<td></td>
<td></td>
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<tr>
<td>courtyard</td>
<td>VC Courtyard: Raise arm to shoulder level and point to the furthest flower that can be reached without taking a step, repeat with the other arm, and under other visual angular perspectives; advance by narrowing the base of support</td>
<td></td>
</tr>
<tr>
<td>skateboard</td>
<td>VC Skateboard: Body shift left-right, and duck to avoid obstacles and collect coins, advance by altering speed or sensitivity</td>
<td></td>
</tr>
<tr>
<td>boat</td>
<td>VC Boat: Stand still and try not to move, ignoring the sensory perturbation caused by a boat moving on the screen, advance by standing in tandem</td>
<td></td>
</tr>
<tr>
<td>octopus</td>
<td>VC Octopus: Raise or lower arm(s) to catch flying bubbles without taking a step; catch with either or both hands depending on the color; bubbles will approach from different directions, advance by narrowing the base of support or standing in tandem, or adjusting speed</td>
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</tr>
</tbody>
</table>

*Not all VR exercises are presented in the table; VT – virtual teacher, VC – virtual challenger. All figures in Table I © Central Michigan University; Reprinted by permission.
All game tasks are multi-planar and multi-directional with rotational and diagonal components. Each allows advancement through several difficulty levels (e.g., increased speed, frequency of obstacles, and distance to an object to intercept). The game tasks are accompanied by music and scheduled by the therapist so that the patient cannot begin the next game until the previous one is completed. Successful performance of each game is rewarded by a number of points that accumulate throughout the entire gaming session. An ultimate goal is to collect as many points as possible by the end of gaming practice.

C. Software and Hardware

The games and scenarios were developed by the group authors on this paper, with the use of WorldViz software (WorldViz LLC, Santa Barbara, CA, USA) with computer graphics performed created with Alias’ Maya package for 3D animation (Maya®, Version 7.0.1; Autodesk, Inc., San Rafael, USA). The gaming system included a Dell Alienware M18 (quad-core 2.2GHz Intel Core i7-2670QM processor) with a graphics accelerator (nVidia GeForce GTX 560M) integrated with the Kinect Motion sensor (Microsoft, Inc). The operating system used was Windows 7 Enterprise (Microsoft, Inc). The images were projected and displayed on an 82-inch screen (1080p Mitsubishi DLP® TV bundle, RealD Beverly Hills, CA, USA, Fig. 1). A custom Windows interface for configuring and running each scenario was created with Visual Studio using the C# programming language. document.

D. Participants

Nine individuals (3 females, 6 males) with chronic (a few to over 14 years post-TBI) mild-to-moderate manifestations of TBI and with mean ± SD of age 32±9 years, participated in this pilot study. Their clinical and demographic data are presented in Table 2. All participants were able to stand unsupported for at least 2 min. They demonstrated a full range of upper extremity motion, had no increase in muscle tone and normal/corrected visual acuity. One participant had a visual field cut compensated for with prism glasses. All participants had completed conventional therapeutic exercise programs and been discharged on having reached a plateau where no further improvement was seen. The stability of the movement deficits was tested prior to the efficacy study by repeating pre-test scales in a subset, documenting no spontaneous change in movement parameters.

Participants had mild-to-moderate coordination deficits affecting gait, postural control, and upper extremity movements, with clinical test scores ranging from: a) 34-53 points on the Berg Balance Scale (BBS) [27], with ≤45 points indicating a high fall risk; b) 10-28 points on the Functional Gait Assessment Test (FGA) [28], with ≤22 points indicating a high fall risk; and c) 2-21 points on the Ataxia Scale according to [29], with 35 points identifying severe ataxia. Participants reached forward without taking a step from 10 to 15.5 inches, measured with the Functional Reach Test (FRT) [30]. None of the participants exhibited severe cognitive or behavioral impairment sufficient to restrict therapeutic practice. All participants, and guardians as necessary, signed an informed consent form, prepared in accordance with Helsinki Declaration and reviewed by the Institutional Review Board.

E. Training Protocol

Eight of nine 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. Boat was discontinued in some participants who did not demonstrate a need for its particular sensory challenge. One participant benefited more from variable practice, as determined by the response seen in initial training sessions. The participant (#9, Table I) became flustered quickly 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.

During the first session, an experienced physical therapist evaluated the participant’s capacity and tolerance for the exercises, selected suitable virtual challenge games and established the baseline for practice amount and difficulty level. Most participants were able to perform about 30% of goal practice levels during the first two sessions and progressed to the maximum load by 13-15th session, with each session lasting 50-55 min, including time for rest. Faded feedback performance was used. During the first therapeutic session, the physical therapist guided the participant through the entire practice, reinforcing and providing supplementary instruction for the exercises. Typical feedback on VT performance included verbal instructions to “mimic PIA’s motions as precise as possible.” During the Skateboard game, participants were instructed to “lean left or right as much as possible without taking a step”; and in the Octopus game they were asked to “bring arm down after each bubble interception” and “reach to pop the next bubble with minimum extraneous arm movements and without taking a step.” 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 are designed to be performed while standing, a potential risk of falling could not be excluded. To prevent falling, participants with high risk of falling were guarded by the therapist. High risk of falling was determined upon completion of clinical evaluation, and generally included participants with low balance scores (≤45 points) on the BBS [27] or ≤22 on the FGA [28] by the clinical judgment of the therapist based on observation during initial sessions. Guarding included standing behind or beside the participant during VR therapy activities performed in standing, in order to protect against falling. Participants with higher balance scores practiced without guarding, but the therapist was close enough to intervene if needed. Should further research be done on participants with higher fall risk that our pilot group, a safety frame and harness may be used.
F. Data Collection and Analysis

The effects of VR therapy on impairment and functional activity (ICF model, WHO) were evaluated by comparing manifestations of TBI-related abnormalities before and after practice. Each participant was evaluated with a battery of clinical tests a times: at baseline (PRE-TEST); immediately after the therapy (POST-TEST); and 1 month after the completion of training (RETENTION). A subset did two PRETESTS, documenting stability of clinical presentation. Evaluations included 4 valid and reliable tests, regularly used in this patient population, and described subsection 2.4 (Ataxia Scale, BBS, FGA, FRT). Clinical measures were compared with the use of one-way repeated measures analysis of variance (ANOVA).

III. RESULTS

Upon completion the therapy participants improved scores on all 4 tests to a different extent, as illustrated in Figure 2. Normality of data distribution was verified with the Kolmogorov-Smirnov test (p > 0.5). Specifically, BBS scores manifested of TBI-related abnormalities before and after practice, on all 4 tests to a different extent, as illustrated in Figure 2.

This effect was anticipated and may be related to several key features of practicing in virtual environment. As was highlighted by several authors, virtual reality allows practice in a realistic, safe, and motivating environment. While utilizing movements similar to those made in the equivalent physical world [33], VR tasks can incorporate elements essential for the successful restoration of motor abilities. These include the manipulation of timing and precision of environmental interactions, something not easily achieved in the real world [34], real-time performance feedback [23,35] and motivation which is reinforced by the competitive nature of VR games and the adjustment of difficulty to offer a level of success [36]. For example, performance of real-world tasks in a regular therapeutic setting is limited by the client’s ability, and frustration and lack of success in these activities can demotivate the patient from practicing [37,38]. In contrast, game-based therapy offers a variety of scenarios in which mistakes do not pose any risk to the participant (e.g. skateboarding, hitting an obstacle) and criteria for performance success can be scaled according to the individual’s ability. Reinforcement of success encouraged participants and increased compliance as result. During this pilot study feedback from participants was solicited regarding the interest and motivational aspects of the program sessions. Feedback was very positive and participants’ comments will be used to refine scenarios.

IV. DISCUSSION

Upon completion of the VR therapy, most participants improved in postural stability, gait, and coordination in upper and lower extremities, thereby confirming efficacy of the VR therapy. Improvements on the BBS (4 points), and FRT (2.5 inches) were within the range of minimal detectable changes (MDC). For BBS the MDC has been established at 2.5 points for the patients with stroke onset > 6 months [31]. The MDC for FRT determined in different studies varied from 1.6 to 4.3 inches, depending on patient population and chronicity [32].

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TABLE II. Demographic data and clinical scores of patients with TBI

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age</th>
<th>TBI onset (yr)</th>
<th>Arm Dominance</th>
<th>Ataxia</th>
<th>FGA</th>
<th>BBS</th>
<th>FRTm(in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>F</td>
<td>30</td>
<td>2.5</td>
<td>R</td>
<td>4</td>
<td>22</td>
<td>44</td>
<td>10.5</td>
</tr>
<tr>
<td>S2*</td>
<td>M</td>
<td>28</td>
<td>7</td>
<td>R</td>
<td>21</td>
<td>10</td>
<td>34</td>
<td>10</td>
</tr>
<tr>
<td>S3</td>
<td>F</td>
<td>44</td>
<td>14</td>
<td>R</td>
<td>6</td>
<td>20</td>
<td>46</td>
<td>12</td>
</tr>
<tr>
<td>S4</td>
<td>M</td>
<td>39</td>
<td>6</td>
<td>L</td>
<td>20</td>
<td>5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>S5*</td>
<td>F</td>
<td>45</td>
<td>1</td>
<td>R</td>
<td>9</td>
<td>43</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>M</td>
<td>21</td>
<td>2</td>
<td>R</td>
<td>28</td>
<td>52</td>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>M</td>
<td>20</td>
<td>1</td>
<td>R</td>
<td>27</td>
<td>53</td>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>M</td>
<td>26</td>
<td>4</td>
<td>R</td>
<td>28</td>
<td>53</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>M</td>
<td>38</td>
<td>1.5</td>
<td>R</td>
<td>4</td>
<td>22</td>
<td>47</td>
<td>14</td>
</tr>
</tbody>
</table>

* - indicates that the subject was guarded during VR game performance
As a conceptual model of the therapy, the Frenkel exercise routine [39] has been adopted. This routine is a commonly accepted exercise sequence for patients with coordination and postural deficits. The sequence was elaborated in the light of fundamental principles of motor learning. Specifically, the VR games and exercises started with maximally guided movement in sitting, and advanced to flexible actions in standing. The virtual teacher exercises at the beginning require participants to match their movements to PIA’s movements, with minimum deviation. The virtual games, performed at the end, allow maximum variability in finding movement strategies to complete the tasks. Thus this sequence provides a logical progression from simple to complex and variable actions.

Another beneficial aspect of VR therapy that distinguishes it from a single-game application is the presence of virtual instructor PIA. Most participants reported that made them feel involved in “real therapy under supervision of an actual therapist”. This therapeutic component was appreciated more by older participants in our study. Younger participants, representatives of the “computer generation” enjoyed more of the gaming aspect without PIA, and also felt they were participating in activities perceived as “normal” for their generation. This feature can be easily adjusted according to participant computer experience and preference in future applications.

In future the therapy may be applied remotely, via telerehabilitation. Supervised in-home via freeware videoconferencing, the VR therapy can be accessible at a time and place convenient for the user without losing specialist expertise. This can reduce the need for travel between clients' homes and the rehabilitation clinic, a benefit for those in rural areas, especially important given the shortage of medical care providers in rural areas [40]. Considering this extension of session use, it is important to address potential safety concerns. Since some of the VR games are designed to be performed while standing, the may be a risk of falling. Our results showed that patients with lower balance score and high risk of falling (<45 points on the Berg Balance Test and ≤22 on the FGA) required guarding during practice. Results from 9 participants are not enough to establish safety criteria through the critical means of these commonly used scales; more subjects are needed. In our pilot study guarding was done by a therapist standing close to the participant during the second part of the VR teletherapy, when games were performed in a standing position. For therapy extension into the home and to participants with more severe balance impairments, safety measures should be used. These could involve various options including training caregivers in guarding, or provision of a safety harness and frame.

V. LIMITATIONS

Although efficacy has been demonstrated, VR therapy has some limitations. The current version is flexible enough to adapt to a range of deficits, but it does not cover the entire spectrum of movement disorders that therapists encounter. In particular it does not adapt enough to accommodate severe abnormalities in muscle tone and strength. It is important to note that NONE of the commonly accepted neurorehabilitation techniques accommodate all patients’ problems. For example, Proprioceptive Neurofacilitation (PNF) [41] and Neurodevelopment (NDT) [42] techniques are not suited well to treat coordination and fine motor control. The task-oriented approach [43] is not widely used for patients with minimal motor activity and severe motor impairments. Constraint-Induced Therapy [44,45] primarily focuses on restoration of upper extremity function, while ignoring whole body coordination and movement. Thus, VR teletherapy is not an exception, but an alternative with its own potential niche in the range of rehabilitation approaches. As another limitation, all exercises were standardized for the purpose of this particular experiment. The goal is to have future therapies more flexible and capable of additional adaptation to individual needs. Finally the subject pool was represented by a small and relatively heterogeneous group of patients with unique sensorimotor and cognitive deficits. This is an unavoidable feature of the brain injury-related manifestations, as there is no a “typical” pattern. All these drawbacks could affect the results of study to some extent, but will be addressed in further applications.

REFERENCES


