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Video-capture virtual reality system for patients with paraplegic spinal cord injury

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Abstract—This article presents results from a feasibility study of a video-capture virtual reality (VR) system used with patients who have paraplegic spinal cord injury (SCI) and who need balance training. The advantages of the VR system include providing the user with natural control of movements, the ability to use as many parts of the body as are deemed suitable within the context of therapeutic goals, and flexibility in the way the system can be adapted to suit specific therapeutic objectives. Thirteen participants with SCI experienced three virtual environments (VEs). Their responses to a Short Feedback Questionnaire showed high levels of presence. We compared performance in the environments with a group of 12 nondisabled participants. Response times for the patient group were significantly higher and percentage of success was significantly lower than that for the nondisabled group. In addition, significant moderate correlations were found between performance within a VE and static balance ability as measured by the Functional Reach Test. This study is a first step toward future studies aimed at determining the potential of using this VR system during the rehabilitation of patients with SCI.

Key words: balance, Functional Reach Test, paraplegia, rehabilitation, spinal cord injury, therapy, training, traumatic injury, video-capture virtual reality, wheelchair.

INTRODUCTION

Damage to the central or peripheral nervous systems can result in a decreased ability of a person to perform activities of daily living (ADL), partly because of cognitive and motor deficits. Trauma to the spinal cord is a particularly devastating injury that often results in loss of sensation and voluntary activity below the level of the injury. Spinal cord injury (SCI) is associated with severe functional deficit and causes an abrupt change in the quality of the patient's life. The incidence of traumatic SCI in the United States is 40 cases per million or approximately 11,000 new cases each year; the prevalence in the United States has been estimated to be 721 to 906 per million population, corresponding to between 183,000 and 230,000 persons (http://www.fscip.org/facts.htm). SCI can affect the physical, psychological,

Abbreviations: ADL = activity of daily living, ASIA = American Spinal Injury Association, FIM = Functional Independence Measure, FRT = Functional Reach Test, GX = Gesture Xtreme, L2 = second lumbar, SCI = spinal cord injury, SD = standard deviation, SFQ = Short Feedback Questionnaire, T3 = third thoracic, VE = virtual environment, VR = virtual reality.

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and emotional aspects of occupational performance, with the extent of impairment and disability dependent on the level of injury [1].

The ultimate goal of people with SCI is to maximize their independence in all aspects of life through rehabilitation, given the limitations imposed by injury [1]. For them to achieve this objective, an essential part of the rehabilitation process is remediation of the motor and sensory deficits. One of the key functional deficits is poor balance; people who have sustained an SCI lack the normal postural synergies and sensory-motor integration of the lower limbs and trunk that regulate upright position. They are therefore obliged to develop compensatory strategies to maintain balance while standing, including activating appropriate muscles of the trunk, neck, and upper limbs before and during postural disturbances. Poor balance and the need for upper-limb support of one or both hands adversely affect functional activities that require standing [2] as well as activities during sitting that involve reaching out for an object within or beyond arm's length [3]. Potten and colleagues have suggested that individuals with SCI with complete thoracic lesions use nonpostural muscles (e.g., latissimus dorsi) to maintain their sitting balance [4]. Patterns of postural control develop as a result of rehabilitation in the low- and high-level thoracic lesions [5].

Balance training improves the functional abilities of patients and promotes independent living in the community [6–7]. Conventional therapy focuses on muscle strengthening and improving balance reactions. According to Bromley [8], while standing behind the patient, the therapist should verbally and physically guide balance training as the patient observes him- or herself in a mirror. The exercises are graded from self-supported sitting to single-arm tasks and, finally, to bilateral-arm activities without the mirror. Most often, the patient performs these exercises sitting on a plinth, although the patient should remain in the wheelchair when posture is very poor or when transferring to and from the chair may injure the skin [8]. Since patients with SCI perform most functional activities while supporting themselves with one arm and reaching out with the other [9], they should exercise sitting balance while reaching for objects. Dean and Shepherd found that task-related motor training (e.g., reaching for objects placed at different distances and directions) of people with stroke improved their balance in reaching activities performed while sitting [3]. In another study, patients with stroke, when given the choice, preferred treatment activities with a functional goal; such activities had a positive effect on the temporal characteristics (e.g., movement time) of their reaching movements while they were seated [10].

Typically, conventional intervention tools tend to be tedious, provide little opportunity for grading the level of difficulty in terms of stimulus delivery, and do not encourage dynamic adaptive postural reactions. Indeed, one of the major challenges facing clinicians in rehabilitation is identifying intervention tools that are effective, are motivating, and enable transfer patients' skills to function in the "real" world. In addition, an important requirement of both an assessment and a treatment tool is to enable comparison of performance of a specific clinical population with the performance of people without that specific impairment. Poorer performance by the patient group indicates that the tasks required by the rehabilitation tool are sufficiently challenging to be useful during assessment and intervention.

One of the emerging rehabilitation tools in recent years is the application of virtual reality (VR)-based technologies [11]. VR entails the use of advanced technologies, including computers and various multimedia peripherals, to produce a simulated (i.e., virtual) environment that users perceive as comparable with real-world objects and events [12–14]. Users interact with displayed images, move and manipulate virtual objects, and perform other actions in a way that engenders a feeling of actual presence and immerses their senses in the simulated environment. Users are provided with visual, audio and, in some instances, haptic and olfactory feedback of their performance.

In recent years, VR technologies have begun to be used as an assessment and treatment tool in rehabilitation [15–19]. The rationale for using VR in rehabilitation is based on a number of unique attributes of this technology [18,20–21]. These include experiential, active learning, which encourages and motivates the participant [22]. In addition, they also include being able to measure behavior in challenging but safe and ecologically valid environments while providing increased standardization of assessment and retraining protocols [23]. VR platforms offer clinicians the capacity to individualize treatment needs while providing the opportunity for repeated learning trials, progressing training by gradually increasing the complexity of tasks, and decreasing the therapist's support and feedback [18].

Several studies have examined the use of VR for balance training. In a study of 30 nondisabled individuals in three age groups (20–29, 30–39, and 40–49 yr), Kim et al.'s initial results showed the potential of using VR for balance training of individuals who are sitting on a stationary bicycle [24]. They found improvement in cycling velocity and a decrease in the deviation from the path after virtual cycling training. Similar results were found in a more recent study by Song, Kim, and Kim [25], using a comparable system with 20 nondisabled participants aged 24 to 45 years. They concluded that these variables might be used to characterize improvement in balance through rehabilitation. In this study, they found that visual feedback regarding the user's weight shift in real time helped to improve postural balance. Lott et al. showed significant differences between functional lateral reach performed in a real versus a virtual environment (VE) in 18 nondisabled adults [26]. They reported that the participants reached significantly farther when virtual objects were presented within the VE using a video-capture VR system than when they were asked to touch the hand of a person who was standing at their sides. They suggested that embedding the reaching task in a game shifts individuals' attention from the possibility of losing balance and thus encourages them to extend their reach beyond what would have otherwise been assumed to be possible. Sveistrup et al. presented initial results of an ongoing study comparing conventional and VR-based balance training of patients with traumatic brain injury [19]. They found a similar improvement in both types of training.

To date, research of the applications of VR in the rehabilitation of SCI is quite limited. Riva described a case report that showed the potential of using VR during locomotion training of a patient with paraplegia [27]. No side effects were reported, and the patient indicated a subjective improvement in his sense of well-being, mood, and quality of sleep. In another study, Ku et al. demonstrated the potential of using a driving simulator to assess and improve driving skills of people with paraplegia [28]. The participants in this study, 15 adult males, reported that their fear of driving with a hand-control unit lessened after the experience in the driving simulator. The authors also found that the driving skills of the SCI group and a group of 10 nondisabled participants were similar, indicating that these skills were not influenced by the method of manipulation (hand vs foot controls). However, significant differences were found between the groups under challenging road conditions, where the SCI group drove more slowly and carefully than did the nondisabled group.

The present feasibility study describes the use of GestureTek's Gesture Xtreme (GX) VR system, a video-capture VR system, which has potentially important applications for the rehabilitation of children and adults with physical and/or cognitive impairment (www.gesturetek.com) [19,29–31]. When using the GX-VR system, users stand or sit in a demarcated area viewing a large video screen that displays one of a series of simulated functional tasks, such as catching virtual balls or skiing down a mountain. Users see themselves on the screen, in the VE, as shown in **Figure 1**; their movements entirely direct the progression of the task.

The GX-VR system has been adapted for use in rehabilitation [19,31–32] (www.gesturetek.com/irex/introduction.php). These adaptations ensure that the system has a number of advantages for use in rehabilitation in general and for balance training specifically. First, the user controls movement within the VE in a completely natural and intuitive manner. The control of movement is not only more natural but also involves the use of as many parts of the body as deemed suitable for defined therapeutic goals. For example, the user may respond to projected balls via a specific body part (e.g., the head or hand) when the intervention is directed toward more precise movements or via any part of the body when the goal of therapy

Figure 1.
A participant with spinal cord injury using Birds & Balls virtual environment.

is a general activation of the whole body. Indeed, training different strategies for maintaining balance is possible, such as using one hand while the other supports the body or using two hands simultaneously while the residual postural muscles maintain trunk equilibrium.

A second advantage of the GX-VR system is that it enables great flexibility in the way it can be interfaced with patients and adapted to suit specific therapeutic goals. The patient can, in accordance with his or her abilities and type of injury, sit or stand while performing within the VEs. Equally important, the therapist can intervene during the session to enhance motor learning or to apply selective resistance or support to facilitate the rehabilitation process. Another advantage is that the virtual stimuli may be programmed to emanate at different heights, speeds, and frequencies within a 2-dimensional plane, thereby providing the patient with various challenges to achieve and maintain his balance. Finally, the existing VEs facilitate a patient's residual motor and sensory abilities within functionally meaningful contexts. Since the ultimate goal of occupational therapists in rehabilitation is to maximize a patient's independence in activities related to daily performance skills, functional relevance and integration of performance components are of paramount importance [33].

The objective of this feasibility study is to report on the use of the GX-VR system with patients who had sustained an SCI at the level of the second thoracic (T2) vertebra and below (i.e., a paraplegic injury). This includes examining relationships between performance on a standard test of static balance and performance within the VEs as well as differences in performance within the VEs between patients with SCI and subjects who are nondisabled. Since persons with disabilities may not function at the same level as the nondisabled, testing control subjects in this preliminary work is important.

METHODS

Preliminary Pilot Study

We first completed a pilot study to establish the VR protocol to be used in the full study. The pilot study group was composed of five participants (two male and three female, 19 to 31 years old (mean age 23.0 ± 5.6 standard deviation [SD]). Four sustained a complete paraplegia (American Spinal Injury Association [ASIA], classification A) and one an incomplete paraplegia (ASIA, classification D) [34].* Their injuries were located at levels ranging from the third thoracic (T3) vertebra to the second lumber (L2) vertebra. The issues addressed in the pilot study included the selection of appropriate VEs, the level of difficulty of the various tasks, and the amount of time engaged at each task. Results from these participants have not been included in the full data set described in this article. The study protocol was approved by the institutional review board at the Chaim Sheba Medical Center.

Subjects

The full study included an additional 13 participants (9 male and 4 female), aged 21 to 53 years (33.6 ± 12.4). Ten of these had sustained complete SCIs, two had incomplete SCIs according to the ASIA's impairment scale at the level of T3 to L2, and one participant sustained an injury at the level of the cauda equina. Time since the onset of the injury to participation in the study ranged from 3 weeks to 4 1/2 months. Twelve participants had sustained traumatic SCIs and one participant had an incomplete postsurgical injury due to a spinal cord stenosis. Eight of the participants were independent in basic ADL in a wheelchair, according to their Functional Independence Measure (FIM) motor [35] scores, which ranged from 75 to 86 (out of a maximum score of 91). Five participants, whose FIM scores ranged from 32 to 67, needed mild to moderate assistance. All the participants had the maximum score of 35 on the cognitive part of the FIM.

Table 1 presents details about the participants. All participants used a wheelchair when performing daily activities. The participant with the lesion at the level of the cauda equina was able to stand with support during the VR session. All participants were tested while hospitalized in the Department of Neurological Rehabilitation at the Chaim Sheba Medical Center (Tel Hashomer, Israel).

Results from the patient group were compared with data from a parallel study of a group of 12 (6 male and 6 female) nondisabled participants, aged 20 to 55 years (29.6 ± 9.5), who performed a similar protocol while sitting on a chair with their hands supported on arm rests.

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*ASIA has developed an impairment scale for neurological classification of spinal cord injury. The scale is based on tests of key muscles and levels of dermatomes and describes the intact sensory and motor level. It consists of five categories (A to E).

Table 1.
Type and level of injury and functional capacity of participants.

Participant	Level of Injury	ASIA Rating	FIM Score
1	T8	A	116
2	T9	A	116
3	L2	B	115
4*	Cauda Equina	—	121
5	T3	A	110
6	T4	A	102
7	T12	A	72
8	T7	A	84
9	T4	C	72
10	T12	A	114
11	T8	A	67
12	T5	A	116
13	T8	A	116

*All participants in seated position except Participant 4 in standing position.
FIM = Functional Independence Measure; ASIA = American Spinal Injury Association; T = thoracic, plus vertebra number; L = lumbar, plus vertebra number; A = complete injury no motor or sensory response below injury; B = incomplete injury sensory, with no motor function preserved below neurological level; C = incomplete injury with motor function preserved below neurological level and more than half of key muscles below neurological level having muscle grade less than 3.

Material

Immersive Virtual Reality System

We used GestureTek's GX-VR system to provide VR experiences within three environments. As mentioned previously, these environments had been adapted to make them suitable for rehabilitation [31].

Birds & Balls. Users see themselves standing or sitting in a pastoral setting while balls of different colors emerge from four edges of the screen in a single plane of action and fly toward them (**Figure 1**). Touching these balls with any part of the body causes them to turn into birds or to burst. Three levels of this game were used; at the easiest level, only two balls are presented simultaneously on the screen. At the second level, four balls are presented, and at the third level, five balls are presented. A change in the velocity of the balls was an additional factor that differentiated between levels 2 (lower velocity) and 3 (higher velocity).

Soccer. Users see themselves as the goalkeeper in a soccer game. Soccer balls are shot at them from different locations, and their task is to hit them with different parts of their body to prevent them from crossing the goal crease. Successfully repelled balls remain white while the ones that enter the goal area change color from white to orange. Because all the participants were not able to perform the third, more difficult level, only two levels of this game were analyzed; at the easiest level, up to two balls are presented simultaneously on the screen, and at the second level, up to three balls are presented. In contrast to Birds & Balls, the Soccer balls appear to approach the user from beyond his or her plane of action and at greater velocity.

Snowboard. Users see a back view of themselves on a snowboard. As they ski downhill, they need to avoid rocks and trees by leaning from side to side and by transferring their weight or moving their whole body. The same level of difficulty was used for all sessions. This environment is different from the other two, since in this setting, the background rather than the virtual objects is moving. In addition, action in this environment is achieved by movements of the whole body rather than primarily the upper limbs.

Performance in all three environments was measured in terms of the rate of success. For Soccer, the percentage of soccer balls repelled from the goal crease was calculated, and for Birds & Balls, the percentage of balls that was touched was calculated. For Snowboard, the percentage of success was calculated from the number of obstacles that were not hit out of the total number of obstacles encountered during the session. For the nondisabled participants, the percentage of success in Birds & Balls was not analyzed, since this game was so easy that almost all participants achieved the maximum score of 100 percent. In addition to percentage of success, for Birds & Balls, the participants' response times were measured (i.e., the time in seconds from when the ball emerged on the screen until it was touched by the participant). For the Snowboard game, the third minute (out of a total of 4 minutes) of each VR experience was analyzed, since it should reflect the participant's best performance; i.e., after participants had practiced but before the onset of fatigue.

Short Feedback Questionnaire

We used the Short Feedback Questionnaire (SFQ), an eight-item questionnaire previously developed by our research group [31], to obtain information about the subjective responses of the participants to the VR experience in each VE. It queried the user's sense of presence, perceived difficulty of the task, and any discomfort that users may have felt during the experience. The first six items of the questionnaire were formulated as an abbreviated alternative to the longer Presence Questionnaire developed by Witmer and Singer [36]. These items assessed the participant's—

1. Feeling of enjoyment.
2. Sense of being in the environment.
3. Success.
4. Control.
5. Perception of the environment as being realistic.
6. Comprehension of computer feedback.
7. Level of comfort during the experience.
8. Perception of difficulty while performing the task.

Responses to the first seven items were rated on a scale of 1 to 5, where 1 = not at all and 5 = very much. Responses to the eighth item were also rated on a 1 to 5 scale, where 1 = very easy and 5 = very difficult. A total mean score for each participant was calculated for the first six items.

Standing or Sitting Balance

The Functional Reach Test (FRT) [37] was adapted such that several subtests were used to test the ability of participants to reach out when they faced a wall as well as when the side of their body was adjacent to a wall. Twelve of the participants performed the tests while sitting in their wheelchairs, and the other participant performed the same test while standing (in accordance with how they performed in the VE). Two tests were performed while participants sat with either the right or left side next to a wall, similar to the original FRT that was adapted by Lynch et al. for SCI [38]. Sitting with the right side of the body near a wall, participants were asked to raise their right arm to 90° shoulder flexion, with elbow fully extended, and to lean forward as far as possible (FRT 1). The distance in centimeters reached by the third metacarpal head (not including the length of the arm) was measured. (Note that exclusion of the length of the arm in the measurement facilitates the comparison of abilities of participants with different anthropomorphic characteristics.) The test was then repeated with the left side of the body adjacent to the wall and with the left arm reaching as far as possible (FRT 2). In contrast to previous studies, we allowed participants to support themselves with their other hand as they would normally do during functional activities.

Several additional measures were added to indicate balance capacity corresponding to the type of movements typically performed in the VEs used in this study. First, we calculated a total FRT score when the side of the body was adjacent to a wall (FRT 3) by combining the distance reached by the right hand and by the left hand (FRT 1 + FRT 2). Second, several additional measures obtained when the participants faced a wall were also included (as described, in part, by Axelson and Chesney [39]). While facing a wall, participants were asked to reach with their right arm as far as possible to the right (FRT 4) and then, with their left arm, to reach as far as possible to the left (FRT 5). The distance in centimeters reached by the third metacarpal head (not including the length of the arm) was measured. In the same position, participants were asked to maximally reach with their dominant arm to the highest point possible on the wall in front of them (FRT 6). The distance in centimeters was measured from shoulder level to the point reached on the wall. We calculated a total FRT score (FRT 7) when the front of the body faced the wall by combining the FRT 4 + FRT 5 + FRT 6 scores.

Functional Independence Measure

We used the FIM, which assesses 18 basic ADL, such as dressing [35], to characterize the functional status of the participant. Thirteen activities constitute the motor part of the FIM and five constitute the cognitive part of the FIM.

Procedure

The study took place in the Department of Occupational Therapy, Chaim Sheba Medical Center, Tel Hashomer, Israel. After signing an informed consent, each participant experienced all three VEs (Birds & Balls, Soccer, and Snowboard). In each environment, the participant was given an opportunity to practice for 1 minute and then to perform the task for an additional 3 minutes. For two of the environments (Birds & Balls and Soccer), the task was progressively increased in difficulty during the 3 minutes. Those with complete SCI and one of the participants with an incomplete SCI performed while sitting in their wheelchairs; the other participant with an incomplete SCI performed while standing, supporting himself with one arm on a table. After each VE, the participants completed the SFQ. Sitting or standing balance and functional status were tested via the outcome measures indicated earlier. Participants of the control group performed a similar VR protocol while sitting on a chair with their hands supported on arm rests.

Data Analysis

Descriptive statistics summarize the participants' status regarding their motor and functional abilities as well as performance within the VEs. We analyzed the difference in performance between the levels of each VE for the SCI group using a paired *t*-test. To explore the relationships between balance capacity and performance within the VEs, we divided the SCI group into two subgroups according to the median score of the two total FRT scores described earlier (FRT 3 and FRT 7); subgroup 1 consisted of participants who scored below the median, and subgroup 2 consisted of participants who scored above it (i.e., had better balance capacity). Because of the small number of participants in each subgroup, we performed the nonparametric Wilcoxon test (*z*-test) to determine whether a significant difference in VR performance existed between the two subgroups. In addition, we performed Spearman correlations (r_S) to further explore the relationships between balance capacity and VR performance within the entire group. The differences in performance between the participants with SCI and the nondisabled participants were examined with an independent sample *t*-test.

RESULTS

Sense of Presence

Both the participants with SCI as well as the nondisabled group's responses to the SFQ showed that they enjoyed the experience and felt high levels of presence for the different environments. No significant differences were found between the groups. The means ± SDs for the SCI group and for the nondisabled participants were 4.33 ± 0.30 and 4.03 ± 0.52 for Birds & Balls, 3.94 ± 0.61 and 3.96 ± 0.38 for Soccer, and 4.12 ± 0.50 and 4.18 ± 0.41 for Snowboard, out of a maximum possible score of 5.0. The only feelings of discomfort reported in the SCI group were from fatigue and pain related to the injury after they participated in the Soccer environment (five participants), Birds & Balls (two participants), and Snowboard (two participants). This injury-related pain was similar, both in location and in intensity, to that experienced by these participants when engaged in conventional physiotherapy and occupational therapy treatment. None of the participants asked to terminate the VR experience because of the pain. Feelings of discomfort were reported by the nondisabled group only during Birds & Balls and Soccer and were related to a feeling of embarrassment (one participant), the lack of realism of the environment or unfamiliar feeling (three participants), the seated position (one participant), and a slight difficulty in eye-hand coordination (one participant).

Performance in Virtual Reality

Performance results of the 13 participants with SCI at the different levels, as well as the participants' perceived difficulty, are shown in **Table 2**. Results of the paired *t*-tests showed that response time at the easiest level of Birds &

Table 2.
Performance within virtual environments and perceived difficulty of task.

Participant	Birds & Balls							Soccer			Snowboard	
	Response Time (s)			Success (%)			Perceived Difficulty	Success (%)		Perceived Difficulty	Success (%)	Perceived Difficulty
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3		Level 1	Level 2			
1	4.82	5.82	5.5	100.0	96.3	90.0	2	55.0	61.0	4	100.0	2
2	3.94	4.12	4.6	94.7	100.0	93.0	1	100.0	80.0	3	79.0	1
3	5.62	5.24	4.9	100.0	90.0	77.5	2	90.9	70.0	3	100.0	2
4*	4.99	6.04	6.0	100.0	100.0	97.0	2	80.0	57.0	4	93.0	2
5	4.73	5.52	6.0	77.8	71.4	87.0	3	90.9	71.0	4	100.0	2
6	4.07	4.32	5.4	100.0	88.9	83.7	4	95.5	70.0	4	92.0	3
7	4.81	5.11	5.2	87.5	75.8	91.2	4	33.3	36.2	3	100.0	3
8	4.88	5.46	6.1	87.5	89.3	84.4	4	76.2	76.4	3	92.0	1
9	4.45	6.32	5.6	88.9	60.0	63.6	3	76.2	57.4	3	91.0	2
10	5.85	5.91	5.8	64.3	66.7	96.8	3	70.0	76.4	4	100.0	2
11	3.41	4.00	3.7	100.0	85.4	73.1	1	70.0	82.5	1	100.0	1
12	4.90	3.95	4.9	100.0	87.2	84.6	3	76.2	78.6	4	94.0	3
13	4.47	5.50	5.0	94.1	93.3	86.8	1	72.7	71.7	3	94.0	1
Mean ± SD	4.7 ± 0.7	5.2 ± 0.8	5.3 ± 0.7	91.9 ± 10.9	84.9 ± 12.7	85.18 ± 9.4	2.5 ± 1.1	75.9 ± 17.7	68.4 ± 12.7	3.3 ± 0.9	98.0 ± 2.7	1.9 ± 0.8

*This participant engaged in all virtual reality tasks while standing. SD = standard deviation.

Balls was significantly shorter than response time at Levels 2 and 3 ($t = 2.5$, $p = 0.03$; $t = 3.5$, $p = 0.005$, respectively). No significant difference was found between the response times of Levels 2 and 3. In addition, the percentage of success at Level 1 of Birds & Balls was significantly higher than percentage of success at Level 2 ($t = -2.7$, $p = 0.02$). No significant differences were found between the percentage of success at the other levels in Birds & Balls or in Soccer, although in Soccer, it almost reached significance ($p = 0.07$). The highest performance scores were obtained in Snowboard, whereas the lowest performance scores were in Soccer. In general, participants reported greater perceived difficulty for the tasks in which they scored worse.

Balance and Virtual Reality Performance

The results of the FRT for each participant are presented in **Table 3**. The distances reached during the various tests varied both with the type of test and the participant. Whereas some participants were able to reach equally well to both sides of the body (e.g., Participant 1 reached forward 35.0 cm with the right arm and 33.0 cm with the left arm when the side of his body was adjacent to the wall), others had a marked asymmetry in their reaching abilities (e.g., Participant 8 reached forward 23.0 cm with the right arm and 32.7 cm with the left arm). In general, participants were able to reach farther when the side of their body was near the wall (40.8 ± 12.9 and 40.0 ± 10.5 cm) than when facing the wall (15.0 ± 7.8 and 10.9 ± 7.8 cm).

The relationships between the FRT and performance within the VEs were examined, as just mentioned, by comparing those participants who scored above the median of the total score of the FRT when the side of the body is near the wall (FRT 3) with those who scored below the median. The group who scored above the median of FRT 3 ($n = 7$) (i.e., those with greater balance capacity) performed significantly better in some of the VEs than did the group who scored below the median ($n = 6$) (i.e., those with less balance capacity); in Birds & Balls (Level 3), the mean response time (in seconds) for the above median FRT 3 group was 4.9 ± 0.66 as compared with 5.8 ± 0.35 for the below median FRT 3 group ($z = -2.42$, $p = 0.014$), and in Soccer (Level 2), the mean

Table 3.
Description of participants' balance capacity in Functional Reach Test (FRT) shown in centimeters.

Participant	Sagittal Plane FRT (Side of Body to Wall)			Coronal Plane FRT (Face to Wall)			
	Right Side to Wall & Reaching Frd FRT 1	Left Side to Wall & Reaching Frd FRT 2	FRT 3*	Reaching Right FRT 4	Reaching Left FRT 5	Reaching Up FRT 6	FRT 7†
1	35.0	37.0	72.0	26.0	23.5	52.0	101.5
2	54.0	44.5	98.5	17.0	5.5	68.0	90.5
3	56.0	56.0	112.0	27.5	1.0	59.0	87.5
4	29.0	23.2	52.2	14.0	19.3	82.5	115.8
5	41.0	29.0	70.0	15.0	8.5	36.5	60.0
6	40.0	49.5	89.5	21.0	18.3	50.0	89.3
7	27.0	32.0	59.0	11.7	10.0	35.0	56.7
8	23.0	32.7	55.7	7.0	5.0	51.0	63.0
9	26.0	29.4	55.4	9.0	4.0	40.0	53.0
10	62.5	55.5	118.0	23.8	22.7	59.0	105.5
11	54.3	48.3	102.6	14.0	8.0	65.0	87.0
12	45.0	42.0	87.0	2.5	2.0	61.0	65.5
13	37.0	41.0	78.0	6.4	14.0	56.5	76.9
Median	40.0	41.0	78.0	14.0	8.5	56.5	87.0
Mean ± SD	40.8 ± 12.9	40.0 ± 10.5	80.8 ± 22.4	15.0 ± 7.8	10.9 ± 7.8	55.0 ± 13.3	80.9 ± 20.1
Minimum	23.0	23.2	52.2	2.5	1.0	35.0	53.0
Maximum	62.5	56.0	118.0	27.5	23.5	82.5	115.8

*Sum of FRT 1 and FRT 2.
†Sum of FRT 4, FRT 5, and FRT 6.
SD = standard deviation, Frd = forward.

percentage of success for the above median FRT 3 group was 75.6 ± 5.03 as compared with 59.9 ± 14.03 for the below median FRT 3 group (z = –2.22, p = 0.022). No significant differences were found between the groups in the rest of the levels or when groups were divided according to the median of the total score of the FRT when facing the wall (FRT 7), although the group who had scores above the median tended to perform better in the VEs across all FRT scores. **Table 4** shows moderate correlations above 0.40 between several FRT scores and VR performance.

Comparison of Performance Between Nondisabled and Spinal Cord Injured

Figures 2 and **3** show the significant differences between the performance scores for the participants with SCI (gray histograms) compared with those of the non-disabled group (black histograms). The mean response time (in seconds) during Birds & Balls for the SCI group at all three levels was significantly longer than for the nondisabled group. At Level 1, the mean ± SD response time was 4.69 ± 0.7 s for the SCI group versus 3.59 ± 0.6 s for the nondisabled group (t = 3.94, p = 0.001). At Level 2, it was 5.18 ± 0.8 s for the SCI group versus 3.96 ± 0.5 s for the nondisabled group (t = 4.45, p = 0.000), and at Level 3, it was 5.3 ± 0.7 s for the SCI group versus 3.94 ± 0.5 s for the nondisabled group (t = 5.71, p = 0.000). In Soccer, the percentage of success of the nondisabled group was higher at both levels, although only the difference at Level 2 reached significance; for the SCI group, percentage of success equaled 68.4 ± 12.7, and for the nondisabled group, it equaled 84.0 ± 10.5 (t = –3.31, p = 0.003). The difference between the two groups for the Snowboard VE was not significant. Interestingly, no significant differences were found in performance between the levels of the tasks in the non-disabled group.

DISCUSSION

The findings of this feasibility study show the potential of using the GX-VR system as an additional tool during the rehabilitation of patients with SCI, although further clinical trial studies are needed to demonstrate the efficacy of such a treatment, compared with conventional balance and performance training. The positive responses to the experience as well as the expressions of interest in having additional sessions with the system suggest that this modality may increase motivation for therapy. The capacity of simulated environments to enhance motivation for treatment has been suggested to be one of the key attributes of using VR in rehabilitation [20,22,27,30,40]. Rizzo et al. suggested that since interactive computer gaming plays an important role in the lives of many people [20], VR-based game-like applications may be used to enhance motivation during rehabilitation. Indeed, based on observation of an individual with paraplegia who participated in locomotor training within a VE, Riva recommended that such exercise routines create a considerable incentive during SCI therapy [27], even if the locomotion is not functional. The high levels of presence reported by participants also has implications for rehabilitation, since the patient typically needs to be able to focus on a specific therapeutic task and not be distracted by real-world events

Table 4.
Spearman correlation coefficients (r_s) and p-values (in parentheses) for relationships between Functional Reach Test (FRT) and performance within virtual environments for tests where r_s was above 0.40 (N = 13).

FRT	Soccer % Success Level 2	Snowboard % Success	Birds & Balls % Success			Birds & Balls Response Time	
			Level 3	Level 2	Level 1	Level 3	Level 2
1	0.56 (0.05)	—	—	—	—	–0.53 (0.06)	—
2	0.50 (0.08)	—	—	—	—	–0.59 (0.04)	–0.48 (0.04)
3	0.59 (0.03)	—	—	—	—	–0.60 (0.03)	–0.47 (0.10)
4	—	0.44 (0.13)	—	—	—	—	—
5	—	—	0.62 (0.03)	—	—	—	0.41 (0.17)
6	0.47 (0.11)	—	—	0.56 (0.05)	—	–0.42 (0.16)	—
7	—	—	0.54 (0.06)	0.58 (0.04)	0.40 (0.17)	—	—

Note: Because of small sample size, nonsignificant correlations above 0.40 are presented.

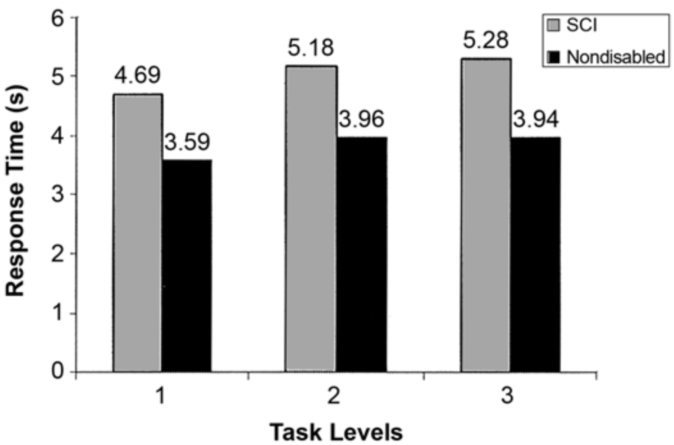

Figure 2.
Means of response times (seconds) during Birds & Balls for participants with SCI (gray) and nondisabled (black) at task Levels 1–3.

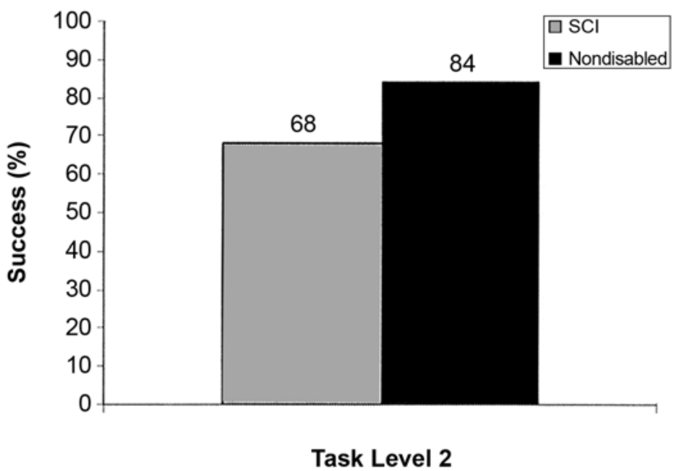

Figure 3.
Means of percentage of success during Soccer for participants with SCI (gray) and nondisabled (black) at task Level 2.

during treatment. Because of constraints of time and space, multiple therapy sessions often occur simultaneously; therefore, helping patients focus on their own individual intervention is advantageous.

The lack of side effects such as nausea or dizziness points to the suitability of the GX-VR system used in the current study for the provision of therapy to patients with SCI [32]. Any discomfort experienced by the participants in the SCI group during VR-based training was comparable with that felt during conventional therapy. This finding provides some evidence that their physiological responses during both VR and conventional tasks were similar, particularly with regard to the amount of perceived effort exerted. Moreover, participants performed the tasks at the different levels of difficulties in all three environments without manifesting frustration or discouragement. The clinician's ability to grade the level of difficulty of the various VEs and the associated appropriate motor responses of the participants demonstrated that use of these VEs conforms to the key rehabilitation principle of matching a therapeutic task to the current ability of the patient.

These results also point to the potential of using the GX-VR system as a means of encouraging physical exercise and thereby reducing the cardiovascular complications and obesity often observed in individuals who have SCI [41–42]. Physical exercise also engenders a sense of well-being [42]. In their discussion of the important effects that exercise has for the rehabilitation of patients with SCI, Durán et al. recommended that an exercise program consisting primarily of rote exercises be included in conventional rehabilitation [41]. This program resulted in significant improvements in functional (i.e., FIM scores) and physical capacity (i.e., amount of weights lifted, number of repetitions of each exercise, and wheelchair skills). In addition to these physiological benefits, participation in sport activities contributes significantly to people with SCI from a social perspective [10]. Since the GX-VR system supports simultaneous (e.g., playing the games at the same time) or sequential (e.g., viewing posted scores resulting from a group of players) interaction by two or more users, competitive incentives amongst users with SCI may be achieved. The VR literature just described as well as the findings of this study suggest that VEs provide an ideal opportunity for such training programs, motivating individuals with SCI to exercise more, thereby increasing their physical capacity and well-being.

Two limitations of this study were the small sample size (N = 13 subjects with SCI) and the type of balance measure used (the FRT, which is a static measure of balance compared with the dynamic balance required during the VR tasks). The present findings, although encouraging, should therefore be interpreted with caution, particularly, the differences in performance within the VE between those participants with low balance capacity according to FRT 3 and those with higher balance capacity according to the same test. After these limitations were considered, these findings indicate the relationships between performance in Soccer environment and the response times in the Birds & Balls environment and static balance capacity. In future studies, using more dynamic measures of balance would be important for researchers to compare what is necessary for performance in the VEs and to test these abilities on both the control and patient subjects.

Apparently, from the moderate correlations that were found (**Table 4**), performance within the VEs was related to the ability to maintain one's balance as measured by the FRT. However, it also entailed additional sensory-motor abilities (e.g., eye-hand coordination) and, perhaps, more complex balance reactions caused by the dynamic nature of the moving virtual stimuli as well as the purposeful reaching task required of the user. Indeed, in contrast to the relatively static equilibrium demands made during conventional therapy, analysis of the videotaped recordings of the VR sessions by experienced therapists revealed that the simulated tasks required that patients maintain balance under conditions similar to dynamic ADL. Thus, the presentation of the virtual stimuli, especially at the higher levels of difficulty, facilitated therapy for diverse equilibrium reactions rather than being limited to the simple transfer of weight, which is usually the focus of conventional treatment.

The present findings suggest VEs may be used to elicit sitting-balance reactions while individuals are reaching, a task that has been suggested to be important for balance control [3,9]. Further support for the effectiveness of VEs is provided by Lott et al.'s findings that showed that the participants reached significantly farther when virtual objects were presented within a VE than when they were asked to touch a person's hand standing nearby [26] (not within a VE). Lott et al. and Sveistrup have suggested that users who reach for objects within VEs become absorbed in the task and are less fearful of destabilization and falling [26,43]. They are therefore more willing to risk the consequences of reaching farther.

The provision of training of sufficient intensity to remediate motor function of people with neurological deficits is another factor when adoption of VR-based therapy versus conventional therapy is considered. During the early stages of SCI rehabilitation, extensive therapy for sitting balance control is provided as a prerequisite for functional training in ADL [7]. In conventional therapy, the patient is usually presented with one stimulus at a time; since the therapist is often occupied in supporting the patient, the delivery of such stimuli may be slow and awkward. An example of this type of intensive motor training program was described by Dean and Shepherd [3], who manipulated tasks by placing real objects in different locations as well as changing the patient's seat height, thigh support, and speed of movement required. They found this program to be effective in improving sitting balance control in people who had had a stroke more than 1 1/2 years before the study. The ability to deliver several stimuli simultaneously from different directions and at different velocities with the GX-VR system greatly facilitates task manipulation. Moreover, automatic stimulus delivery leaves the therapist free to physically guide the patient as suggested by Bromley [8]. Since the provision of augmented stimuli increases the number of balance-related movements per session, further study of the use of VR-based intervention for remediation of balance deficits is warranted.

Finally, although the attributes of using VR as an assessment tool have been discussed extensively in the literature over the past decade [12,23,44], the psychometric characteristics of assessments performed within VEs remain to be established. The different VR performance values between the nondisabled group and the SCI group found in this study can be considered as a first stage in establishing validity of the GX-VR system as an assessment tool of balance and reaching abilities of patients with paraplegic SCI. In addition, one may consider the FRT correlation results described here a foundation for establishing concurrent validity of this system. However, outcome measures more suited to dynamic balance for both the SCI and nondisabled groups would enhance this test of validity. Additional data from larger numbers of participants who have a greater range of ages and whose balance deficits emanate from different pathologies are needed to increase the validity and utility of this tool.

CONCLUSIONS

The results of this study showed correlations between static balance ability and performance within VR and differences between the performance in VR of the SCI group and nondisabled group. Interaction with virtual stimuli in functional environments appears to enhance motivation and enjoyment during a therapy-like session. Moreover, interaction within VEs appears to agree with rehabilitation goals that included training conditions that are more dynamic, realistic, and relevant to everyday activities and entail balance reactions. The GX-VR system has the potential to be used as a tool in the rehabilitation of patients in general and of those with paraplegic SCI specifically. Additional research, specifically a randomized clinical trial that measures the efficacy of such a treatment compared with conventional balance and performance training, is needed to establish the efficacy of VR as an intervention tool.

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