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Three-Dimensional Augmented Reality System for Balance and Mobility Rehabilitation in the Elderly: A Randomized Controlled Trial

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We attempted to evaluate the clinical efficiency of a novel three-dimensional interactive augmented reality system (3D-ARS) for balance and mobility rehabilitation. This system enables participant training with a realistic 3D interactive balance exercise and assessing movement parameters and joint angles by using a kinetic sensor system. We performed a randomized controlled trial in a general hospital. Thirty-six participants (age, 56–76 years) who could independently walk and stand on one leg were recruited. The participants were randomly assigned to either group. The control group ($n = 18$) underwent a conventional physical fitness program such as lower-extremity strengthening and balance training thrice per week for 1 month. The experimental group ($n = 18$) experienced 3D-ARS training thrice per week (1 session = 30 minutes) for 4 weeks. Training comprised a balloon game for hip exercise, cave game for knee exercise, and rhythm game for one-leg balance exercise. Lower-extremity clinical scale scores, fall index, and automatic balance score were measured by using Tetrax® posturography before, during, and after training. Significant group (3D-ARS vs. control) × time (before and after exercise) interaction effect was observed for Berg balance scale (BBS) scores ($p = 0.04$) and timed-up-and-go (TUG; $p < 0.001$). Overall improvements occurred in stability index, weight distribution index, fall risk index, and Fourier transformations index of posturography for both groups. However, score changes were significantly greater in the 3D-ARS group. Significant group × time interaction effect was observed for the fall risk index. This demonstrates that the 3D-ARS system can improve balance in the elderly more effectively.

Keywords: fall risk, aged, postural balance, rehabilitation, virtual reality exposure therapy

Introduction

Falls and fall-related injuries are the most common and serious medical problems among the elderly. Annually, 35–45 percent of community-dwelling people ≥ 65 years and 50 percent of elderly people report falls.[1,2] In the elderly, impaired motor performance is associated with motor retardation, decreased muscle force, and decreased balance function.[3] The fifth most common cause of death is unintentional injuries in people aged ≥ 65 years; 66.7 percent of these are related to falls and their life-threatening complications, for example, hip fracture.[2,4,5]

To prevent falls in the elderly, physical activity is important, especially for improving proprioceptive function and balance.[6,7] To encourage physical activity and improve proprioceptive function, specific interventions are required to restore balance function; they should be effective and enjoyable. Therefore, researchers have focused on developing novel systems that enhance the effectiveness of therapy through interactive computer-generated multi-modal feedback environments.[8] Systems providing various feedback and immersing the user in a virtual environment are referred to as virtual reality (VR) training environments, whereas systems providing combined training in virtual and physical environments are referred to as augmented reality (AR) training environments. Both environments can provide meaningful and intuitive feedback on a subject's movement. The feedback also offers guidance and motivation and may

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help the elderly to improve their quality of movement and gain confidence in balance function, while accomplishing the system's goal. There is much research related to the effectiveness of using VR or AR for lower limb rehabilitation purposes in patients with neurologic disease.[9–11]

Cognition function, proprioceptive input during exercise, and learning ability decrease gradually with increasing age; thus, an AR-based exercise program could be useful for older adults. Such systems provide intuitive external feedback on movement, thereby augmenting proprioception arising from intrinsic sensory organs whose function could be compromised by aging, simultaneously encouraging sensory-motor integration. Lower-extremity exercises using an AR demonstrably enhance balance in elderly people; however, most studies have targeted patients with neurological deficits.[12,13] The utility of this novel AR system for balance rehabilitation in healthy elderly is not evaluated. Therefore, there is little evidence regarding its efficacy compared with conventional balance exercises to improve lower-extremity function.

Tetrax® tetra-ataxiametric posturography is based on measurement and computerized elaboration of electronic signals emitted by four footplates, one for each heel and toe.[14] Increased postural sway is observed when subjects are asked to close their eyes as compared with standing with their eyes open; sway-referencing visual information to head movement leads to increased postural sway compared with normal visual inputs.[15] The Tetrax was used to measure postural stability in previous studies and demonstrated the high test–retest reliability.[16–19]

In our previous study, a three-dimensional interactive augmented reality system (3D-ARS) was developed to improve lower-extremity function and balance in elderly people.[20] The 3D-ARS integrates traditional rehabilitation and motor learning theories with high-resolution motion capture and sensing technologies, smart physical objects, and interactive computer graphics and sound. We assessed the usability of the system as a training modality by observing the measurements revealed by the system, but the study did not have a control group or objectively assessed clinical outcomes assessed.

Therefore, this study aimed at evaluating the effectiveness of the system in improving lower limb function by examining clinical outcomes using the Tetrax for balancing function after 4 weeks of 3D-ARS training.

Methods

Participants

Our study was conducted at Eulji hospital and the surrounding community. Thirty-six community-dwelling and ambulatory older adults were recruited through local announcements. All participants were residents of Nowongu, Seoul, Korea and volunteered to participate in the study. The study protocol was approved by the local ethics committee of our hospital. A physician (not directly working with the research study) assessed participant eligibility and briefly described the purpose and nature of the study to the participants. A one-page general summary of the study, including purpose and procedures, was provided. All participants gave informed consent and were briefed about the tasks and instrumentations before the study commenced.

Inclusion criteria were: (a) age 55–80 years; (b) Mini-Mental State Examination (MMSE) score[21] >25; (c) the ability to understand the nature of the study and provide informed consent; and (d) independent in ambulatory functions, with/without an assistive device (cane or walker) and standing on one leg. Exclusion criteria were any medical condition that prevented participation in an exercise program, such as cancer, kidney disease, uncontrolled diabetes, seizure disorder, mental disorder, or cardiovascular-related problems and current medication that impaired balance such as anti-depressants, anti-anxiety drugs, anti-convulsants, and anti-histamines. Impaired vision or auditory function that prevented participation in our program, recent fracture, neuromuscular disorders with deficits, or neurological disorder with deficits (e.g., stroke, multiple sclerosis, Parkinson disease) were also criteria.

Estimation of sample size was based on a previous similar study. The primary end-point was the Tetrax posturographic parameter (fall risk index) and clinical Berg balance scale (BBS). A sample size of 15 was sufficient to detect the differences of fall risk index (23 ± 21.15)[16] and a sample size of 10 was adequate to detect the differences of BBS (4 ± 3)[22] by using an independent two-sample test; a significant level of 0.05 (two-sided) with 80 percent power was obtained by using PASS (version 12; NCSS, LLC, Kaysville, Utah). Thus, we determined a sample size of 36 participants considering a 10 percent dropout rate.

The participants were randomly assigned to the control or experimental group. Group assignment codes were placed in envelopes and sealed. Each participant randomly selected an envelope with the group assignment enclosed, which was opened by the research assistant after baseline assessment.

Control groups ($n = 16$) underwent a conventional physical fitness program comprising lower-extremity strengthening and endurance training thrice per week for 1 month (30 minutes per session). Before training, the control group was instructed regarding the exercise program and technique by a senior resident of the physical medicine and rehabilitation department. The program comprised individual lower-extremity strengthening (hip flexion, side-leg raise, squat), balance exercise, and endurance training (walking and cycling).[22] They were monitored regarding their regular exercise performance weekly via phone. The experimental group ($n = 18$) underwent 12 sessions of 3D-ARS training (30 minutes per session) for 4 weeks. The training level was adjusted to individual motor abilities by the research assistant, who monitored participation and safety issues. A 75 percent attendance rate was determined as adherence in both programs.[23] Two participants in the control group were excluded for low adherence (Fig. 1). The participants did not receive any other training to eliminate possible confounding effects.

Three-dimensional interactive augmented reality system

Setup. We used the 3D-ARS training system reported in our previous study, utilizing a Microsoft Kinect sensor to track a subject's whole-body motion and interaction with virtual objects in a 3D environment that was displayed on a large screen.[20] The augmented environment was generated by superimposing video-captured real images with virtual

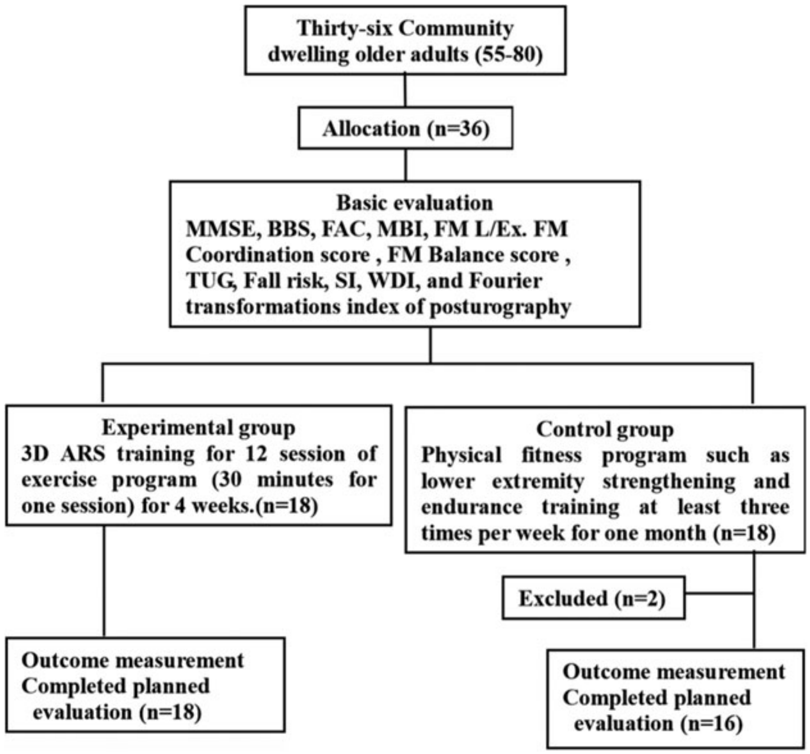

FIG. 1. Patient flow diagram. 3D-ARS, three-dimensional interactive augmented reality system; MMSE, Mini-Mental State Examination; BBS, Berg balance scale; FAC, functional ambulation categories; MBI, Modified Barthel index; FM L/Ex, Fugl Myer-Lower extremity score; TUG, timed-up-and-go; SI, stability index; WDI, weight distribution index.

object images that were rendered by using a personal computer. Therefore, the 3D-ARS training program enabled subjects to interact with virtual objects displayed on a screen that was placed in front of the subject as well as to view the subject's appearance in real time.

Types of tasks. Three tasks were designed for users to enable specific motions of specific joints: the balloon game, cave game, and rhythm game. Each game focused on training a specific part: The balloon game enabled hip exercise by encouraging hip flexion and extension while touching a falling balloon, the cave game made subjects flex and extend their knees to avoid obstacles in a cave, and the rhythm game enhanced one-leg standing ability by making subjects step on a specific point that appeared rhythmically on the floor. Exercise dynamics (response time, success rate) and kinematic variables (joint angle of hip and knee) are described in detail in our previous preliminary study.[20]

Outcome measures

All participants underwent clinical evaluation before and after training, including the following lower-extremity clinical scale scores (a) BBS, (b) Timed-up-and-go (TUG) test, (c) Functional Ambulation Category (FAC), (d) Modified Barthel Index (MBI), (e) Lower-extremity subscale of the Fugl-Meyer Assessment (FMA-LE), (f) Fugl-Meyer Motor Assessment Co-ordination section (FMA-C), (g) Fugl-Meyer Motor Assessment Balance section (FMA-B), (h) and automatic balance score using Tetrax posturography. A single physical therapist who was blinded to group allocation and had >10 years' experience was the tester for all outcomes. All participants were briefed about the tasks and practiced the programs before evaluation. The BBS is widely used to test a person's static and dynamic balance abilities: score range, 0–56, higher scores indicate superior balance.[24] The TUG is measured as time (seconds) required to perform the following actions: stand up from a chair, walk 3 m at normal walking speed, turn around, walk back, and sit down.[25] The TUG is used to examine functional mobility.[26] The FAC is a clinical gait assessment scale and evaluates six levels of walking ability, which correlates with walking velocity and step length.[27] The 50-item Fugl-Meyer motor scale is a widely used measure assessing motor function in the extremities.[28] The lower-extremity subscale of the Fugl-Meyer Assessment is a subscale measuring lower-limb motor recovery.[29] It examines movement, co-ordination, and reflex action of the hip, knee, and ankle joints. The balance section of FM is scored on a three-point scale (0, cannot perform; 1, partially performs; 2, performs fully) and the score range is 0–14, with higher scores indicating better lower limb balance performance. The co-ordination section of FM is scored on a three-point scale (0, cannot perform; 1, partially performs; 2, performs fully) and the score range is 0–6, with higher scores indicating better co-ordination.[30,31]

Tetrax tetra-ataxiametric posturography (Tetrax; Sunlight Medical, Ramat Gan, Israel) utilizes two paired force plates measuring vertical pressure fluctuations over both heels and forefeet with the subject in a relaxed position with the arms hanging loosely. Stability, weight distribution, Fourier, and fall risk indices are calculated. For controlled modification of sensory input from the visual, vestibular, and somatosensory systems and for the assessment of the compensatory ability within the postural system, eight different position tests were performed (Table 1).[32] Stability index is a measure of the amount of sway, summed over the four footplates and divided by the subject's weight. It ranges from 10 to 1,500. The higher the score, the greater the sway. Weight distribution

Table 1. Testing Conditions for the Eight Posturographic Tests

Positions	*Head position*	*Eyes*	*Ground*	*Purpose*
NO	Neutral	Open	Solid	Neutral position
NC	Neutral	Closed	Solid	Elimination of visual system
PO	Neutral	Open	Elastic	Elimination of somatosensory system
PC	Neutral	Closed	Elastic	Elimination of somatosensory and visual system
HR	Rotated to the right	Closed	Solid	Elimination of visual system and vestibular stress
HL	Rotated to the left	Closed	Solid	Elimination of visual system and vestibular stress
HB	Reclined	Closed	Solid	Elimination of visual system, vestibular and cervical stress
HF	Inclined	Closed	Solid	Elimination of visual system, vestibular and cervical stress

HB, position with head raised backward by 30° and eyes closed; HF, position with head forward about 30° and eyes closed; HL, position with head turned to the left and eyes closed; HR, position with head turned to the right and eyes closed; NC, neutral head position with eyes closed; NO, neutral head position with eyes opened; PC, neutral head position with eyes closed and standing on pillows; PO, neutral head position with eyes opened and standing on pillows.

index is the standard deviation of the four weight distribution scores from the invariable mean of 25 percent. This parameter reflects the amount of ''unevenness'' of the weight percentages.[14] Fourier index was measured in six different head positions and two positions standing on pillows, and it was analyzed offline.[33] The Tetrax software subdivides the frequency of postural sway into four categories: F1: low frequencies (<0.1 Hz), F2–F3: lower-medium frequencies (0.1–0.5 Hz), F5–F6: higher-medium frequencies (0.5–1.0 Hz), and F7–F9: high frequencies (above 1 Hz). Increased sway at higher-medium frequency reflects the somatosensory response mediated by lower-extremity motor function.[19] The fall risk index score shows the degree of risk of falling, which is measured on a 0–100-point scale (0–35: low risk, 36–58: moderate risk, 59–100: high risk). A higher index score means unstable posture.

Statistical analysis

Data are presented as means, standard deviations, and frequencies (percent). Independent two-sample *t* test and Chi-square test were used to compare the means and frequencies between the experimental and control groups for demographic and baseline characteristics. Differences between baseline and after 4 weeks were calculated. Differences of all outcome variables were normally distributed (Kolmogorov-Smirnov test *p* value >0.05). The paired *t* test was used to compare within-group pre-treatment and post-treatment results, and the linear mixed model was used to compare differences in groups across time (group × time interactions). Results were considered statistically significant if the *p* value was <0.05 and had trends if the *p* value was <0.2. All data were analyzed by using the SPSS software (version 18; SPSS, Inc., Chicago, IL) or the SAS software (version 9.2; SAS, Inc., Cary, NC).

Results

There was little difference between groups in age, weight, height, MMSE scores, BBS scores, FAC scores, MBI scores, FMA-LE scores, FMA-C scores, FMA-B scores, TUG, or fall risk index (Table 2). The pre-exercise independent two-sample *t* test showed no significant group differences in MMSE scores, BBS scores, FAC scores, MBI scores, FMA-LE, FMA-C, FMA-B, TUG, or fall risk index.

Improvement of lower-extremity clinical scale scores after exercise

The 3D-ARS and control groups showed improvement in the balance and mobility scores after intervention, demonstrated by statistically significant improvements in the BBS TUG, FMA-LE, and FMA-B scores (Table 3). The linear mixed model results (p value, F statistic, degree of freedom) demonstrated significant group (3D-ARS vs. control) × time (before and after exercise) interaction effect for BBS scores [$F(1, 32) = 4.24$, $p = 0.042$], TUG [$F(1, 32) = 28.85$, $p < 0.001$], and fall risk index [$F(1, 32) = 4.74$, $p = 0.033$] (Table 3).

Improvement of posturography index after exercise

Improvement in stability index. Significant improvements were observed in the stability index of NC (neutral head position with eyes closed), PC (neutral head position with eyes closed and standing on pillows), HR (position with head turned to the right and eyes closed), HL (position with head turned to the left and eyes closed), and HB (position with head raised backward by 30° and eyes closed) during posturography in the 3D-ARS group; none were observed in the control group (Table 4). Although the results of the linear mixed model demonstrated no significant group (3D-ARS vs. control) × time (before and after exercise) effect, the trend was seen in PC [$F(2, 32) = 3.04$, $p = 0.091$], NO [neutral head position with eyes opened; $F(2, 32) = 2.63$, $p = 0.114$], NC [$F(2, 32) = 1.92$, $p = 0.192$], HL [$F(2, 32) = 2.37$, $p = 0.134$], and HB [$F(2, 32) = 2.41$, $p = 0.149$].

Improvement in weight distribution index. There were significant improvements in the weight distribution index of NO, NC, PC, HL, and HF (position with head forward about 30° and eyes closed) on posturography after intervention in the 3D-ARS group; none were observed in the control group (Table 5). The results of the linear mixed model demonstrated the trend of group (3D-ARS vs. control) × time (before and after exercise) interaction effect in NO [$F(1, 32) = 4.21$, $p = 0.058$], PC [$F(1, 32) = 2.50$, $p = 0.124$], HL [$F(1, 32) = 1.80$, $p = 0.189$], and HF [$F(1, 32) = 2.90$, $p = 0.098$].

Improvement in Fourier transform index. There were significant improvements in the Fourier transformations

Table 2. Demographic and Baseline Characteristics

	3D-ARS group (n = *18*)	*Control group* (n = *16*)	p
Sex			
Male	9 (50%)	8 (50%)	1.000
Female	9 (50%)	8 (50%)	1.000
Age	64.7 ± 7.27	65.0 ± 4.77	0.895
Weight (kg)	64.55 ± 10.12	67.17 ± 10.07	0.456
Height (m)	1.64 ± 0.08	1.65 ± 0.90	0.702
BMI (kg/m^2)	24.09 ± 2.77	24.72 ± 2.36	0.485
MMSE	29.06 ± 0.99	29.25 ± 0.77	0.534
BBS	54.56 ± 1.54	55.13 ± 1.02	0.210
FAC	5 ± 0	5 ± 0	1.000
MBI	100 ± 0	100 ± 0	1.000
FM lower extremities score	33.1 ± 0.90	33.31 ± 0.60	0.445
FM co-ordination score	6 ± 0	6 ± 0	1.000
FM Balance score	13.06 ± 0.87	13.25 ± 0.77	0.499
TUG	7.85 ± 0.72	7.91 ± 0.56	0.784
Fall risk index	42.22 ± 29.29	31.75 ± 21.06	0.237

Note: values are mean ± *SD*.

3D-ARS, three-dimensional interactive augmented reality system; BBS, Berg balance scale; BMI, body mass index; FAC, functional ambulation categories; FM, Fugl-Meyer; MBI, Modified Barthel index; MMSE, Mini-Mental State Examination; *SD*, standard deviation; TUG, timed-up-and-go.

index of posturography after intervention in the 3D-ARS group, which were not observed in the control group (Table 6). The linear mixed model results (*p* value, *F* statistic, degree of freedom) demonstrated significant group (3D-ARS vs. control) × time (before and after exercise) interaction effect or tendency was observed in several parameters (Table 6).

Discussion

In this study, a randomized pilot study was conducted to assess and validate the feasibility of using the 3D-ARS to improve lower limb function, including balance stability in the elderly in comparison to a control group that received a conventional physical fitness program.

Both groups showed significant improvements in BBS, FM, and TUG after training. A significant interaction effect was observed, indicating that the experimental group showed greater improvements, significantly in balance ability. This could mean that although both training methods could improve lower limb functions, the 3D-ARS has a greater effect on scores such as the BBS and TUG, which requires more dynamic movements. It could be understood that the 3D-ARS training enabled patients to improve their dynamic movements.

Moreover, the Tetrax results showed also the superiority of training with the 3D-ARS. The fall risk index, which is estimated from Tetrax and represents one's fall risk, showed significant interaction effect in the 3D-ARS group compared with the control group. One sample comparison of the pre- and post-examination with the Tetrax for each group revealed significant enhancements in Fourier, weight distribution, and stability index in most of the measuring conditions in the 3D-ARS group, whereas there were significant enhancements only in a few conditions in the control group. When comparing the stability Index of Tetrax, the 3D-ARS group showed improvements in postural sway after training, but the control group did not show any improvements. In addition, the improvement in postural sway was prominently observed in most of the closed eye conditions. This result indicates that the subjects' proprioception was particularly improved by the 3D-ARS training. In elderly people who usually depend on their visual information to achieve balance, 3D-ARS training could effectively improve lower limb proprioception, so dependency on visual information is reduced.

In Fourier index results, the 3D-ARS group showed more significant improvements in the low, medium-low, and medium-high frequency ranges (F1, F2–F4, and F5–F6) than in the higher frequency ranges (F7–F8). However, the control group showed no significant improvements. Particularly, the scores of the medium-high frequency range (F5–F6: 0.5–1 Hz) were high in case of lower limb proprioception deficits.[14] Therefore, the improvement of the scores of F5–F6 in the 3D-ARS group indicates that the 3D-ARS training could facilitate the proprioceptive response from the lower limbs. In addition, the improvement of the low frequency (F1: 0.01–0.1 Hz) components score after 3D-ARS training represents the improvement in application and integration of visual information to control posture.[34] These results suggest that 3D-ARS training could enhance the static balance by improving proprioceptive and visual control in elderly people.

Our results indicate that the 3D-ARS training could have superior effects on balance ability, including lower limb functions. The superior improvements in the static and dynamic balance abilities in the 3D-ARS group indicate that the 3D-ARS has particular components that enable it to improve balance abilities, as compared with the conventional training method. These are the strengths of our study. The components could be listed as follows:

First, the 3D-ARS requires whole-body movements to maintain balance while performing tasks; such movements facilitate sensory monitoring and integration. Actually, balance is achieved through integrating information received from the sensory organs and the execution of co-ordinated

Table 3. Comparison of Clinical Evaluations Before and After Three-Dimensional Interactive Augmented Reality System Training Between Pre- and Post-Examination

	3D-ARS group (n = 18)				*Control group* (n = 16)				
	Before	*After*	*Difference (after-before)*	p^b	*Before*	*After*	*Difference (after-before)*	p^b	p^a
BBS	54.556 ± 1.542	55.500 ± 0.924	0.944 ± 0.998	0.001*	55.125 ± 1.025	55.500 ± 0.894	0.375 ± 0.500	0.009	0.042*
FAC	5	5	—	—	5	5	—	—	—
MBI	100	100	—	—	100	100	—	—	—
FMA-LE	33.111 ± 0.900	33.611 ± 0.608	0.500 ± 0.618	0.003*	33.313 ± 0.602	33.625 ± 0.500	0.313 ± 0.479	0.020*	0.335
FMA-C	6	6	—	—	6	6	—	—	—
FMA-B	13.056 ± 0.873	13.722 ± 0.461	0.667 ± 0.686	0.001*	13.250 ± 0.775	13.688 ± 0.479	0.438 ± 0.629	0.014*	0.320
TUG	7.853 ± 0.716	7.348 ± 0.667	−0.504 ± 0.216	<0.0001*	7.914 ± 0.563	7.766 ± 0.621	−0.149 ± 0.163	0.002*	<0.0001*
Fall risk index	42.222 ± 29.291	31.000 ± 18.166	11.222 ± 22.885	0.053	31.750 ± 21.063	34.500 ± 21.927	2.750 ± 12.305	0.386	0.033*

Note: values are mean ± *SD*. *p* Values were derived from a paired *t* test for continuous data.
[a] *p* Values were derived from a linear mixed model for continuous data.
[b] *p* Values were derived from a paired *t* test for continuous data.
*$p < 0.05$.
FMA-B, Fugl-Meyer Motor Assessment Balance section; FMA-C, Fugl-Meyer Motor Assessment Co-ordination section; FMA-LE, Lower-extremity subscale of the Fugl-Meyer Assessment.

and synchronized movements[35,36]; loss of balance occurs when sensory information is inaccurate, when execution of automatic righting movements is inadequate, or both.[35] Considering this perspective, when whole-body movements are made while most of the attention is devoted to utilizing sensory information may facilitate the mechanism that enables an individual to maintain balance unconsciously (e.g., unconscious proprioception).

Second, the 3D-ARS requires movement adjustment to accomplish the goal of the game. This process provides an easy way for the participants to monitor errors in their movements by providing a mirror image of their actions that is superimposed on the game contents in real time. This provides a subject with images in the third person's perspective, which could provide objective visual feedback regarding movements and game contents. This may help subjects monitor their own posture, recognize errors in their movements, and easily obtain information regarding the adjusted goals based on the error.

This information is particularly helpful for the elderly who often lack the ability to recognize their errors. Generally, people who have difficulty in balancing are inclined to be relatively cautious when confronted with novel and complex motor tasks, especially those involving balance,[37,38] because of their higher anxiety and fear levels that have resulted in lower levels of self-efficacy. The 3D-ARS provides feedback regarding posture explicitly through the screen in real time and, thus, promotes the subject's sense of proprioception during movement.

Third, the 3D-ARS draws the subject's attention more actively by showing the outcomes of the movements; the movement itself often does not hold the subject's attention that closely. An external focus of attention during exercise can make the exercise more effective. Instructions or feedback that induce an external attentional focus have been found to result in more effective motor performance than those inducing an internal focus by directing attention to the body movements themselves, or no focus instructions.[38,39] In this case, patients were asked to make their movements to accomplish the goals provided on the screen by directing attention to the movement effects in the 3D environment.

This study has some limitations. First, the small sample size may have obscured the results in other variables except the BBS and fall risk index. Second, the participation of a research assistant in the experimental group may have caused a bias in the data collection. The assistant monitored the participation and safety issues during 3D-ARS training; however, the control group underwent self-guided physical exercise and their weekly performance was monitored via phone. Third, we could not perform follow-up investigations. The after-effects of intervention, including actual fall risk, need to be studied. In addition, we could not conduct a sub-analysis to compare the three AR tasks to elucidate the usefulness of each AR task.

In summary, we could confirm that the 3D-ARS has stronger effects on the enhancement of balance ability. This may be because the 3D-ARS encourages subjects to make their movements according to the contents provided on the screen while they look at the screen. It could facilitate the conscious motor learning mechanism and the unconscious automatic mechanism more effectively.

Table 4. Comparison of Stability Index Before and After Three-Dimensional Interactive Augmented Reality System Training Between Pre- and Post-Examination

	3D-ARS group (n = *18*)				*Control group* (n = *16*)				
	Before	*After*	*Difference (after-before)*	p^b	*Before*	*After*	*Difference (after-before)*	p^b	p^a
NO	15.001 ± 6.248	13.345 ± 5.244	−1.656 ± 4.765	0.159	15.055 ± 3.964	16.102 ± 4.375	1.047 ± 4.935	0.411	0.114*
NC	25.078 ± 9.194	20.693 ± 7.011	−4.385 ± 5.411	0.003**	22.355 ± 6.056	21.567 ± 5.4	−0.788 ± 9.422	0.742	0.192*
PO	17.781 ± 6.859	16.303 ± 8.167	−1.478 ± 6.342	0.337	20.071 ± 8.346	20.101 ± 4.566	0.030 ± 5.132	0.982	0.455
PC	32.595 ± 11.602	28.232 ± 7.03	−4.363 ± 7.668	0.027**	29.581 ± 4.583	29.623 ± 5.298	0.042 ± 6.972	0.981	0.091*
HR	22.366 ± 9.893	19.128 ± 8.107	−3.238 ± 5.845	0.031**	20.207 ± 4.761	19.841 ± 7.438	−0.367 ± 7.732	0.852	0.228
HL	23.335 ± 8.861	19.617 ± 6.842	−3.712 ± 5.750	0.014**	22.218 ± 7.979	22.567 ± 6.22	0.349 ± 9.425	0.884	0.134*
HB	24.662 ± 8.712	20.979 ± 6.775	−3.682 ± 4.275	0.002**	20.759 ± 5.353	20.582 ± 6.478	−0.177 ± 8.452	0.934	0.149*
HF	22.388 ± 8.591	20.634 ± 7	−1.755 ± 8.755	0.407	20.643 ± 5.082	20.388 ± 6.837	−0.255 ± 7.485	0.893	0.598

Note: values are mean ± *SD*.
[a]p Values were derived from a linear mixed model for continuous data.
[b]p Values were derived from a paired t test for continuous data.
$*p < 0.2$; $**p < 0.05$.

Table 5. Comparison of Weight Distribution Index Before and After Three-Dimensional Interactive Augmented Reality System Training Between Pre- and Post-Examination

	3D-ARS group (n = *18*)				*Control group* (n = *16*)				
	Before	*After*	*Difference (after-before)*	p^b	*Before*	*After*	*Difference (after-before)*	p^b	p^a
NO	5.263 ± 2.518	3.377 ± 1.194	−1.886 ± 2.084	0.001**	5.48 ± 3.152	5.603 ± 1.302	0.123 ± 3.519	0.891	0.058*
NC	5.034 ± 2.273	3.881 ± 1.395	−1.153 ± 2.217	0.041**	6.156 ± 2.656	6.228 ± 3.007	0.072 ± 3.485	0.936	0.225
PO	5.308 ± 3.604	4.343 ± 2.128	−0.966 ± 2.468	0.115	6.539 ± 2.659	6.754 ± 2.708	0.214 ± 3.649	0.818	0.273
PC	5.64 ± 3.079	4.308 ± 1.895	−1.332 ± 2.263	0.023**	6.517 ± 3.24	6.443 ± 2.39	−0.074 ± 2.379	0.903	0.124*
HR	4.732 ± 2.447	3.911 ± 1.407	−0.821 ± 1.716	0.058	5.24 ± 2.351	5.196 ± 3.093	−0.044 ± 2.660	0.948	0.314
HL	5.181 ± 3.008	3.776 ± 1.913	−1.405 ± 2.594	0.035**	5.951 ± 3.206	6.095 ± 3.113	0.144 ± 4.061	0.889	0.190*
HB	5.129 ± 3.256	4.372 ± 1.917	−0.757 ± 2.697	0.250	5.881 ± 2.721	5.777 ± 2.991	−0.104 ± 3.806	0.915	0.565
HF	5.709 ± 2.646	3.814 ± 1.481	−1.895 ± 2.437	0.004**	5.159 ± 3.021	4.945 ± 2.632	−0.214 ± 3.297	0.799	0.098*

Note: values are mean ± *SD*.
[a]p Values were derived from a linear mixed model for continuous data.
[b]p Values were derived from a paired t test for continuous data.
$*p < 0.2$; $**p < 0.05$.

Table 6. Comparison of Fourier Index Before and After Three-Dimensional Interactive Augmented Reality System Training Between Pre- and Post-Examination

	3D-ARS group (n = *18*)				*Control group* (n = *16*)				
	Before	*After*	*Difference (after-before)*	p[b]	*Before*	*After*	*Difference (after-before)*	p[b]	p[a]
F1									
NO	18.058 ± 9.265	14.889 ± 6.731	−3.17 ± 9.169	0.161	18.327 ± 10.478	18.486 ± 9.662	0.159 ± 9.577	0.948	0.309
NC	21.228 ± 11.848	15.621 ± 11.847	−5.607 ± 10.001	0.031**	20.264 ± 12.375	19.606 ± 8.026	−0.658 ± 14.442	0.858	0.251
PO	17.014 ± 8.104	13.724 ± 6.389	−3.290 ± 5.524	0.022**	19.432 ± 8.368	19.329 ± 13.422	−0.104 ± 11.945	0.973	0.339
PC	26.291 ± 15.309	19.604 ± 11.841	−6.686 ± 9.585	0.009**	25.198 ± 12.717	23.904 ± 13.894	−1.294 ± 14.364	0.724	0.203
HR	17.133 ± 10.703	12.383 ± 5.416	−4.749 ± 8.410	0.028**	14.11 ± 7.136	14.827 ± 7.973	0.718 ± 10.360	0.786	0.099*
HL	16.451 ± 7.904	12.578 ± 5.651	−3.873 ± 7.841	0.051	16.795 ± 4.943	16.602 ± 6.915	−0.194 ± 7.166	0.915	0.165*
HB	22.81 ± 12.279	17.339 ± 11.103	−5.471 ± 8.303	0.012**	20.289 ± 8.202	19.993 ± 7.771	−0.295 ± 8.594	0.893	0.084*
HF	21.202 ± 9.348	12.62 ± 7.63	−8.583 ± 10.021	0.002**	19.173 ± 8.758	18.833 ± 10.876	−0.340 ± 8.711	0.878	0.016**
F2–F4									
NO	24.56 ± 11.827	19.853 ± 5.76	−4.707 ± 8.913	0.039**	24.023 ± 8.437	23.532 ± 10.286	−0.492 ± 11.756	0.869	0.244
NC	32.904 ± 12.755	25.963 ± 9.026	−6.941 ± 9.891	0.009**	30.329 ± 6.683	30.421 ± 7.435	0.092 ± 9.047	0.968	0.039**
PO	21.879 ± 10.367	17.378 ± 5.159	−4.501 ± 9.584	0.063	22.84 ± 8.55	22.142 ± 7.38	−0.698 ± 9.233	0.767	0.249
PC	35.919 ± 12.176	31.335 ± 6.589	−4.584 ± 9.170	0.049**	33.302 ± 9.7	33.822 ± 9.356	0.520 ± 11.226	0.855	0.154*
HR	30.629 ± 11.286	25.673 ± 7.244	−4.956 ± 7.397	0.011**	27.517 ± 9.209	26.416 ± 9.88	−1.101 ± 15.249	0.777	0.368
HL	29.808 ± 12.176	25.297 ± 8.898	−4.511 ± 7.438	0.020**	26.021 ± 7.704	25.932 ± 8.919	−0.089 ± 10.934	0.975	0.173*
HB	33.616 ± 13.098	30.042 ± 10.93	3.574 ± 6.064	0.023**	30.378 ± 4.922	29.685 ± 6.443	−0.693 ± 8.677	0.754	0.266
HF	32.259 ± 11.717	24.532 ± 8.185	−7.727 ± 12.478	0.018**	29.453 ± 8.557	29.237 ± 11.113	−0.216 ± 15.476	0.956	0.127*
F5–F6									
NO	6.339 ± 3.061	5.167 ± 1.758	−1.172 ± 2.277	0.043**	6.59 ± 1.883	6.897 ± 2.826	0.308 ± 3.095	0.697	0.119*
NC	10.867 ± 5.415	8.211 ± 2.808	−2.656 ± 4.411	0.021**	9.251 ± 2.11	9.394 ± 3.771	0.143 ± 4.730	0.905	0.084*
PO	7.249 ± 3.038	5.773 ± 2.514	−1.476 ± 2.694	0.033**	7.847 ± 3.746	8.05 ± 2.907	0.203 ± 2.879	0.781	0.089*
PC	12.554 ± 3.329	10.476 ± 2.498	−2.078 ± 3.283	0.016**	10.802 ± 2.18	10.578 ± 2.908	−0.224 ± 2.925	0.764	0.094*
HR	8.507 ± 3.704	6.939 ± 2.714	−1.568 ± 2.821	0.031**	7.126 ± 2.422	7.057 ± 2.516	−0.069 ± 3.541	0.939	0.180*
HL	9.735 ± 5.107	7.716 ± 2.811	−2.019 ± 4.080	0.051	8.018 ± 3.58	8.026 ± 2.958	0.008 ± 4.313	0.994	0.169*
HB	8.593 ± 2.048	7.252 ± 2.761	−1.341 ± 2.389	0.030**	7.234 ± 2.141	7.35 ± 2.444	0.116 ± 2.660	0.864	0.102*
HF	9.674 ± 3.875	6.987 ± 2.496	−2.687 ± 3.771	0.008**	8.126 ± 3.619	7.973 ± 3.268	−0.153 ± 5.403	0.911	0.119*
F7–F8									
NO	1.226 ± 0.486	1.001 ± 0.34	−0.225 ± 0.411	0.033**	1.279 ± 0.539	1.258 ± 0.452	−0.021 ± 0.820	0.920	0.379
NC	1.776 ± 0.775	1.562 ± 0.682	−0.215 ± 0.399	0.036**	1.572 ± 0.527	1.541 ± 0.466	−0.032 ± 0.747	0.868	0.391
PO	1.529 ± 0.686	1.346 ± 0.483	−0.183 ± 0.677	0.267	1.603 ± 0.812	1.588 ± 0.671	−0.015 ± 0.872	0.946	0.532
PC	2.324 ± 1.011	2.086 ± 0.644	−0.238 ± 0.518	0.069	2.11 ± 0.667	2.024 ± 0.468	−0.087 ± 0.807	0.674	0.516
HR	1.543 ± 0.773	1.283 ± 0.51	−0.260 ± 0.572	0.071	1.347 ± 0.376	1.316 ± 0.362	−0.031 ± 0.364	0.736	0.180*
HL	1.673 ± 0.686	1.457 ± 0.418	−0.216 ± 0.528	0.101	1.522 ± 0.628	1.506 ± 0.548	−0.016 ± 0.973	0.950	0.470
HB	1.867 ± 0.783	1.555 ± 0.499	−0.312 ± 0.555	0.029**	1.612 ± 0.425	1.582 ± 0.296	−0.030 ± 0.510	0.818	0.134*
HF	1.777 ± 0.652	1.385 ± 0.604	−0.392 ± 0.793	0.051	1.642 ± 0.63	1.617 ± 0.694	−0.025 ± 0.849	0.908	0.202

Note: values are mean ± *SD*.
[a]p Values were derived from a linear mixed model for continuous data.
[b]p Values were derived from a paired t test for continuous data.
$*p < 0.2$; $**p < 0.05$.

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The authors have no competing interests to declare.

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