Research Article

The effects of semi-immersive virtual reality therapy on standing balance and upright mobility function in individuals with chronic incomplete spinal cord injury: A preliminary study

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Background: Individuals with chronic incomplete spinal cord injury (iSCI) commonly face persistent balance or mobility impairments. Virtual reality (VR) therapy is a useful rehabilitation approach; however, little is known about its effects in individuals with chronic iSCI.

Objective: To investigate the effects of semi-immersive VR therapy on standing balance and upright mobility function in individuals with chronic iSCI.

Methods: Ten subjects with chronic iSCI underwent VR therapy 30 minutes a day, 3 days a week, for 6 weeks. Limit of stability (LOS) and the Berg Balance Scale (BBS) were used to evaluate standing balance function. The Timed Up & Go (TUG) test, Activities-specific Balance Confidence (ABS) Scale, and Walking Index for Spinal Cord Injury-II (WISCI-II) were used to measure the subject's upright mobility function. Outcomes were assessed and recorded pre- and post-intervention.

Results: After semi-immersive VR therapy, LOS and BBS scores were significantly increased. In addition, the TUG test results increased significantly over time, while ABC scale scores and WSCI-II levels improved significantly.

Conclusion: This study is the first to assess the effects of semi-immersive VR therapy for patients with chronic iSCI and limited functional abilities. These results indicated that semi-immersive VR therapy has a positive effect and is a useful intervention for standing balance and upright mobility function in patients with chronic iSCI.

Keywords: Semi-immersive, Virtual reality therapy, Incomplete spinal cord injury, Standing balance, Upright mobility

Introduction

Balance is the ability to control one's center of gravity (COG) within the base of support (BOS) to compensate against external perturbation through appropriate responses by the muscle and nervous system. The afferent sensory information received through the proprioceptive, visual, and vestibular systems is an important factor in balance control.¹ To prevent falls, a subject's COG must be maintained over the BOS using motor and sensory strategies. In particular, standing balance is one of the most important determinants of efficient and safe walking function.^{2,3} However, patients with incomplete

spinal cord injury (iSCI) frequently have impairments in muscle strength, sensation, and abnormal muscle tone, making it difficult for them to regain balance function.⁴ Most studies reported that much functional recovery occurs in the first 3 months and can continue as long as 1 year after spinal cord injury.⁵ Therefore, intensive acute-stage rehabilitation is important. However, improvements in function continue beyond 1 year post-injury in a number of individuals.^{6,7} In cases of chronic iSCI, the potential for functional recovery is highly correlated with injury level and severity. In fact, their functional recovery potential remains high.^{6,8,9}

Recent advances in technology such as virtual reality (VR) therapy have been used effectively in the rehabilitation medical field and provide the advantage of

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creating multiple sensory inputs and task-specific approaches by creating a virtual environment that is similar to that of the real world. VR is a type of user-computer interface that implements real-time simulation of an activity or environment and allows user interaction via multiple sensory modalities.¹⁰ VR has the advantage of providing real-time performance and graduated stimulus as well as augmenting patients' attention and motivation.¹¹ The VR apparatus used depends on the level of immersion, which can be classified into non-immersive, semi-immersive, and immersive.¹² Non-immersive VR involves a computer-generated environment in which an avatar is projected onto a screen or wall in front of the patient such as that provided by the Nintendo™ Wii Fit. The use of non-immersive VR in rehabilitation seems useful¹³; however, software to individualize treatments and adapt the intervention to each patient's requirements has yet to be developed.¹⁴ Immersive VR, in which the viewer is a part of the environment, involves a device with a head-mounted display that provides images within a computer.¹² Immersive VR has the advantage of providing a more realistic VR environment via high immersion;¹⁴ however, some people who use VR experience symptoms such as vomiting or dizziness (cybersickness).¹⁵

A semi-immersive VR system overlays virtual images onto real images (not avatars) to increase the informative content. Semi-immersive VR allows individualized programs to be provided to individual patients, and immersion is higher than non-immersive VR in that real images are used in the virtual environment. In addition, unlike immersive VR, it has fewer side effects such as "cybersickness." For this reason, the use of semi-immersive VR systems is recommended in rehabilitation medicine.^{14,15} Semi-immersive VR therapy has already been proven to be an effective intervention method for balance or walking function in various subjects, such as community-living older adults,¹⁶ those with brain tumors¹⁷ or traumatic brain injuries,¹⁸ and patients post-stroke.¹⁹ Nevertheless, to date, there have been few studies on the effects of semi-immersive VR therapy on functional ability in patients with chronic iSCI. Wall *et al.*¹³ recently reported that VR therapy improves balance and walking ability in patients with chronic iSCI. However, the VR apparatus employed in that study was the Nintendo™ Wii Fit, a non-immersive VR system. Non-immersive VR therapy limits one's awareness of posture and the movements of the extremities and trunk because it provides visual information via an avatar. Therefore, it is difficult to provide multiple sensory stimulation in real time.²⁰ In addition, there is a limit to providing appropriate training tasks for patients

with impaired functional activity.²¹ Therefore, the purpose of this pilot study was to examine the effects of semi-immersive VR therapy on standing balance and upright mobility function in patients with chronic iSCI. We hypothesized that semi-immersive VR therapy would effectively improve standing balance and upright mobility function.

Methods

Study design and subjects

This study was conducted in the university's neurological rehabilitation center and 10 subjects were recruited in a sample of convenience. All subjects had a medical history of a chronic (>1 year post injury) American Spinal Injury Association Impairment Scale score of C or D. Inclusion criteria for this study were: (1) ability to walk independently with or without assistive device for >10 m; and (2) ability to tolerate standing for at least five minutes without external support. Inclusion criteria were: (1) lower-limb orthopedic impairments or pain; (2) use of spinal stabilization braces that may limit mobility; (3) inability to recognize an object presented on a display due to visual impairment; and (4) inability to follow intervention program (Table 1). Each subject received an explanation of the study's purpose and methods prior to participation and provided informed consent according to the ethical principles of the Declaration of Helsinki.

Intervention

Each subject underwent semi-immersive VR therapy 30 minutes per day, 3 times a week for 6 weeks. An Interactive Rehabilitation Exercise (IREX; Gesture Tek; Toronto, Canada) system was used for the VR therapy. The IREX system consists of a television screen, camera, red gloves, and a green screen and mat as a background. Of the 20 programs available on the IREX, six were included: "soccer," "conveyor," "volleyball," "formula racer," "airborne," and "snowboard." Each program was performed for 4 minutes with a 1-minute break between programs.

The six intervention protocols are as follows. (1) Soccer: the participant simulates the role of a soccer goalkeeper by blocking a ball in front of a virtual soccer net, which requires weight shifting during shoulder flexion and abduction. (2) Conveyor: the participant has to move virtual boxes from one conveyor belt to another in a virtual industrial setting in which conveyor belts can be placed at a variety of heights and distances on the screen and the participants perform trunk rotation and shoulder D1 and D2 patterns. (3) Volleyball: the participant plays a simulated

Table 1 Subject's demographic and clinical characteristics.

Subjects	Age/Sex	Height (cm)	Weight (kg)	Dominance (right/left)	Neurological level	Time since injury (months)	AIS	SCIM-III scores
1	33/F	159	52	right	C2	21	D	89
2	50/M	168	61	right	C4	18	D	72
3	48/M	175	68	left	C4	24	D	63
4	44/F	157	57	right	C6	25	D	67
5	52/M	171	65	left	T1	17	D	81
6	43/M	174	69	left	C7	13	D	82
7	52/M	168	65	right	C7	19	C	71
8	54/M	170	66	right	C4	16	C	59
9	29/F	156	54	left	T1	23	C	72
10	37/F	161	59	right	C6	16	C	69

M, Male; F, Female; C, Cervical; T, Thoracic; AIS= American spinal cord association impairment scale; SCIM-III= Spinal cord independence measure-III.

beach volleyball match against a robot opponent and lifts her arms above her head and hits the virtual ball back over the net, which requires hand-eye coordination and weight shifting in multiple directions. (4) Formula racer: the participant is seated in a Formula 1 racing car and drives the car through a racecourse, shifting their weight to the left and right while navigating. (5) Airborne: the participant steers a parachute through obstacles on the way down to landing on a target,

controlling the flight direction by raising and lowering one or both arms laterally. Raising both arms in the virtual world increases one's position, while lowering both arms decreases one's position. In addition, lateral trunk flexion in the virtual world appears to tilt one's position in the sagittal plane. (6) Snowboard: accurately simulating real snowboarding down a narrow slope, the object of this game is to avoid virtual obstacles (i.e. rocks, trees, snowmen) by leaning side to side and jumping if possible while snowboarding.

The six chosen intervention programs were proven effective at improving balance and mobility function in hemiplegic patients with stroke.^{19,22} Semi-immersive VR therapy was provided to stimulate the development of diverse trunk control, multiple directional weight-shifting, agility, and upper-extremity movements in the standing position. As the patients' abilities to perform the six intervention programs improved, we gradually increased the complexity of the tasks and decreasing the therapist's support and feedback (Table 2).

Table 2 Semi-immersive VR therapy intervention protocols.

Intervention	Increasing the level	Skills practice during intervention		
		Hand movement	Trunk control	Weight shifting
Soccer	Adjusts ball speed and angular velocity of the shoulder	○	X	X
Conveyor	Adjusts the location or directions of the conveyor belts and belt speed	○	○	X
Volleyball	Adjusts ball speed and robot opponent's defense	○	X	○
Formula racer	Adjusts Racing car speed and increase the number of obstacles	X	○	○
Airborne	Adjusts the height of hands reaching and wind speed	○	X	○
Snowboard	Adjusts speed of descent or increase the number of obstacles	X	○	○

Outcome measures

Outcomes measurements were obtained before and after 6 weeks of semi-immersive VR intervention. Two measurements were taken within 1 week before and after VR therapy.

Standing balance function

Limit of stability (LOS) and Berg Balance Scale (BBS) tests were performed to measure the subjects' standing balance function. Computerized balance performance data were collected using the balance SD (Biodex Medical System, Inc., New York, USA). The LOS test protocol was used to quantitatively determine standing balance performance. The test-retest reliability of the LOS test has an intraclass correlation coefficient (ICC) of 0.72.²³ This test challenges subjects to move and control their COG within their BOS.²⁴ Eight targets

(forward, backward, right, left, forward-right, forward-left, backward-right, backward-left) were randomly highlighted, and the subject reached the target by weight shifting and returning to the center position on the screen. The subjects were instructed to move the COG cursor as quickly and accurately as possible toward the highlighted target without losing balance or stepping as soon as a visual signal, in the form of a circle, moved from the starting target. Three trials were recorded and the average was used in the statistical analysis. A higher LOS score indicated superior standing balance ability.²⁵ In this study, the statistical analysis used LOS scores of the overall and four directions (forward, backward, more affected, less affected). The formulas for calculating overall LOS (OLOS) score and directional LOS (DLOS) scores are as follows:²⁴

$$\text{OLOS (\%)} = \sum_{i=1}^{i=4} (\text{DLOS score}) \div 4 (\text{average of four targets})$$

$$\text{DLOS (\%)} = \frac{\text{Straight Line Distance to Target}}{\text{Actual Distance Traveled}} \times 100$$

In addition, each subject's standing balance ability was determined by the BBS, which is composed of 14 categories, each of which is scored from 0 to 4. The total score is 56, and higher scores are associated with superior mobility independence and balance ability.^{26,27} The BBS is both valid and reliable for evaluating the SCI population.²⁷

Upright mobility function

The Timed Up and Go (TUG), Activities-Specific Balance Confidence (ABC) scale, and Walking Index for Spinal Cord Injury II (WISCI II) scale were used to measure the subjects' upright mobility function. The TUG is a simple and quick measurement of balance and mobility. The patient sits in a chair, stands upon receiving the verbal instruction "Start," walks for 3 meters, and then returns to sitting in the

chair. The TUG test has excellent test-retest and inter-rater reliability in the SCI population.²⁸

The ABC scale was used to assess the subject's self-reported confidence performing various upright mobility tasks.²⁹ The ABC scale has very good inter-rater and test-retest reliabilities when administered to frail elderly persons;³⁰ however, its use has not been validated for persons with SCI. For community-dwelling older adults, a score < 67.0% was determined to be the cut-off for fall risk.³¹

The WISCI-II was used to classify each patient's level of walking independence and use of assistive devices and/or braces required for walking. The WISCI-II is a descriptive measure with 20 levels ranging from 0 (the client is unable to walk) to 20 (the client can ambulate for 10 meters with no devices, braces, or physical assistance). The WISCI-II has excellent validity and reliability in the chronic SCI population.^{32,33}

Statistical analyses

The data were analyzed with PASW statistical software ver. 18.0 (SPSS Inc., Chicago, IL, USA). A descriptive analysis of the clinical and functional variables was obtained by calculating the mean and standard deviation (SD) for the quantitative variables. A paired t-test was used to analyze the intervention effects on standing balance function within the group (pre- to post-intervention) for the parametric measures such as the LOS, TUG, and ABC scales. The Wilcoxon signed-rank test was used to compare the differences pre- and post-intervention for nonparametric measures such as the BBS and WISCI-II. Significance was assigned at values of $P < 0.05$ for all analyses.

Results

All subjects successfully completed the required tests and intervention; their characteristics are listed in Table 1. The mean age of the 10 subjects was 44.20 ± 8.66 years (range, 29–54 years) and the mean time post-spinal cord injury was 19.20 ± 3.93 months (range, 13–25 months). Among the 10 subjects, eight subjects had lesions at the cervical cord level, while two had lesions at the thoracic cord level. All subjects were had an American spinal cord association Impairment Scale (ASI) score of C or D. The Spinal Cord Independence Measure-III (SCIM-III) score, which indicates the daily living activity level, was 72.50 ± 9.14 (range, 59–89) (Table 1).

After the 6-week application of semi-immersive VR therapy, on the computerized standing balance test, OLOS score was significantly increased from pre- to post-intervention (32.00 to 46.40, respectively; $P <$

Table 3 Standing balance function pre and post intervention.

Standing balance parameters		Pre intervention	Post intervention
LOS	Overall	32.00 $\pm$ 6.33 ^a	46.40 $\pm$ 5.73
	Forward	32.40 $\pm$ 8.23	35.80 $\pm$ 7.43
	Backward	31.40 $\pm$ 6.39	33.00 $\pm$ 5.52
	More affected	28.80 $\pm$ 6.26	42.40 $\pm$ 5.03
	Less affected	34.60 $\pm$ 6.69	48.40 $\pm$ 4.16
BBS		35.70 $\pm$ 3.23	40.10 $\pm$ 2.60

^aMean $\pm$ SD, * $P < 0.05$, ** $P < 0.01$.

LOS, Limit of stability; BBS, Berg balance scale.

0.01). In particular, the more and less affected DLOS scores were significantly improved after therapy (28.80 to 42.40 and 34.60 to 48.40, respectively; $P < 0.01$); however, forward and backward DLOS scores did not differ significantly after therapy. In the clinical standing balance test, the BBS score was significantly increased post-intervention (35.70 to 40.10, respectively; $P < 0.01$) (Table 3) (Figure 1).

The upright mobility function results showed that the TUG time was significantly decreased (19.35 to 17.14, respectively; $P < 0.05$), while the ABC scale score was significantly increased (67.90 to 76.85, respectively; $P < 0.05$). The WISCI-II score after intervention showed significant improvement from 16.30 (15 level (5), 16 level (1), 17 level (1), 18 level (2), 19 level (1)) to 17.90 (15 level (1), 16 level (2), 17 level (2), 19 level (2), 20 level (3), ($P < 0.05$)) (Table 4) (Figure 2).

There were no dropouts during the 6-week study period; in addition, no adverse effects were reported by the participants during the semi-immersive VR therapy.

Discussion

Following a spinal cord injury, individuals commonly mention recovery of walking function as an ultimate goal of rehabilitation.³⁴ However, poor standing balance function is one of the primary factors leading to impaired walking function. This study investigated the effect of semi-immersive VR therapy on standing balance and upright mobility function in patients with chronic iSCI. After 6 weeks of semi-immersive VR therapy, standing balance and upright mobility performance were significantly improved.

Figure 1 Improvement in pre and post intervention of balance function. Percentage of improvement = $(\text{Post-test value} - \text{Pre-test value}) \div \text{Pre-test value} \times 100$. * $P < 0.05$, ** $P < 0.01$.

Post-intervention, the OLOS score increased significantly. These results show an improved ability to move and adjust COG while standing without losing balance. Specifically, for the LOS measure results for each direction, there was a significant increase in DLOS score in the more affected and less affected directions (i.e. frontal plane); however, no significant changes were seen in the forward and backward directions (i.e. sagittal plane). This means that the adjustment ability was improved in the frontal plane. The subjects were required to move their trunk and upper limbs in a virtual environment and move their weight in multiple directions while performing various tasks such as moving virtual objects, turning a ball, and avoiding obstacles. These results indicate that standing balance was improved in the process of maintaining balance through the subject's self-generated perturbation.^{11,22} In the VR therapy programs, the participants were able to move the COG and their body positions without limitation. Semi-immersive VR equipment primarily provides visual information about two-dimensional virtual reality through a screen located in front of the subject and the tasks were designed to utilize trunk control, reaching, and stepping in the lateral direction (i.e. using the hip strategy). Therefore, when performing most of the tasks provided, weight shifting was more likely to occur in the frontal plane than in the sagittal plane, the reason for the improved LOS is the improved control in the frontal plane.

The BBS test results for the subjects post-intervention significantly improved. These results are similar to those of the study by Kim *et al.*²² in which the LOS test was used to assess the balance function within a fixed BOS (i.e. controlled condition), while the BBS test evaluated balance function in the functional aspect (i.e. uncontrolled condition). In this study, significant improvements on the BBS and LOS tests indicated that the semi-immersive VR therapy is an effective intervention for improving functional balance in patients with

Table 4 Upright mobility function and pre and post intervention

Upright mobility parameters	Pre intervention	Post intervention
TUG	19.35 ± 3.23 ^a	17.14 ± 3.61
ABC scale	67.90 ± 8.50	76.85 ± 6.92
WISCI-II	16.30 ± 1.57	17.90 ± 1.91
	15(5), 16(1), 17(1), 18(2), 19(1)	15(1), 16(2), 17(2), 19(2), 20(3)

^aMean ± SD, * $P < 0.05$, ** $P < 0.01$.

TUG= Timed up and go test; ABC scale= activities-specific confidence scale; WISCI-II= Walking index for spinal cord injury-II.

Figure 2 Improvement in pre and post intervention of mobility function. Percentage of improvement = $(\text{Post-test value} - \text{Pre-test value}) \div \text{Pre-test value} \times 100$. * $P < 0.05$, ** $P < 0.01$.

chronic iSCI. Among the VR programs provided, programs such as the use of “soccer,” “conveyor,” and “volleyball” induced upper-limb movements as well as forward, lateral flexion, and trunk rotation at various heights. In addition, programs that simulate “snowboard,” “formula racer,” and “airborne” induced lateral weight shifting without limiting lower-limb movements, contributing to improvements in the BBS categories related to dynamic balance.

After the intervention, the TUG test, a measure of upright mobility performance, showed a significant decrease in time, while the ABC scale score increased significantly. WISCI-II levels also increased significantly after the intervention. These results demonstrated that semi-immersive VR therapy effectively improves the upright mobility function of chronic iSCI subjects. Wall *et al.*¹³ reported no significant change in TUG test scores after VR treatment with a Nintendo™ Wii Fit in patients with chronic iSCI. The TUG test is a complex task requiring multiple skills such as turns, transfers, standing up, and walking; however, the Nintendo™ Wii Fit has been described as featuring a limited set of specific functional tasks that can be employed to improve mobility.¹³ Conversely, McEwen *et al.*¹⁹ reported positive effect on balance and mobility outcomes after the application of semi-immersive VR therapy in patients with chronic stroke. Their study found that TUG scores were significantly reduced after intervention in the group receiving semi-immersive VR therapy. In this study, The TUG test scores decreased significantly, representing improved ability to perform multiple skills such as turns, transfers, standing, and sitting. This result is thought to directly influence mobility improvements through trunk control at various heights and weight shifting training in various directions for the lower limbs.^{11,19,35}

Semi-immersive VR therapy has been found to positively affect a subject’s self-reported balance confidence (i.e. ABC scale score). Balance confidence is associated with the activity and participation levels of subjects with impaired balance function due to neurological impairment, and improvements in balance confidence result in a decreased fear of falling and improved upright mobility activity.³⁶ The improvement in balance and movement abilities through performance training of unpredictable tasks conducted in a virtual environment would have affected improvements in confidence even in an irregular environment (i.e. public place). In addition, the WISCI-II levels of all subjects improved after the intervention: subject 1 improved from level 19 to 20, subject 2 from level 17 to 19, subject 3 from level 18 to 20, subject 4 from level 15 to 18, subject 5 from level 18 to 20, subject 6 from level 16 to 17, subject 7 from level 15 to 16, subject 8 from level 15 to 15, subject 9 from level 15 to 16, and subject 10 from level 15 to 17. These results indicate that the need for a device, brace, or physical assistance is reduced or eliminated during walking.

There were several limitations to this study. First, although this was a preliminary study, it is difficult to generalize its results because of the small sample size. Second, no control group was utilized and semi-immersive VR therapy was not compared with other balance and mobility rehabilitation strategies. Therefore, the treatment effect could not be accurately verified. Finally, no follow-up measures were taken after the intervention; therefore, the carryover effect of semi-immersive VR therapy was not confirmed.

Conclusion

In conclusion, this study found that semi-immersive VR therapy effectively improves balance and upright mobility function in patients with chronic iSCI. Real-time repetitive training through an unpredictable scenario in a virtual environment is considered an effective intervention technique to improve postural adjustment control. However, there is a need to design various virtual intervention programs to overcome the limitations of visual information using 2D semi-immersive VR apparatus. Further studies should include a larger sample size and a randomized controlled trial to determine efficacy of such an intervention compared with conventional balance training. In addition, it is necessary to study the optimal equipment by comparing the effects of VR therapy according to immersion level (i.e. non-immersive, semi-immersive, immersive) in patients with chronic iSCI and impaired functional abilities.

Acknowledgements

The authors would like to thank you all the participations in this study.

Disclaimer statements

Contributors None.

Declaration of interest None.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest Disclosure No conflict of interest.

Ethics approval None.

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