

EFFECT OF VIRTUAL REALITY-BASED BALANCE TRAINING VERSUS CONVENTIONAL BALANCE TRAINING IN PATIENTS AFTER ANKLE FRACTURE: A RANDOMIZED CONTROLLED TRIAL

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DOI: <https://doi.org/10.5281/zenodo.22890059>

Keywords

Virtual Reality, Balance Training, Ankle Fracture, Post-Immobilization Rehabilitation, Berg Balance Scale, Star Excursion Balance Test, Postural Stability.

Article History

Received: 01 June 2026

Accepted: 23 August 2026

Published: 08 September 2026

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Abstract

Background: Post immobilization joint stiffness, muscle atrophy and proprioceptive deficits affecting static and dynamic balance are common sequelae of ankle fractures.

Objective: To compare VR-guided and conventional balance exercises for improving postural stability, dynamic balance and ankle dorsiflexion in people recovering from immobilized ankle fractures.

Methodology: A single-blinded RCT included 22 adults 11 in each group recovering from medically stabilized ankle fractures. Participants received either 30 minutes of VR-based postural and gamified balance training or conventional balance exercises, 3–5 days per week for 6–8 weeks. Balance and ankle mobility were assessed before and after treatment using the BBS, SEBT, and ankle dorsiflexion ROM. Data were analyzed using the Wilcoxon signed-rank and Mann–Whitney U tests.

Results: The VR group showed greater improvements in balance, reach distance, and ankle dorsiflexion than the conventional therapy group. Both groups were comparable at baseline, with no significant pre-intervention differences ($p > 0.05$). The VR group achieved higher post-intervention mean scores for BBS (51.91 ± 3.239), SEBT posteromedial reach (85.50 ± 4.6763), SEBT composite score ($82.36\% \pm 3.9795$), and ankle dorsiflexion ROM ($17.18^\circ \pm 2.183^\circ$) compared with the conventional therapy group which recorded BBS 42.36 ± 3.585 , SEBT posteromedial reach 71.78 ± 4.3575 , SEBT composite score 69.04 ± 3.9026 , and ROM $12.64^\circ \pm 1.502^\circ$.

Conclusion: VR-based postural rehabilitation can improve static and dynamic balance, postural control and ankle dorsiflexion after ankle fracture immobilization. Using real-time visual feedback and engaging games may support better functional recovery than traditional exercises.

INTRODUCTION

The ankle joint complex, including the talocrural, subtalar and distal tibiofibular syndesmosis is important in weight bearing and force transmission during ambulation, standing and physical activity. Disruption of the distal tibia, lateral malleolus or medial malleolus adversely impacts the entire lower kinetic chain alignment and biomechanical integrity. These fractures may occur due to high energy events like accidents, fall and torsional injuries like simple slips or sports injuries and falls occurring in the course of daily activities. (1)

After ankle fracture immobilization, the effects can extend beyond the ankle itself. Normal walking requires proper ankle dorsiflexion and plantarflexion during heel strike, mid-stance and push-off. Immobilization can reduce ankle mobility and may lead to compensatory movements at the knee, hip and lower back. All of these altered movement patterns apply stress on other joints, affecting the absorption of ground reaction forces thus leading to uneven weight distribution throughout the limb.(2)

From the perspective of healthcare, long term deficits after a fracture cause significant functional and economic burdens on the patient. Patients after ankle immobilization often face huge period of lost work, delayed return to sports or recreational activities, and lingering functional impairments.(3) In other cases such as inadequate or incomplete rehabilitation, individuals suffer from a high risk of secondary issues just as post-traumatic osteoarthritis, chronic ankle instability (CAI), dynamic instability while standing as well as recurrent injuries in the lower limbs. Thus, it is essential to ensure the complete restoration of biomechanical functionality, range of motion and dynamic ankle joint stability during the early stages of physical therapy after immobilization.(4) One of the most important phases of post ankle fracture rehabilitation involve the phases from complete immobilization to active weight-bearing. Patients show a mixture of severe neurosensory impairments or muscular weakness, and structural rigidity all this period. As structural integrity is addressed by bone union, the integrity of

the neuromuscular system is important for functional stability. Peripheral mechanoreceptors present in the ankle joint capsule, lateral ligaments and periarticular muscle tendons are also affected by immobilization.(5)

Afferent feedback from the fractured ankle to the central nervous system is continually misdirected, delayed, or maybe deteriorated. Thus, if unexpected postural sways or load changes occur, the peripheral sensory disruption hinders central motor planning and thus causing the delay in the recruitment of lower limb musculature. (6)

Arthrogenic Muscle Inhibition is a major effect of proprioceptive disturbance following immobilization. Joint swelling, discomfort, and altered sensory input cause AMI an automatic, presynaptic reflex inhibition of surrounding musculature, especially the tibialis anterior, gastrocnemius-soleus complex, peroneus longus, and peroneus brevis. The ankle complex loses its dynamic muscular guarding mechanism in the absence of sufficient eversion and dorsiflexion muscle response leaving the joint solely dependent on static structural restrictions.(7)

Proprioceptive degradation, muscular atrophy and articular stiffness all contribute to a large "stability gap" during the post-immobilization phase. Patients show worsened static and dynamic balance increased postural sway velocity and increased center of pressure displacement. When performing weight-bearing tasks including stair navigation, single-leg stance, and dynamic walking over uneven surfaces, these deficiencies reduce functional stability. (8)

Standard physical therapy programs emphasize progressive joint mobilization, range-of-motion exercises, muscle strengthening, and balance training to treat post-immobilization deficits. The conventional clinical standard of care in orthopedic physical therapy is represented by conventional balance therapy. Through increasing weight-bearing demands, this treatment method uses therapist-guided exercises to restore both static and dynamic equilibrium.(9)

Before moving on to dynamic multi-planar exercises standard balancing exercise progressions usually start with static, single-leg standing

exercises on hard surfaces. To create mechanical instability, therapists use specialized hand tools such as foam pads, rocker boards, wobble boards, and BOSU balance trainers. (10) Because the ankle complex must make quick compensatory muscle modifications, these unstable surfaces put lower limb proprioceptors to the test. Common rehabilitation exercises include weight shifting, tandem standing, backward walking, single-leg reaching and theraband strengthening. Although conventional balance training provides a structured approach to recovery, it has some limitations in clinical practice.(11)

Conventional exercise therapy depends on self-directed, repetitive motions in which the patients are often uninterested. This leads to a major concern "the boredom factor" that causes decreased desire, poor performance in exercise and less adherence to treatment plans in general. Wooden balance boards or foam pads that are the conventional balance aids do not offer real-time visual feedback or quantitative data results about the dynamic ankle joint angles, center of gravity displacement or postural swayback.(12)

If proprioceptive problems are not addressed, they may increase the risk of falls and contribute to long-term joint instability and repeated minor injuries. If proprioceptive problems are not addressed, they may increase the risk of falls and contribute to long-term joint instability and repeated minor injuries. VR systems include task-specific mobility requirements with real-time visual, auditory and real-time biofeedback by engaging patients in controlled virtual environments setups.(13)

VR incorporation is predicated on fundamental concepts of neuroplasticity and central motor learning in balance therapy. Repetitive, goal-oriented, high-intensity movement practice combined with instantaneous awareness of performance and results is necessary for effective motor learning. VR environments meet these objectives of the training by converting standard balance drills into gamified, task-specific tasks. Patients can engage with virtual targets, navigate virtual terrain, avoid virtual impediments and execute directed reaching tasks that call for

dynamic lower extremity control using digital interfaces.(14)

Additionally, the gamification of the rehabilitation improves psychological immersion, focus, and patient motivation. During high-repetition exercises, interactive rewards, scoring metrics, and increasing difficulty levels improve cognitive engagement, divert attention from localized movement-related anxiety and reduce perceived effort.(15)

Nevertheless, post-traumatic orthopedic disorders cannot be readily inferred from neurological research findings. Lesions in the central brain or spinal cord inside undamaged peripheral joints are the main cause of neurological impairments. On the other hand, post-ankle fracture deficits include particular ankle-joint proprioceptive loss, localized peripheral mechanical stress, structural joint stiffness, ligamentous disruption, and local articular edema. (16) Clinical validation is necessary to meet the biomechanical requirements of reestablishing talocrural kinematic alignment, correcting localized arthrogenic muscle inhibition, and restoring ankle range of motion.

The majority of lower extremity VR research in orthopedics concentrates on general age-related fall prevention, broad knee ligamentous reconstructions, or chronic ankle instability (CAI) in athletes. The viability, therapeutic effectiveness, and success metrics of incorporating VR early in post-fracture orthopedic therapy are not well studied by standardized methods. By comparing the outcomes of immersive VR training to traditional exercise regimens on static stability, dynamic postural control, ankle range of motion and functional mobility in post-fracture patients in this study.

Materials and Methods:

This study was designed as a single-blinded randomized controlled trial (RCT) to compare the effects of Virtual Reality (VR)-based balance training and conventional balance therapy on functional recovery, static balance, dynamic stability, and ankle dorsiflexion range of motion in patients recovering from ankle fracture after immobilization. The study was conducted from

Sehet Medical complex and Gangaram hospitals in Lahore, Pakistan, over a period of six months. The study population consisted of adults recovering from medically stabilized ankle fractures, either managed surgically or conservatively, who were in the post-immobilization phase and had been medically cleared for full weight-bearing. The minimum required sample size was 22 participants with 11 participants allocated to each group, as calculated using G*Power software. Participants were recruited using simple random sampling and were randomly allocated into either the experimental VR-based training group or the conventional therapy group.

Participants aged 18–60 years with a documented ankle fracture managed either surgically or conservatively were included. Eligible participants were in the post-immobilization recovery phase, medically stabilized, cleared for full weight-bearing, and able to walk with minimal to no pain. Participants were also required to provide written informed consent and commit to the complete 6–8-week intervention program. Patients with neurological disorders affecting balance or motor control, severe visual or vestibular impairments, active infection, significant or sharp pain during weight-bearing or walking, cognitive impairment affecting the ability to follow instructions or safely use VR equipment, other significant lower-limb injuries, or a history of photosensitive epilepsy or frequent seizures were excluded from the study.

Data were collected using the Berg Balance Scale (BBS), Star Excursion Balance Test (SEBT), and active ankle dorsiflexion range of motion. The BBS was used to assess static and functional balance and consisted of 14 items with a maximum score of 56, with higher scores indicating better functional performance. The SEBT was used to evaluate dynamic balance and neuromuscular control through multidirectional reaching tasks, while ankle dorsiflexion range of motion was assessed to determine changes in sagittal-plane ankle mobility. Baseline measurements were recorded before the intervention, and post-intervention assessments were conducted following completion of the

treatment program. Eligible participants were randomly assigned to two treatment groups. The experimental group received Virtual Reality-based balance training, while the control group received conventional balance exercises. The study was single-blinded, in which the outcome assessor remained unaware of the participants' group allocation to minimize assessment bias. At baseline, participants were educated regarding the training protocol assigned to their respective group.0][cite: 2]

Group A: VR Participants in the experimental group received a structured 30-minute balance training session consisting of 15 minutes of postural training and 15 minutes of interactive VR gaming. The postural training involved guided weight-shifting exercises with real-time visual feedback through the VR headset to facilitate correction of the participant's center of gravity. The remaining 15 minutes consisted of interactive VR-based tasks requiring dynamic postural control, including reaching toward virtual targets and avoiding virtual obstacles. The difficulty level was progressively adapted according to the participant's improvement in balance. All sessions were performed under therapist supervision. Training was provided 3–5 days per week for 6–8 week.

Group B: Participants in the conventional therapy group received 30 minutes of standard clinical balance exercises. The intervention included static balance exercises such as single-leg standing and tandem walking, followed by dynamic balance exercises using equipment such as BOSU balls and wooden balance boards. Exercise difficulty was progressively increased according to the participant's tolerance, including progression from bilateral to unilateral support and from stable to unstable surfaces. The exercises were performed in a standard clinical setting without the use of digital or immersive technology. Training was provided 3–5 days per week.

Before participation, all subjects were informed about the study procedures and provided written informed consent. Confidentiality and anonymity of participant information were maintained throughout the study, and participants were

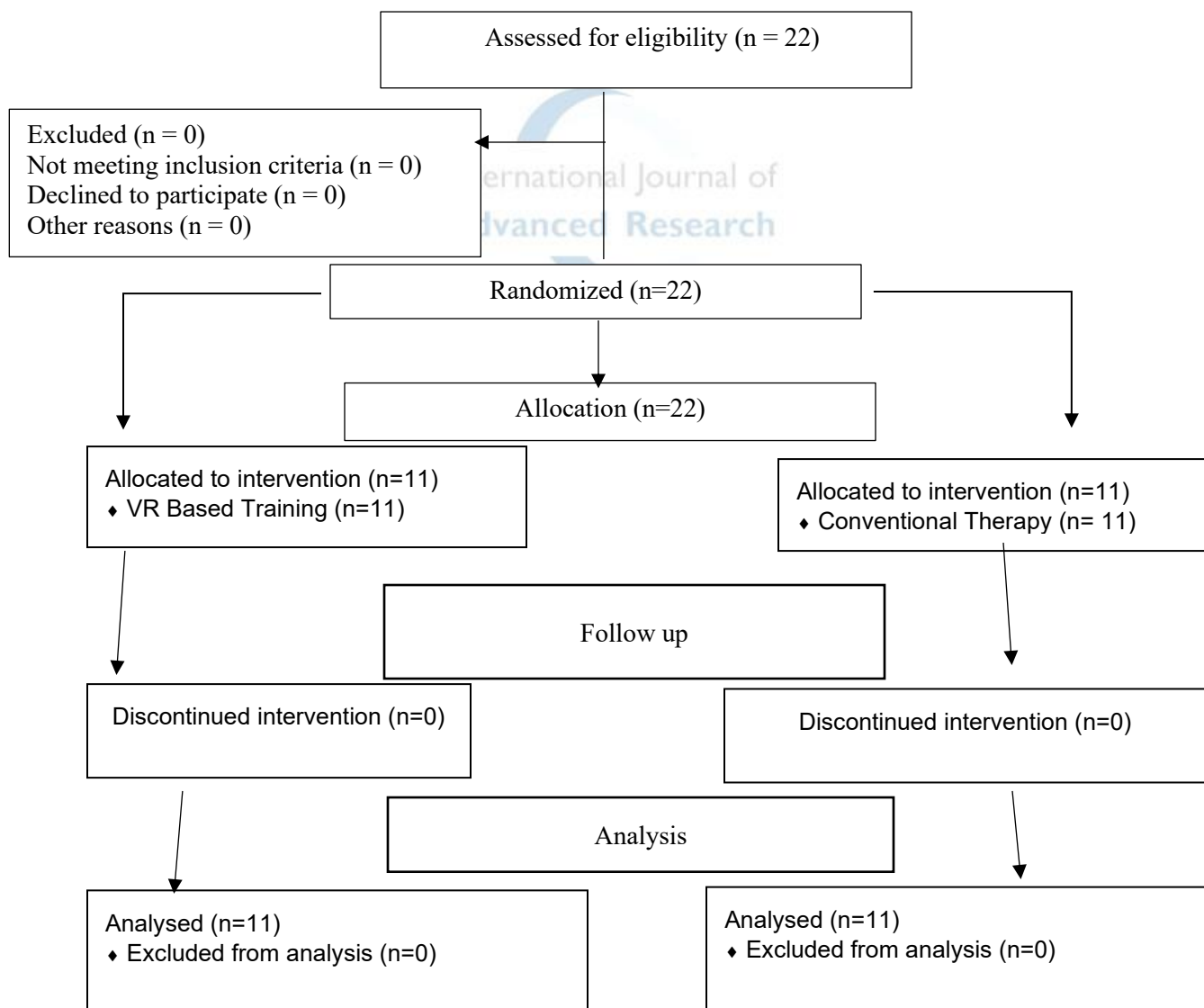
informed of their right to withdraw from the study at any stage.

Statistical analysis:

The data were analyzed using descriptive and inferential statistical methods. Descriptive statistics were used to summarize the demographic characteristics and outcome measures. Quantitative data were presented as mean $\pm$ standard deviation (SD), while the outcome measures included the Berg Balance Scale (BBS), Star Excursion Balance Test in the posteromedial

direction (SEBT-PM), SEBT composite score, and active ankle dorsiflexion range of motion (ROM DF). The Wilcoxon signed-rank test was used to assess changes in outcome measures from pre-intervention to post-intervention within the groups. The Mann-Whitney U test was used to compare the outcome measures between the VR-based training and conventional therapy groups. The statistical significance level was set at $p < 0.05$. The thesis reports statistically significant within-group improvements for BBS, SEBT-PM, SEBT composite score and ROM DF with $p < 0.001$.

Consort flow diagram



Results

A total of 22 patients recovering from medically stabilized ankle fractures participated in the study and were randomly allocated into two treatment

groups with 11 participants in each group. The Conservative Therapy group had a mean age of 33.55 ± 8.993 years, while the Virtual Reality (VR) group had a mean age of 38.45 ± 8.466 years.

Test of Normality

Variable	K-S Statistic	Df	K-S p	Shapiro-Wilk Statistic	Df	Shapiro-Wilk p
BBS Pre	.193	22	.032	.894	22	.022
SEBT PM Pre (%)	.128	22	.200*	.964	22	.578
SEBT Comp Pre (%)	.124	22	.200*	.938	22	.179
ROM DF Pre (°)	.237	22	.002	.821	22	.001

Table 1. Between-group comparison of outcome measures

Outcome Measure	Time	Mann-Whitney U	Z-value	p-value
BBS	Pre	47.500	-0.834	0.404
BBS	Post	1.000	-3.899	<0.001
SEBT-PM (%)	Pre	50.000	-0.660	0.510
SEBT-PM (%)	Post	12.000	-3.166	0.002
SEBT Composite (%)	Pre	59.000	-0.066	0.947
SEBT Composite (%)	Post	3.000	-3.760	<0.001
ROM DF (°)	Pre	39.000	-1.432	0.152
ROM DF (°)	Post	8.500	-3.445	0.001

Table 1 presents the between-group comparison of outcome measures at baseline and after the intervention. It showed no statistically significant differences between the groups at baseline for BBS ($p = 0.404$), SEBT-PM ($p = 0.510$), SEBT composite score ($p = 0.947$), and ROM DF ($p =$

0.152). In contrast, statistically significant between-group differences were observed after the intervention for BBS ($p < 0.001$), SEBT-PM ($p = 0.002$), SEBT composite score ($p < 0.001$), and ROM DF ($p = 0.001$).

Table 2. Within-group comparison of outcome measures

Outcome Measure	Positive Ranks	Mean $\pm$ SD	Z-value	p-value
BBS Post - Pre	22	29.91 ± 2.73	-4.113	<0.001
SEBT-PM Post - Pre	22	42.36 ± 3.58	-4.107	<0.001
SEBT Composite Post - Pre	22	59.7 ± 4.78	-4.107	<0.001
ROM DF Post - Pre	22	56.8 ± 3.03	-4.120	<0.001

Table 2 presents the within-group analysis of the outcome measures. It demonstrated statistically significant improvements from pre-intervention to post-intervention in BBS, SEBT-PM, SEBT

composite score, and ROM DF. All 22 participants showed positive ranks, with no negative ranks or ties, and all changes were statistically significant ($p < 0.001$).

Table 3. Post-intervention descriptive comparison between treatment groups

Outcome Measure	Conventional Therapy Group Post Mean $\pm$ SD	VRGroup Post Mean $\pm$ SD	Between-group p-value
BBS	42.36 $\pm$ 3.585	51.91 $\pm$ 3.239	<0.001
SEBT-PM (%)	71.78 $\pm$ 4.3575	85.50 $\pm$ 4.6763	0.002
SEBT Composite (%)	69.04 $\pm$ 3.9026	82.36 $\pm$ 3.9795	<0.001
ROM DF (°)	12.64 $\pm$ 1.502	17.18 $\pm$ 2.183	0.001

Table 3 presents the descriptive comparison of post-intervention outcome measures between the two treatment groups. The VR group recorded higher post-intervention mean values for all measured outcomes compared with the Conventional Therapy group.

Discussion:

The current study indicated that balance training using Virtual Reality based protocols leads to significantly greater enhancements in both static and dynamic balance, also with ankle joint ROM, as compared to the conventional balance therapy for patients recovering from immobilization after ankle fractures. While both groups resulted in statistically significant improvements within each group from baseline ($p < 0.001$), comparisons made post-intervention showed notable differences in favor of the VR group in all measured parameters.

Kim et al. (2019) assessed a VR exercise program using Nintendo Wii Fit Plus against traditional TheraBand and balance board workouts in 21 individuals with functional ankle instability. The results showed that participants in the VR group have greater improvements in overall static balance and medial-lateral dynamic balance. However, Kim et al. used a gaming Wii Fit Plus which did not offer specialized clinical biofeedback, whereas the current study included a dynamic weight-shifting protocols and continuous center-of-gravity tracking. While Kim et al. focused on chronic non-traumatic ankle instability, this

study focuses on the acute structural, neural, and articular challenges that are distinct to immobilization after fracture.(17)

In another study Harris et al. (2025) conducted a wobble board program of 4 weeks to compare with VR-based balance training between 54 athletes suffering from chronic ankle instability, by using the SEBT and the Cumberland Ankle Instability Tool (CAIT) scales. The findings showed that the both groups showed improvement, the VR cohort achieved significantly better reach distances in the posteromedial and posterior directions of the SEBT. The current research expands on these results by confirming that improvements in dynamic reach in adult populations going through structured rehabilitation after fractures.(18)

A systemic meta-analysis conducted by Jin et al. (2022) highlighted the advantages of integrating VR systems such as ITreadmill VR and Dynstable VR 3D into postoperative rehabilitation, giving significant enhancements in strength of lower limb muscle and gait speed over an 8-week duration. Similarly, Li et al. (2021) showed that an 8-week program utilizing the Dynstable Virtual Balance Trainer considerably improved neuromuscular control in comparison to conventional therapy training program. The findings from this research directly support the findings of Jin et al. and Li et al., validating that interactive feedback mechanisms speed up physical recovery. (19)

Zhang et al. (2021) explored that training frequently with the TechnoBody. Virtual Balance

System for two months significantly decreased the speed and sway length of center-of-pressure during single-leg stance tasks. While Zhang et al. emphasized on static postural elements, this thesis includes both static measures (BBS) and dynamic functional assessments (SEBT), confirming that the observed reductions in postural sway correspond directly to enhanced stability in multi-directional reaching during weight-bearing activities.(9)

The systematic review conducted by Vaida et al. (2024) highlighted the gamified real-time visual position feedback decreases perceived effort while enhancing movement pattern adjustment. The data from the trial provides clinical support for Vaida et al.'s findings, showing that a structured 30-minute treatment plan 15 minutes of postural feedback followed by 15 minutes of interactive gaming may result in statistically significant improvements across all primary outcomes.(20)

This research provides new empirical insights into orthopedic physical therapy rehabilitation, emphasizing that after ankle fractures are immobilized, impaired mechanoreceptors hinder afferent feedback, that leads to presynaptic inhibition of surrounding muscles. This research highlights that real-time VR visual feedback can highly compensate for impaired peripheral somatosensory signals. Due to deliverance of continuous visual information of the center-of-mass movement, VR enables the central nervous system to adjust postural alignment, effectively circumventing neural inhibition and causing a speedy recovery in neuromuscular. This thesis emphasizes on engaging in interactive visual target-reaching within a virtual reality environment improves active, end-range ankle movements while bearing weight, causing joint capsule remodeling and more effective restoring of talocrural kinematic mobility as compared to the manual stretching or unsupervised wobble board exercises. The VR group showed significant outcomes in normal dynamic reach. This shows that game-based, task-oriented movement challenges help in dynamic lower-limb stability and postural adjustments more effectively than conventional static balance exercises plans.

Limitations

- A small sample cohort thus causing an increased risk of a Type II error and also causing decrease the clinical generalizability of the results.
- Study used a single-blind design because of methodological constraints. While the outcome evaluators were blinded to the group assignments, both the participants and treating clinicians knew which group they belonged to. This awareness may have influenced participants' responses or performance through novelty effects or expectations, potentially introducing performance bias.
- Assessment was limited to immediate post-treatment functional metrics. Therefore, the long-term effects of VR interventions on persistent joint stability, prolonged functional capacity, and long-term fall prevention are unknown.
- Future studies should include objective physiological measures such as surface electromyography (sEMG) of lower-limb musculature and central brain imaging to quantify the underlying neuromuscular adaptations and neuroplastic cortical changes induced by VR balance protocols.

Recommendations

- Future studies should conduct follow-up assessments at 3, 6 and 12 months after the intervention to evaluate long-term retention determining the lasting preventive effects of VR training on post-traumatic osteoarthritis.
- Clinical trials should aim for larger, multi-center sample sizes to achieve optimal statistical power and increase generalizability of findings across different demographic populations.
- Future studies should include neuroimaging methods to quantitatively assess real-time neural activation, muscle recruitment, and central nervous system neuroplasticity induced by VR visual biofeedback.
- Future research should compare the differential impact of VR interventions across specific anatomical fracture classifications and treatment approaches to identify optimal protocols based on surgical hardware or soft-tissue healing status.

- They should conduct trials to compare clinical VR balance systems with low-cost home-based head-mounted displays or mobile VR systems in terms of patient compliance, cost-effectiveness and feasibility of telerehabilitation models for remote post-fracture recovery.

Conclusion:

Combining balance training with VR may improve balance and range of motion in patients recovering from ankle fractures. VR provides engaging visual and motor activities that can enhance patient participation and support neuromuscular recovery. Therefore, VR-based balance training may be a useful addition to conventional rehabilitation to improve functional recovery and reduce fall risk.

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