Short-term Practice with Customized 3D Immersive Videogame Improves Arm-Postural Coordination in Patients with TBI

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Abstract — **This paper describes the effects of short-term practice with the custom-made 3D immersive videogame Octopus on arm-postural coordination in patients with traumatic brain injury (TBI). Unlike many other custom-designed virtual environments, Octopus includes an actual gaming component with a system of multiple rewards, making the game challenging, competitive, and fun. While standing, 6 individuals with mild-to-moderate manifestations of TBI practiced reaching and popping virtual bubbles with the left or right hand avatar. The bubbles, blown by the Octopus, followed a specific trajectory. Interception of the bubbles allowed flexible use of the postural segments (trunk and legs) for balance maintenance and arm transport. Participants practiced ten 90-s gaming trials during a single session, followed by a retention test. Whole-body kinematics was analyzed using principal component analysis. As a result of the short-term practice, the participants improved in game performance, arm movement time, and precision, mostly by adapting efficient arm-postural coordination strategies. Of the 6 participants, 5 showed an immediate increase in arm forward reach and single-leg stance time. These results support the feasibility of using the custom-made 3D game for retraining of arm-postural coordination disrupted as a result of TBI.**

Keywords - virtual reality; motor rehabilitation; postural control

I. INTRODUCTION

Traumatic brain injury (TBI) disrupts the central and executive mechanisms underlying arm and postural (trunk and legs) coordination [1]. Behaviorally, such disruption limits postural stability when performing arm movements, increases the fall risk, deteriorates motor skills, and eventually decreases the quality of life of TBI survivors [2], [3], [4]. Despite the importance of arm-postural coordination, surprisingly little attention is paid to its restoration by conventional rehabilitation, which generally treats the affected upper extremities, postural control, and gait separately. This lack of attention is related to the complexity of TBI-related coordination deficits and the inconsistency in their evaluation. Moreover, it can be difficult to address specific coordination problems with real-world tasks, as well as challenging to adapt these tasks to the abilities of TBI survivors. The development of virtual reality (VR)-based gaming exercises and their use in TBI rehabilitation may help to address these problems.

There has been considerable recent interest in implementing custom-designed VR-based training paradigms into neurological rehabilitation. Utilizing movements similar to those made in the real world, VR tasks incorporate elements essential for successful retraining, including manipulation with the timing and precision of object interactions, real-time performance feedback, varied practice, and reinforced motivation [5], [6], [7], [8], [9]. Numerous custom-made VR-based applications have been tested and shown to be feasible in various patients populations, including stroke, vestibular disorders, cerebral palsy, and even spinal cord injury.

Despite the growing number of VR applications, some gaps remain in their development as rehabilitation tools. Similar to conventional rehabilitation, most virtual environments simulate arm movements, balance, walking, and cognitive tasks separately, with minimal attention paid to complex whole-body motions. This fact limits the use of VR applications in patients with multiple sensorimotor abnormalities such as TBI-related deficits. Furthermore, most customized VR paradigms lack actual gaming elements that could make the task challenging, competitive, motivating, and fun.

Virtual-reality paradigms with built-in animation scenarios frequently ignore the basic principles of game development, such as the inclusion of a gaming story, conflict, reward system, and level-based increases in difficulty. Considering these principles would advance game development for rehabilitation.

While deficient in custom-made virtual environments, the above basic gaming elements are found in popular "off-the-shelf" games. Although available as alternative products, off-the-shelf games cannot replace customized tasks, because of the inflexible gaming content, absence of strict requirements for defining and monitoring the precision of motor performance, and lack of equivalency to movements performed in the real world [10], [11]. For example, all large-amplitude whole-body movements resembling tennis-liked activities can be performed in the framework of a Wii game with only a hand manipulating a controller. Such a distorted spatial calibration diminishes the rehabilitation benefits of this gaming system.

Considering the drawbacks of existing VR-based exercises, we developed a customized videogame (Octopus) for use by patients with TBI. Unlike many other custom-designed virtual environments, Octopus focused on training arm-postural coordination, utilized the basic principles of game design, and included tasks calibrated according to the patient's anatomical features and movement abilities. This paper describes the game design, practice protocol, and effect of a short-term gaming practice on the arm and postural coordination of patients with TBI.

II. METHODS

A. Apparatus and Software

The gaming system consisted of a PC (Intel Core 2 Duo Processor, Palo Alto, USA) with a graphics accelerator (nVidia GeForce Go 7300, Santa Clara, USA) integrated with a 6-camera system for motion capture (Qualisys AB, Gothenburg, Sweden). Using real-time captured data, avatars of the participant's hands were created with 3 markers attached to each hand, and synchronized with the VR gaming scenario. The image was projected in 3D format onto an 82-inch screen (1080p Mitsubishi DLP® TV bundle, RealD Beverly Hills, CA, USA) and was viewed by the participant in the first-person view via shutter glasses (RealD Professional CrystalEyes 5). The glasses did not interfere with the infrared signal irradiated by the motion capture system.

The gaming scenario was developed using WorldViz software (WorldViz LLC, Santa Barbara, CA, USA) with computer graphics performed with Alias' Maya package for 3D animation (Maya®, Version 7.0.1; Autodesk, Inc., San Rafael, USA).

B. Gaming Scenario

In the gaming scenario, all actions occur in an underwater world populated with seaweeds and corals (Fig. 1A-B). The main character, Octopus, is located in the middle of the screen. Octopus blows bubbles towards the participant, whose presence in the underwater landscape is indicated by the right and left hand avatars.

The gaming task is to reach and pop (intercept) as many bubbles (targets) as possible with the left or right hand. Once launched, each target randomly follows 1 of 5 radial (circular) trajectories (Fig. 2A-B), designed so that the target in overhead position corresponded to participants height with arm raised up. At the shoulder level the target is 25-30 cm beyond the length of the arm, outstretched forward. This reaching distance is considered as the lower border for norms on the Berg Balance test [12]. This trajectory allows flexibility in the reaching strategy used to intercept the target. When approaching it in a strictly sagittal plane, the participant can reach the target overhead (by maximally extending the arm upwards), at shoulder level (by extending the arm forward), or somewhere between these two critical points. Catching the target at the shoulder level might take less time, but it also causes greater postural displacement, since requires that the participant lean his/her entire body forward.

In the frontal plane, bubbles are aligned along a semicircle, all within reaching distance with a 45º interval between trajectories (Fig. 2B). Visual representations of the hand and bubble are matched in size.

The gaming session begins with a narration that presents the story of Octopus, provides the gaming instructions, and describes the reward system. In part, the narrative instructs the participant to pop as many bubbles as possible for 90 s without leaving an initial position, losing balance, or taking a step. Each successful bubble trajectory interception is rewarded with points, which accumulate throughout the gaming trial and serve as the criteria of performance success (performance score). When a certain score, is exceeded, a new character appears on the Octopus landscape. The ultimate goal is to collect as many characters as possible in each gaming session.

The result of the first gaming trial is used to establish a baseline score. Each following trial is rewarded with an additional character when the number of bubbles popped is ≥110% of the score on the previous trial. The Octopus blows bubbles regularly every 4 s at a speed of 1.5 m/s. Successful interception causes the next bubble to appear earlier (immediately after) and thereby increases the bubble flow rate.

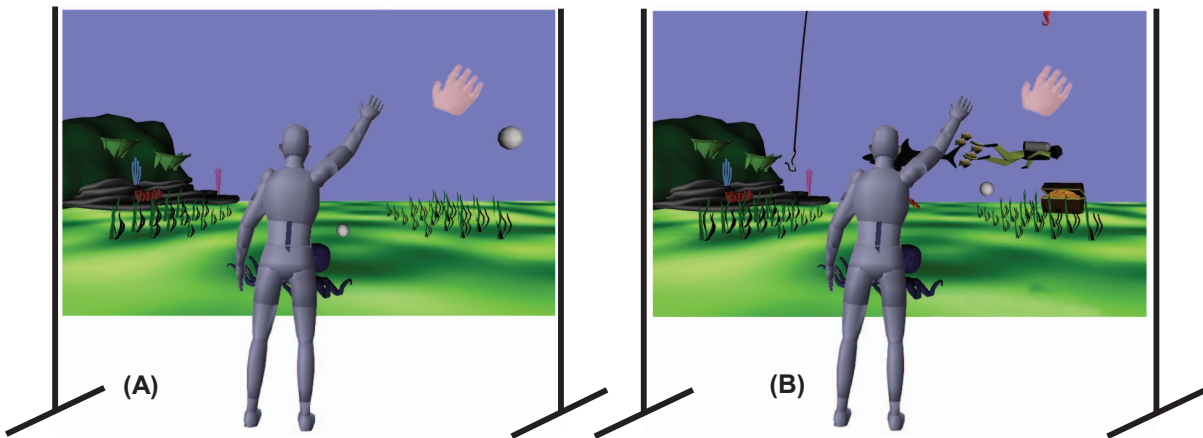All participants practiced the Octopus game with the same gaming parameters.

Figure 1. Experimental setup with subject standing in front of the screen with the Octopus scenario projected. Images are taken from the first (A) and last (B) gaming trials.
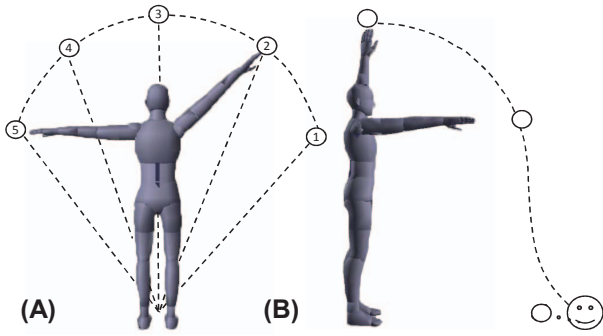
Figure 2. Calibration of virtual space with bubble trajectories in the frontal (A) and sagittal (B) planes.

C. Subjects

The feasibility of the game was tested in 6 individuals with chronic mild-to-moderate manifestations of TBI. Table I shows the clinical and demographic data for the subjects enrolled in the study. 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, reported normal stereovision, and normal/corrected visual acuity.

Participants had mild-to-moderate coordination deficits affecting gait, postural control, and upper extremity movements, with clinical test scores ranging: a) 39-53 points on the Berg Balance test [12], with 45 points indicating a high fall risk; b) 19-28 points on the Functional Gait Assessment Test [13], with 22 points indicating a high fall risk; and c) 5-13 points on the Ataxia Test according to Klockgether [14], with 35 points identifying severe ataxia. The participants had low scores (< 10 points) on the Motion Sensitivity Test [15], indicating that no adverse effect (e.g., dizziness, nausea, or disorientation) likely would occur as a result of head or 3D environment motions. Measured as part of the Berg Balance test, the forward reach (item #6) and single-leg stance (item #12) were ranked and included in the total score, and were analyzed separately in terms of absolute values (e.g., forward reach in cm and single-leg stance in s, not exceeding 30 s).

The expanded cognitive assessment results (not shown) indicated that no participant exhibited severe abnormalities that might significantly restrict game performance.

D. Training Protocol

Participants practiced the Octopus game 10 times during a single practice session. Each 90-s game included ~20-25 reach-to-pop movements, with a total of 200-250 repetitions per session. To avoid fatigue, a 1-2 min rest period was allowed between trials, with a total gaming session time of 40-45 min. A retention test of 2 gaming trials was administered 30 min after the end of the practice. The 2 retention trials replicated the first and last (with the complete number of virtual objects/characters) gaming trials of the practice session.

The forward reach and single leg stance items of the Berg Balance test were repeated twice, at the beginning (pretest; Table I) and end (posttest) of the gaming session, to evaluate the effects of the short-term practice. On average, each gaming session lasted for ~1 h, including time for the practice itself and rest.

E. Data Collection and Analysis

For data analysis, bubble trajectories in the x, y, and z directions were synchronized with the whole-body movements. These data were recorded by Qualisys system for motion analysis at 100 Hz, using 30 reflective markers placed on the major bony landmarks. Reaching-to-pop bubble #3 (Fig. 2A) with the dominant hand (right hand in all participants) was analyzed kinematically according to the following parameters: arm movement time, arm trajectory curvature, and arm-postural coordination.

The trajectory curvature, analogous to Levin's index of curvature [16], was calculated as the ratio of the actual arm trajectory length to the shortest path to the target. A ratio of 1 indicates no arm deviation from the shortest path, while a ratio of 2 indicates that the arm trajectory was twice as long as the shortest distance between the initial and final arm positions.

The arm-postural coordination was analyzed in terms of movement variation and the contribution of body segments, using principal component analysis (PCA) as described by Mah et. al. [17] and modified by Alexandrov et al. [18].

From kinematic data, the angular displacements of 9 body segments (i.e., 2 hands, 2 forearms, 2 upper arms, 1 trunk, and 2 legs) were computed in the sagittal (flexion-extension) plane, typically relative to the sagittal movement of the bubble.

TABLE I
DEMOGRAPHIC DATA AND CLINICAL SCORES OF PATIENTS WITH TBI

Subject	Age	Sex	Years Since TBI	Arm Dominance	FGA Score	Ataxia Score	Berg Balance Score				
								#6 Forward Reach (cm)		#12 Single Leg Stance (s)	
							Total	Pre-test	Post-test	Pre-test	Post-test
S1	24	M	1.5	R	27	8	52	28	29	<30	<30
S2	23	M	2	R	19	13	42	23	25	8	10
S3	39	M	5	R	20	11	39	11	13	9	15
S4	29	M	2.8	R	22	7	44	19	18	7	10
S5	33	F	3	R	25	8	48	24	27	15	25
S6	21	F	1	R	28	5	53	29	31	<30	<30

Note: Scores are explained in detail in the text.

The leg, consisting of the thigh and shank, was analyzed as a single segment since the angular displacement at the knee joint was minimal for this task.

The vector of temporal variation of the 9 segmental angles φ_i around their mean values φ_{mi} (i=1,2…8,9) was represented in PCA as a weighted sum of orthogonal and normalized compounds, i.e., a sum of principal components (PCs):

$$
\begin{pmatrix} \varphi_1(t) - \varphi_{m1} \\ \varphi_2(t) - \varphi_{m2} \\ ... \\ \varphi_8(t) - \varphi_{m8} \\ \varphi_9(t) - \varphi_{m9} \end{pmatrix} = \begin{pmatrix} w_{1,1} \\ w_{1,2} \\ ... \\ w_{1,8} \\ w_{1,9} \end{pmatrix} \bullet \xi_1(t) + \begin{pmatrix} w_{2,1} \\ w_{2,2} \\ ... \\ w_{2,8} \\ w_{2,9} \end{pmatrix} \bullet \xi_2(t) + ... \begin{pmatrix} w_{3,1} \\ w_{3,2} \\ ... \\ w_{3,8} \\ w_{3,9} \end{pmatrix} \bullet \xi_3(t)
$$

where w_{ij} was the weight of the segmental angle variation φ_j in the ith PC. Each ith PC in the equation above was defined by a vector of 9 constant normalized weights w_{ij} (j = 1,2…8,9), called PC loading, and by a corresponding time-dependent scaling factor $\xi_i(t)$, called PC factor. The PC loading had a positive (or negative) sign when the corresponding segment shifted toward (or away from) the bubble. The PC loading indicated the contribution of each individual segment to the arm-postural coordination, with a mean PC loading >0.7 being considered significant. The covariation matrix used for the PCA included non-normalized values, rather than normalized values based on a correlation matrix, to enhance the contribution of relatively small segments.

Each movement parameter was measured in a time window between the initial bubble launch and its interception. Performance success was measured as the number of popped bubbles in a 90-s trial. Preliminary individual data were averaged across 6 subjects, each performing 5-6 reaches/trial of the selected bubble with the right (dominant) arm. The means were compared between the 1st and 10th trials using the paired t-test.

III. RESULTS

While practicing the game, the participants were not instructed on how to move to catch a bubble successfully. The bubble trajectory could be intercepted using different combinations of arm and postural segment displacements. Figure 3 shows the sagittal displacements of the bubble, hand, trunk, and legs in a representative participant during the first trial (Fig. 3A) and the ninth trial (Fig. 3B), by which the performance has been tremendously improved. The gray body model in both figures serves as a link between the trajectories and illustrates the participant's movements. His initial attempt to reach the bubble was characterized by a longer and less-accurate hand movement (Fig. 3A). The target trajectory was intercepted at an almost overhead position that required minimal postural involvement. By the end of the practice session on the ninth trial (Fig. 3B), the hand trajectory became shorter, less curved, and the bubble trajectory was intercepted earlier than on the first trial. To reach the bubble, the participant leaned forward and used his leg to counterbalance the forward body shift. This later strategy revealed the greater involvement of postural segments into arm transport.

All participants improved in game performance during the practice session, increasing the number of bubbles popped from 19.4 ± 5.6 (mean ± SD) on the first trial to 27.5 ± 4.3 on the last trial. Improvement occurred despite the inclusion of additional virtual objects, which appeared after each successful gaming trial and distracted participants' attention. The increased number of popped bubbles through the end of the practice session was proportional to the decreased time of bubble trajectory interception (Fig. 4A) from 1.7 ± 0.4 s to 1.3 ± 0.3 s ($p < 0.05$). The movement time measured during the retention test (1.5 ± 0.4 s, $p < 0.05$) indicates that the changes were retained over the 30-min retention interval.
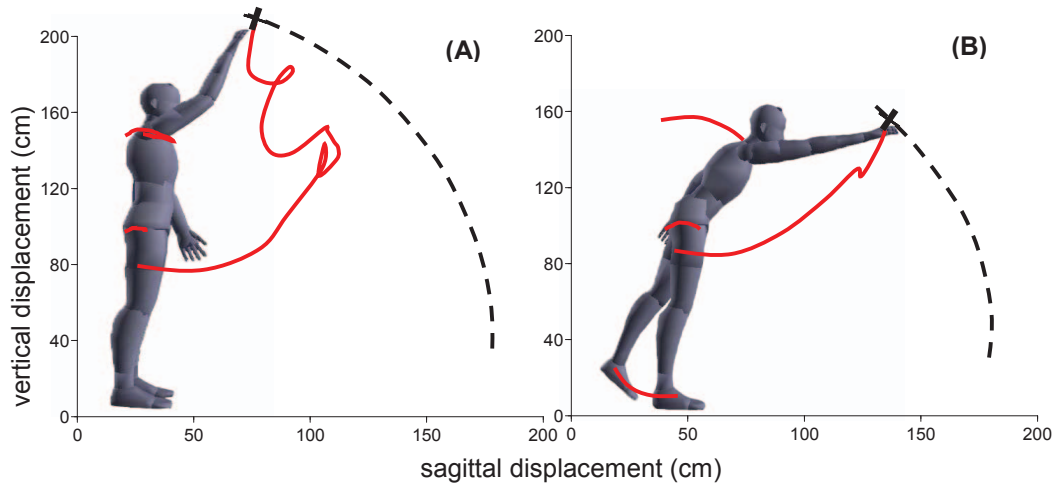

Figure 3. Trajectories of the arm (hand), trunk (C7), and legs (hip) in sagittal plane during the first (A) and ninth (B) gaming trials in a representative participant. Gray model serves as a link between segment trajectories to illustrate body movements. The bubble trajectory is marked by a dashed line. The cross indicates the point of hand/bubble trajectory interception
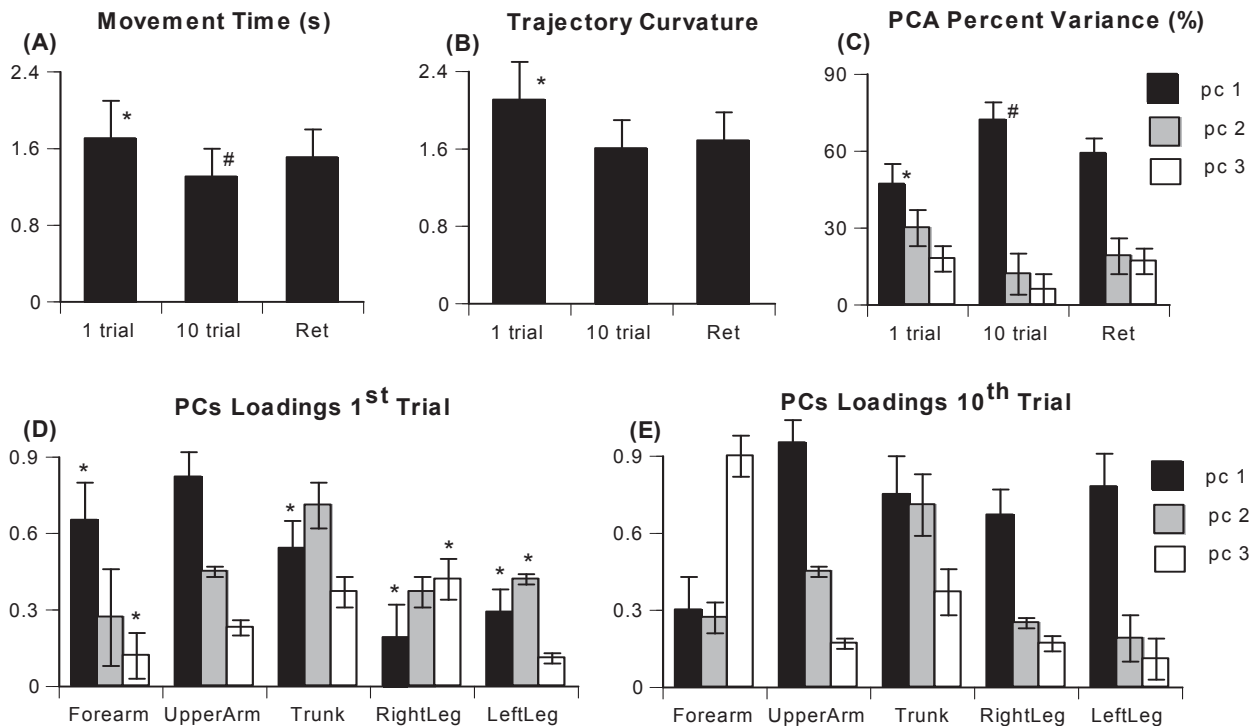
Figure 4. Means and standard deviations of the hand movement time (A), trajectory curvature (B), percentage of variance explained by the first 3 PCs (C), and segmental loadings on the first 3 PCs during the first (D) and last (E) trials, averaged across all subjects. * identifies significant difference between the first and last trials; #- identifies significant difference between the last and retention trials.

As a result of the gaming practice, the trajectory curvature (Fig. 4B) decreased through the end of the practice session, from 2.1 ± 0.4 on the first trial to 1.6 ± 0.3 on the last trial, with partial retention over the retention interval. This result indicates that, while playing the game, our participants acquired more efficient strategies of arm movements to the target.

The movement variation and relative contribution of different body segments to arm transport were analyzed using PCA. About 95% of the variance in the angular displacements of the 9 segments was accounted for by the first 3 PCs (Fig. 4C). The amount of variance explained by PC1 was significantly different for reaches-to-pop during the first gaming trial (47 ± 8) than for those during the last trial (72 ± 7). The percentage of angular variance associated with PC1 provided a strong representation of the relationship between the segments when popping the bubbles. This relationship was increased ($p < 0.01$) by the end of the practice session, and partially remained over the retention interval ($p > 0.05$),

Figure 4D-E shows the PC loadings from the 5 body segments (right forearm and upper arm, trunk, and right and left leg) that significantly contributed to the whole-body movement when intercepting the bubble. The upper arm loadings in PC1 across the first and last trials indicated that, regardless of the trial, this segment consistently contributed (>0.7) to the bubble popping and represented the reaching synergy. The forearm loading during the last trial was smaller than during the first one ($p > 0.05$), probably due to the reduced excursion of the forearm motion relative to the upper arm.

The pattern of loading coefficients for the postural segments (trunk and legs) was markedly different ($p < 0.05$). These coefficients were much smaller on PC1 during the first trial, indicating their weak coupling to arm motion. In PC2 and PC3, the postural segment loadings were larger, with trunk motion being coupled (PC2; >0.7) and the legs contributing insignificantly (PC3; <0.7). The loadings of the postural segments, on PC1 increased dramatically by the end of practice (>0.7), signifying that these body parts became greater contributors to the arm transport ($p < 0.05$). Significant changes ($p < 0.05$) were observed by the ninth trial for the trunk segment and by the eights trial for the leg segments (not shown). High loadings for the legs and trunk in PC1 on the last trial, combined with the fact that PC1 explained 72% of the variance, indicated that these segments were tightly synchronized with arm motion, forming the synergetic pattern of the whole-body motion. Means of the segmental loadings during the retention test were not included in the preliminary results.

After completing the practice session, 5/6 participants displayed improved reaching distances and single-leg stance times (Table 1).

IV. DISCUSSION

Overall, all of our participants benefited from game practice during a single session, displaying improved game performance, arm movement time, trajectory curvature, forward reach, and single-leg stance time. These game performance changes were partially retained over the 30-min retention interval. These facts support the feasibility of using the customized game in patients with TBI.

Although not specifically analyzed, all improvements most likely were caused by changes in movement strategies. According to the PCA results, a participant's initial effort to pop a bubble began with exploring all possible gaming solutions, making the performance very variable. Consistent with classical theories of motor learning [19], at this stage the participant tended to constrain postural displacements, thereby minimizing the central control of multiple degrees of freedom. Later gaming tasks were performed with greater involvement of postural segments, including the trunk and, in some cases, the legs. This strategy allowed faster arm transport towards the target. Moreover, the arm and postural segments began moving in a more coordinated manner, increasing movement efficiency and decreasing movement time of reaches-to-pop. This finding is consistent with the results of Kaminski [20] who, using an example of reaching forward while standing, showed that stronger arm and postural coupling allows faster movement performance.

As unsolicited feedback, a participant reported that the gaming practice gave her an "awareness" of whole-body movements. She expressed amazement that such "forgotten" movements could be made during a gaming session without loss of balance or taking a step. While performing activities of daily living that required arm movements while standing, the participant had previously "stiffened" her body to minimize the risk of falling. Upon completing the gaming session, she reported that she had learned how to control her body and was no longer afraid of instability. Indeed, training the patients in how to gain control, rather than in how to stabilize posture, was an ultimate goal of the gaming practice.

The benefits of the greater involvement of postural segments in arm reach-to-pop movements may be disputable. According to Levin et al. [21] and others, trunk involvement in arm transport during seated reaches is a pathological compensatory synergy in patients after stroke. Although compensatory trunk movements may improve the performance of the paretic arm initially, this strategy prevents further long-term recovery of more efficient arm movement patterns [22]. A short-term practice with trunk restraint results in greater reach-to-grasp improvements in patients with chronic stroke than practice without trunk compensatory involvement [23]. The same finding is true for seated activities where balance maintenance is not critical. In contrast, trunk and leg movements are an essential part of activities such as dressing, doing laundry, and cooking when performed in a standing position. For these tasks, gaining control of the arm-postural interaction guarantees successful and safe performance and cannot be excluded without a detrimental effect.

The short-term effect of practicing Octopus and the partial skill retention over time provide strong evidence of the feasibility of this type of videogame in patients with TBI. These games potentially can be used to regain arm-postural control and to encourage maximal use of available coordination strategies. However, we did not address whether the gaming intervention improved functional outcomes. Longer-term practice in the framework of different types of randomized controlled trials is necessary to assess changes in functional performance. Testing the therapeutic effect of customized videogames became easier with development of relatively inexpensive motion tracking solutions, e.g. Xbox 360 Kinect motion sensor. Integrated with WorldViz software, this tracking device allows practicing custom-designed games at regular in- or out-patient clinical settings as well as at patient's home. This tremendously increases the usability and cost-efficiency of the gaming approach.

Another study limitation was enrollment of relatively unimpaired individuals, who had full ranges of motions. We can predict that people with restricted arm movements would utilize postural segments for arm transport to a greater extent. This was not confirmed experimentally yet and will be considered in further research.

ACKNOWLEDGEMENT

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