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Impact of whole-body vibration training on ankle joint proprioception and balance in stroke patients: a prospective cohort study

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Abstract

Background Although whole-body vibration (WBV) training is acknowledged for its benefits in enhancing motor functions across several neurological disorders, its precise influence on ankle joint proprioception and balance in stroke patients is still not well understood. This research seeks to assess the impact of WBV training on ankle joint proprioception and balance in stroke patients, thereby filling this important research void.

Methods In this prospective cohort study, thirty-five stroke patients were randomly assigned to either the WBV group ($n = 17$) or a control group ($n = 18$) using a random number table method. The control group received daily general rehabilitation for four weeks, while the WBV group received an additional 30 min of WBV training each day with the Trunsan S110 Vibration Training System. Blinded outcome assessments were conducted at baseline and post-treatment, utilizing the Berg balance scale (BBS), Functional reach test (FRT), Romberg test length (RTL) and area (RTA), and completion rates of ankle joint dorsiflexion-plantar flexion (DP) and inversion-eversion (IE) tests. Follow-up assessments were performed after four weeks of intervention, focusing on RTL, RTA, DP, and IE as primary outcomes.

Results Analysis of intra-group changes from baseline to post-treatment revealed significant improvements across the BBS, FRT, RTL, RTA, and DP and IE assessments ($p < 0.001$). Notably, the WBV group showed significant enhancements compared to the control group in DP and IE ($p < 0.001$ and $p < 0.05$, respectively), with mean values increasing from 13.556 to 16.765 (23.7%) and from 5.944 to 8.118 (36.6%), respectively. However, WBV did not provide additional benefits over the control treatment for balance recovery parameters such as BBS, FRT, RTL, and RTA ($p > 0.05$).

Conclusions This study demonstrates that WBV therapy is equally effective as conventional methods in enhancing proprioception and balance in stroke patients, but it does not provide additional benefits for balance recovery. WBV significantly improves proprioceptive functions, particularly in DP and IE parameters. However, it does not surpass traditional rehabilitation methods in terms of balance recovery. These findings indicate that WBV should be incorporated into stroke rehabilitation primarily to enhance proprioception rather than to optimize balance recovery.

Trial registration This study was retrospectively registered in the ISRCTN Registry on 29/07/2024 (https://www.isrctn.com/, ISRCTN64602845).

Keywords Stroke, Whole-body vibration, Ankle joint proprioception, Balance function, Berg balance scale

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Background

Stroke ranks as the second leading cause of death worldwide and is a significant contributor to disability [1, 2], highlighting the need for novel rehabilitation strategies post-stroke [3, 4]. Existing rehabilitation methods, including exercise therapy, occupational therapy, and acupuncture, frequently face limitations due to patients' health conditions, cognitive capacities, and available resources [5–16].

Whole-body vibration (WBV) training, a form of muscle vibration technology, has emerged as a promising method due to its ability to enhance neuromuscular activation and proprioceptive feedback through varied frequencies and amplitudes of vibration [17–24]. Initially introduced in 1892, WBV has evolved to employ platforms that deliver vibrations across the entire body, targeting a broad range of muscle groups and addressing balance and proprioceptive challenges holistically. Widely utilized in athletics to enhance performance, WBV is being increasingly adopted in medical rehabilitation for conditions like Parkinson's disease, multiple sclerosis, and stroke. It shows promise in aiding motor function recovery and improving balance and proprioception [20–22].

However, the efficacy of WBV in promoting functional recovery after a stroke is still a matter of debate. Some studies highlight significant benefits in neuromuscular activation and circulation, which are essential for recovery, whereas other research suggests only modest improvements in muscle strength and balance [25–29]. Notably, these studies (primarily retrospective cohort studies) concentrate on static and dynamic balance rehabilitation, with less emphasis on proprioceptive recovery, particularly ankle joint proprioception, which plays a key role in maintaining balance and mobility. Furthermore, when investigating the restoration of balance, the Berg balance scale (BBS) is used solely due to its convenience, introducing high subjectivity. This issue can be overcome by adopting other balance assessment measures, including functional reach test (FRT), Romberg test length (RTL) and area (RTA).

Therefore, this prospective cohort study aims to fill this gap by examining the effects of WBV on balance and proprioception in stroke patients, focusing particularly on ankle joint proprioception. We hypothesize that WBV training will significantly improve both balance and proprioceptive abilities. This research will utilize the BBS, FRT, RTL, and RTA values, as well as completion rates of ankle joint dorsiflexion-plantar flexion (DP) and inversion-eversion (IE) tests, to comprehensively evaluate these functions, potentially offering new insights into effective stroke rehabilitation practices.

Methods

A prospective cohort study was employed for this research, conducted in the Rehabilitation Medicine Department, the First Affiliated Hospital of the University of Science and Technology of China from March 2020 to May 2022. The study strictly adhered to ethical guidelines, ensuring participant confidentiality and data security. It was approved by the Ethics Committee of the First Affiliated Hospital of the University of Science and Technology of China (IRB, Institutional Review Board, 2022-ky403) and conducted in accordance with the Declaration of Helsinki. All participants were thoroughly informed about the details of the treatment plan and voluntarily signed the consent agreement prior to their inclusion in the study, ensuring informed consent was obtained in accordance with ethical standards. Moreover, this study adheres to CONSORT guidelines.

Subject

Stroke inpatients were enrolled from March 2020 to May 2022. The selection process involved a thorough screening to ensure adherence to the inclusion and exclusion criteria. Initially, based on the inclusion criteria, 58 stroke patients were selected. Subsequently, according to the exclusion criteria, 23 individuals were excluded, leaving a total of 35 participants. The demographic and physical characteristics, including age, gender, height, weight, affected side, course of the disease, and hematencephalon/cerebral infarction were recorded in all patients.

Eligible participants were first-episode stroke patients, defined as individuals with no prior stroke events. Stroke diagnosis was confirmed through CT or MRI, with characteristic imaging features: low attenuation in ischemic strokes or high/mixed-intensity signals in hemorrhagic strokes, accompanied by hemiplegia. Participants had stable vital signs (heart rate: 60–100 bpm; blood pressure: 90/60 to 120/80 mmHg; respiration: 16–26 breaths per minute; temperature: 36.5–37.3 °C) and cognitive function (mini-mental state examination (MMSE) score $>$ 27) [30]. They also needed to be at Brunnstrom stage III or higher in the lower limbs, ensuring that all participants had reached at least the third stage of motor recovery post-stroke, allowing for voluntary control of synergies. Spasticity was measured by the modified Ashworth scale (MAS) of less than 2, ensuring participants had minimal spasticity and allowing for better voluntary control of movement. Additionally, they were required to maintain independent standing balance.

Participants were excluded for any of the following reasons: (a) Severe complications such as major neurological deficits or severe aphasia that could impede study involvement. (b) Severe cardiovascular conditions posing significant health risks, including hypertension (systolic ≥ 180 mmHg or diastolic ≥ 120 mmHg) [31], heart failure with an ejection fraction < 35%, symptomatic coronary artery disease, and severe valvular heart disease, following American College of Cardiology and American Heart Association guidelines. (c) Advanced bone and joint diseases affecting participation, such as severe osteoarthritis, rheumatoid arthritis, recent or unhealed fractures, or significant post-surgical limitations. (d) Recent lower extremity venous thrombosis, defined as episodes within the last six months, which could be aggravated by study activities. (e) Cognitive impairments severe enough to interfere with understanding instructions or providing informed consent, like advanced dementia or significant intellectual disability, regardless of MMSE scores.

Randomization and blinding

Thirty-five stroke patients were randomly divided into two groups using a random number table method: the WBV group ($n = 17$) and the control group ($n = 18$). After the four-week treatment, the data from both groups were provided to a data analyst who was blinded to the group allocation, ensuring that they did not know which set belonged to the WBV group or the control group.

Interventions

All patients received treatment according to the established schedule, with varying starting points for the intervention, based on their enrollment date. The treatment sessions were administered by experienced physical therapists, each with at least 3 years of clinical experience in stroke rehabilitation. To ensure blinding, the therapists were not informed of the group allocations (WBV group or control group) during the course of the study. This blinding procedure was implemented to reduce potential bias in treatment delivery and outcome assessments.

Participants in the control group underwent a general rehabilitation routine once daily for six days each week, over a period of four weeks. The regimen was carefully structured to incorporate elements of each therapy modality. The rehabilitation routine methods include four therapies [32, 33]:

(1) Physiotherapy equipment (8:30–9:30 AM): This includes 15 min of neuromuscular electrical stimulation at 20 mA with cyclic patterns, and functional electrical stimulation for 15 times, adjusting the current intensity between sensory and motor thresholds. Additionally, intermittent pneumatic compression (IPC) was applied at 60 mmHg, comprising cycles of 40 s of inflation and 20 s of deflation, totaling 20 min per session.
(2) Exercise therapy (10:00–11:30 AM): This session includes nerve stimulation techniques with 20 min of Bobath treatment. Muscle strength training focused on the shoulder, elbow, wrist, hip, knee, and ankle joints, under a physical therapist's supervision. Each joint underwent four training sets, comprising ten repetitions per set at 50–70% of the one-repetition maximum. Additionally, the session incorporated cardiorespiratory training at a moderate intensity, targeting 40–60% of heart rate reserve for 30 min, and balance function exercises.
(3) Acupuncture treatment (3:00–3:20 PM): Traditional acupuncture therapy for 20 min per session.
(4) Occupational therapy (4:00–4:30 PM): This includes activities of daily living (ADL) training, where participants practiced basic self-care tasks such as dressing, grooming, bathing, toileting, and eating. The focus of the ADL training was to help improve functional independence in performing these essential daily activities.

For those in the WBV group, an additional 30 min of WBV training (5:00–5:30 PM) supplemented the control group's regimen (Trunsan S110 Vibration Training System). This WBV training utilized a vibration frequency of 10–20 Hz and an amplitude of 4.00–6.00 mm. All treatment sessions were conducted by therapists with equivalent levels of expertise.

Outcome measures

Proprioception and balance functions were assessed by a trained physical therapist who was blinded to the group assignments both before and after the four-week treatment period. This evaluator was distinct from those administering the interventions, ensuring that potential bias in the outcome assessment process was minimized.

Balance functions

Balance functions were assessed using the BBS, a 14-item scale evaluating various balance aspects such as sitting to standing and standing on one foot, scored from 0 to 4, with higher scores indicating better balance (0–56 points) [34–37]. The BBS is widely regarded for its reliability and validity in stroke populations, with an intraclass correlation coefficient (ICC) of 0.93–0.97 for evaluation reliability [38]. Equipment included a ruler, two chairs, a footstool, a 15-foot walkway, and a stopwatch. Despite its usefulness, the BBS is subjective, so we incorporated the FRT for a more objective assessment, measuring the maximum reach distance beyond arm's length in a standing position [39]. The mean of three measurements was recorded in centimeters. The FRT has demonstrated excellent test–retest reliability, with an ICC of 0.92 for "yardstick" reach and 0.98 for interobserver measurements, supporting its reproducibility in balance assessments [40].

Additionally, the TecnoBody PROKIN System (PK252) was used for the Romberg test, conducted in a quiet, well-lit room. Participants stood with eyes open and closed for 30 s (as depicted in Fig. 1), with three repetitions and three-minute rest intervals between trials to ensure consistency and reliability [41, 42]. The center of pressure (COP) path length and displacement area ratios were calculated, with values larger than 1 indicating decreased stability and higher reliance on visual input for balance. Previous studies have validated the Romberg test as a reliable measure for evaluating balance and postural stability in stroke patients [43].

Proprioception testing

Three major methods for testing proprioception are threshold detection of passive motion, joint position reproduction, and active movement extent discrimination [44]. Based on our review, joint position reproduction is crucial for assessing proprioception and impacts gait in stroke patients [45, 46]. We used the TecnoBody PROKIN System (PK252) for ankle joint movement assessment through DP and IE tests. This system has been validated as a reliable tool for proprioception and balance assessment in neurological conditions [47].

The therapist set a safe range for ankle motion, demonstrated the procedure, and had participants stand on the test board with feet shoulder-width apart. Each DP and IE test lasted 120 s, followed by a 30-s rest, repeated three times to average the results [48]. Participants placed the affected foot on the balance board and the unaffected foot on a stationary support, tracing lines on a monitor to match pre-drawn system lines and targets.

Patients aimed to accurately target objectives along the vertical (DP) and horizontal (IE) axes. Success rates, such as hitting a blue marker 16 out of 20 times (80%), were calculated based on motion range and speed.

Fig. 1 Stand with their feet upright along the marked line and balance the instrument

Statistical analysis

Given the constraints imposed by the availability of participants, we performed a post-hoc power analysis to determine the statistical power of our study using PASS software. Drawing from previous research [3, 49], we anticipated a mean difference of 11 points in the BBS scores as a result of the WBV therapy, with an observed standard deviation ranging between 5 and 7. Based on these parameters, and setting the alpha error (α) at 0.05, we calculated that our study possesses a statistical power exceeding 99%.

Data were analyzed using SPSS 26.0 (SPSS, Inc., Chicago, IL). The measurement data were expressed as mean ± standard deviation (SD). Upon confirming the homogeneity of variances, independent samples t-tests were utilized for inter-group analyses, while paired-sample t-tests were employed for intra-group comparisons. For data sets not following the normal distribution, Mann–Whitney U tests and Wilcoxon signed-rank tests were employed. A correlation analysis was performed to explore the correlation between DP (times) and IE (times). Moreover, multiple linear regressions were conducted to explore the existence of confounders. A p-value of less than 0.05 was deemed indicative of statistical significance.

Results

Participants' demographic and baseline characteristic comparison

To ensure that the intervention and control groups were comparable at baseline, their demographic and physical characteristics were analyzed. This is critical for attributing any observed effects specifically to the intervention rather than to underlying differences between groups. Table 1 presents a comparison of demographic and physical characteristics between the WBV group and the control group (CG) with 35 participants. Both groups showed similar distributions in terms of number of participants, gender ratio, average age, height, weight, and side of the body affected by the condition. Specifically, there were 17 participants in the WBV group and 18 in the CG, with gender distributions nearly identical. The average ages, heights, and weights between the groups were comparable, as indicated by nonsignificant p-values (0.838 for age, 0.931 for height, and 0.769 for weight). Similarly, the distribution of the affected side and types of brain issues (hematencephalon or cerebral infarction) did not differ significantly between the groups.

Table 1 Comparison of demographic and physical characteristics among groups

	WBV	CG	*p*-value
Numbers	17	18	-
Male/female	9/8	11/7	0.738
Age (yrs)	58.9 ± 9.74	54.17 ± 10.842	0.838
Height (cm)	167.4 ± 7.32	166.7 ± 7.31	0.931
Weight (kg)	66.0 ± 8.75	65.9 ± 8.94	0.769
Affected side (L/R)	7/10	10/8	0.505
Course of the disease (M)	15.2 ± 6.41	13.9 ± 7.73	0.443
Hematencephalon/cerebral infarction	5/12	6/12	0.808

WBV Whole-body vibration, *CG* Control group, *L* Left, *R* Right, *M* Month. Mean ± standard deviation

In terms of the course of the disease (the time from stroke onset to the start of the intervention), participants in both groups were predominantly in the chronic stage of stroke recovery (more than 6 months post-stroke). The WBV group had a mean disease course of 15.2 ± 6.41 months, while the control group had a mean disease course of 13.9 ± 7.73 months. The difference between the groups was nonsignificant ($p = 0.443$), indicating comparable timeframes since stroke onset. As such, any differences in treatment outcomes can be attributed to the intervention rather than differences in the time from stroke onset.

Effect of WBV on dorsiflexion-plantar flexion and inversion-eversion performances

Having established the demographic equivalence of our study groups, we next evaluated the impact of WBV on specific rehabilitation outcomes, focusing on ankle joint proprioception and balance. Our scrutiny of the balance recovery potential of WBV, as compared to traditional therapies, revealed parity between the treatments. Statistical analyses showed no significant superiority of WBV over the control in enhancing balance post-stroke, with *p*-values exceeding the threshold for significance (BBS-treatment $p = 0.422$, FRT-treatment $p = 0.154$, RTL-treatment $p = 0.114$, RTA-treatment $p = 0.155$), suggesting equivalent efficacy between the two approaches.

In contrast to the balance parameters, the WBV group showed statistically significant improvements in parameters related to ankle joint proprioception compared to the control group following the four-week treatment period. Specifically, both the frequency and percentage improvements in DP performance yielded a *p*-value < 0.001, underlining a robust response to the WBV therapy that significantly surpasses conventional intervention outcomes (Fig. 2a). Likewise, IE performance enhancements were noted with a *p*-value of 0.012, underscoring the potential of the WBV therapy to effectively boost lower limb motor functions, crucial for restoring proprioception (Fig. 2b).

Furthermore, the effect sizes (Cohen's d) for the proprioception outcomes were calculated to be 1.74 for

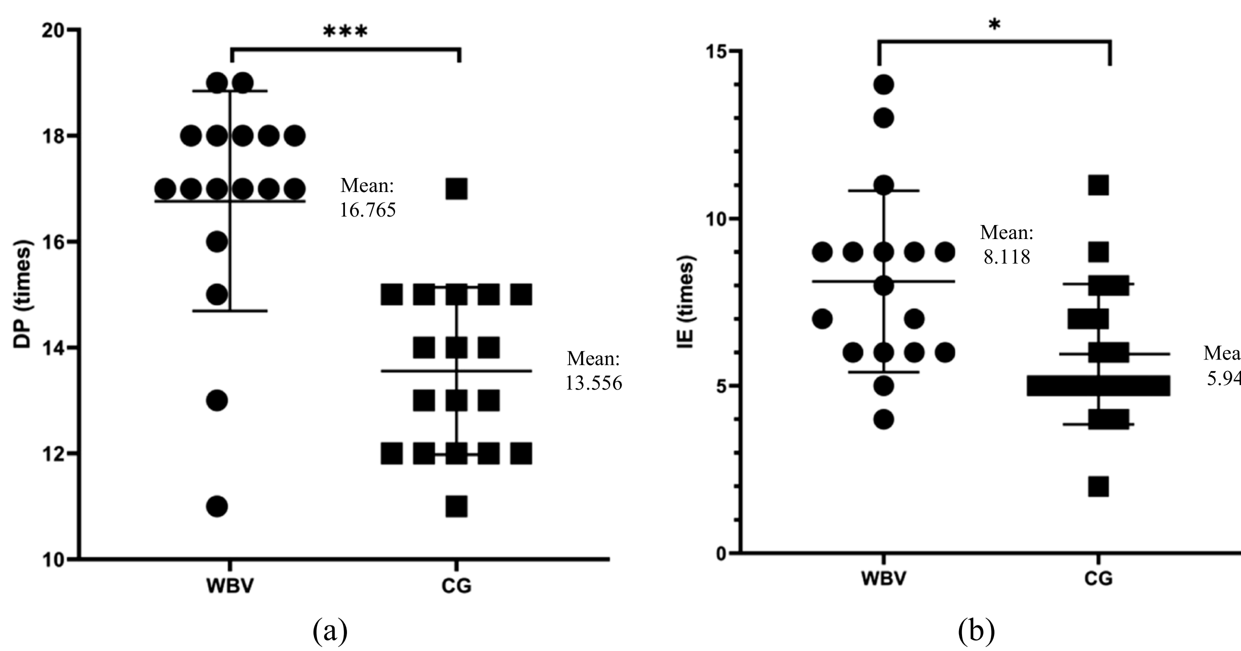

Fig. 2 Performances of DP (**a**) and IE (**b**) between two groups (taking times as an example). WBV: whole-body vibration; CG: control group; DP: dorsiflexion-plantar flexion; IE: inversion-eversion

DP and 0.90 for IE, indicating large and moderate-to-large effects, respectively. These effect sizes further emphasize the clinical significance of WBV in enhancing ankle joint proprioception in stroke patients.

Our analytical approach began with the Shapiro–Wilk normality test to determine the data distribution properties, guiding our selection of appropriate statistical tests. For data sets confirming normal distribution, including BBS, FRT, RTL, and RTA, we applied independent samples t-tests to compare means between the WBV and control groups. This method proved suitable for these data, confirming equal variances through Levene's tests. In contrast, for data sets like DP treatment and IE at baseline, which did not follow a normal distribution (p-values less than 0.05), we utilized the Mann–Whitney U test. This non-parametric test is ideal for comparing median differences when data lack normality.

The methodological rigor of employing both parametric and non-parametric tests based on the data distribution properties enhances the reliability and validity of our findings. Such detailed attention to statistical methods not only fortifies the integrity of our results but also enriches our understanding of WBV's therapeutic efficacy on physical performance outcomes.

Correlation patterns between DP and IE times post-treatment

To further understand the influence of WBV on specific rehabilitation outcomes, we conducted a correlation analysis between DP (times) and IE (times) following treatment (Fig. 3). In the control group, the Pearson correlation coefficient (r) was 0.6659, indicating a moderate to strong positive correlation between DP and IE times after treatment. This suggests that improvements in DP are associated with similar improvements in IE within this group.

Conversely, the WBV group exhibited distinctly different correlation dynamics. Here, due to the non-normal distribution of DP times post-treatment, the Spearman's rank correlation coefficient (r) was -0.1198, indicating a very weak negative relationship between DP and IE times. This stark contrast in correlation patterns between the groups highlights the differential impacts of the WBV treatment compared to the control, suggesting that WBV may influence the coordination between these two types of movements differently.

Variations in balance functions and ankle joint proprioception from baseline to post-treatment

Upon analyzing the intra-group changes from baseline to post-treatment, as expected, our data indicate significant

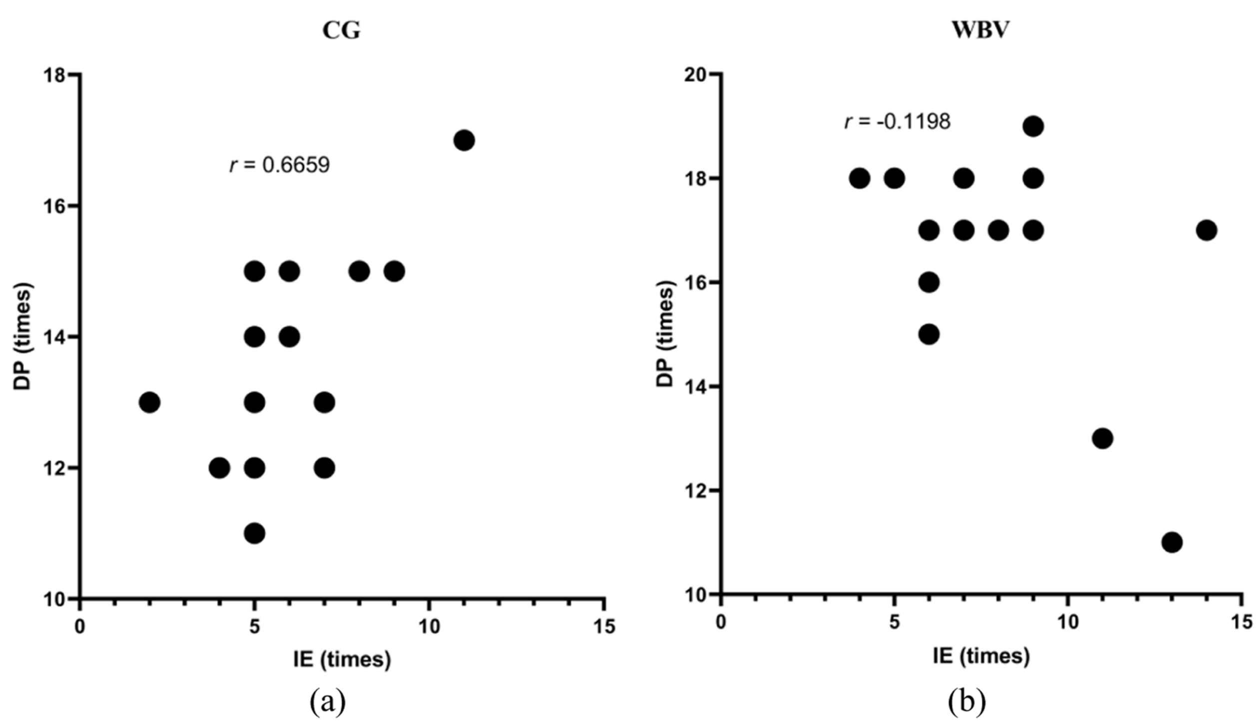

Fig. 3 Correlation between DP (times) and IE (times) post-treatment in (**a**) CG and (**b**) WBV groups. WBV: whole-body vibration; CG: control group; DP: dorsiflexion-plantar flexion; IE: inversion-eversion

enhancements in key measures associated with balance and ankle joint proprioception. Specifically, the metrics derived from the BBS, FRT, RTL, RTA, and assessments of DP and IE demonstrated uniform improvement, as evidenced by uniform p-values < 0.001 within both the WBV and CG groups (Fig. 4).

As presented in Fig. 4(a), in the WBV group, there was a significant increase in the BBS scores, indicating a notable enhancement in balance. The FRT results followed suit, with a marked increase pointing to improved reach stability. Additionally, both the RTL and RTA scores decreased, suggesting better control and stability during standing (Fig. 4b). When evaluating the ankle joint proprioception, significant improvements were found in DP and IE metrics both in times and percentage. Similarly, the CG group showed remarkable improvements in the BBS, FRT, RTL, RTA, DP, and IE assessments, as demonstrated in Fig. 4(c) and (d).

The statistical significance of these intra-group improvements was determined using appropriate statistical methods tailored to the data distribution properties of each measure. For datasets exhibiting a normal distribution, paired-sample t-tests were conducted, consistently revealing p-values < 0.001, indicative of highly significant improvements post-treatment. In instances where normal distribution criteria were not met, the Wilcoxon signed-rank test was employed. This non-parametric test further validated the significant enhancements within both groups in terms of DP and IE measures post-treatment, with all comparisons yielding p-values < 0.001.

Multiple linear regression analysis of WBV impact on ankle joint proprioception

To further investigate the specific contributions of the WBV therapy to improvements in ankle joint proprioception, a multiple linear regression analysis was performed. This statistical approach was also utilized to discern the influence of WBV against a backdrop of various other potential influencing factors.

The analysis considered DP and IE performance improvements as outcomes. Independent variables included demographic data (age and gender), physical characteristics (height and weight), clinical information (affected side, course of the disease, and brain disease type), and group allocation (WBV or CG).

The model's R^2 values indicated moderate to substantial explanatory power, accounting for 53.8% of the variation in DP performance and 27.7% for IE performance (taking DP-treatment (%) and IE-treatment (%) as examples, as shown in Tables 2 and 3). The regression analysis revealed significant differences in the independent variable of Group based on the intervention of WBV treatment. Compared to individuals without the intervention of WBV treatment (control group), those with the WBV intervention demonstrated an increase in DP performance (B = 15.7, SE = 3.37, t = 4.7, p < 0.001). Similarly, possessing WBV intervention was associated with an additional increase in IE performance (B = 9.8, SE = 4.54, t = 2.2, p = 0.041), suggesting that the WBV treatments are significantly associated with changes in DP and IE performances, controlling for other factors. The statistical insignificance of other variables consolidates the argument that the improvements were not confounded by demographic or clinical factors. This methodical investigation substantiates the positive impact of the WBV therapy on post-stroke recovery of ankle joint performance, enhancing the understanding of its role in rehabilitation programs.

Discussion

In this four-week prospective cohort study, we assessed the effectiveness of WBV therapy on balance functions and proprioception in stroke patients. The intra-group analysis revealed significant improvements in BBS, FRT, RTL, RTA, DP, and IE for both the WBV and control groups, confirming the overall efficacy of the rehabilitation protocols used. However, inter-group comparisons revealed that WBV did not confer additional benefits over the control treatment in enhancing balance recovery parameters (BBS, FRT, RTL, and RTA). These findings suggest that while WBV is as effective as conventional therapy in improving general proprioceptive and balance metrics post-stroke, it does not outperform traditional methods in specifically augmenting balance capabilities. This underscores the need for a nuanced understanding of WBV's role in stroke rehabilitation, particularly in relation to optimizing proprioceptive outcomes without necessarily enhancing balance recovery beyond that of standard rehabilitation practices.

Our study's findings that WBV did not significantly enhance balance functions beyond the improvements observed with conventional therapies are consistent with previous research. Several factors could account for these results. Firstly, biomechanism. WBV training induces muscle contractions and enhances motor neuron activation through a vibrating platform. However, this neuromuscular stimulation may primarily benefit proprioception (such as ankle joint proprioception) rather than significantly impacting balance function [50, 51]. Secondly, external factors. Methodological differences across studies, such as the type and severity of stroke in participants and the WBV protocols used (e.g., changes in vibration frequency and amplitude), may lead to inconsistent results. Additionally, the lack of standardization, with no unified guidelines for WBV parameters, causes variations in vibration frequency, amplitude, mode, posture,

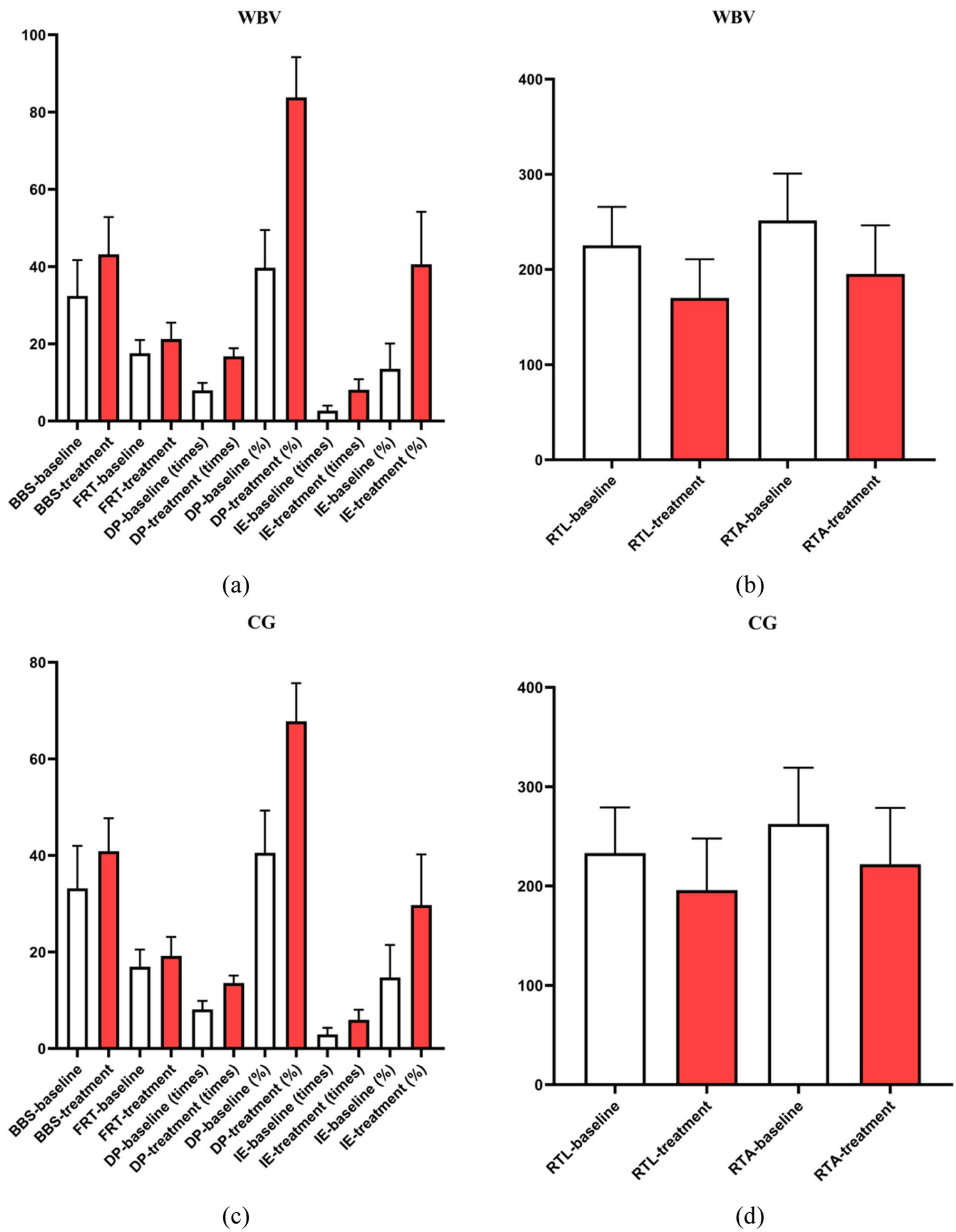

Fig. 4 Intra-group analyses of the WBV and CG groups. WBV: whole-body vibration; CG: control group; BBS: Berg balance scale; FRT: functional reach test; DP: dorsiflexion-plantar flexion; IE: inversion-eversion; RTL: Romberg test length; RTA: Romberg test area

Table 2 Multiple linear regression analysis for the dependent variable of DP-treatment (%)

Constant and variable	B (Unstandardized coefficient)	Standard error	*t*-statistic	Significance (*p*-value)
(Constant)	137.624	82.720	1.664	0.108
Group	15.707	3.368	4.663	0.000
Age	0.711	3.961	0.179	0.859
Gender	1.121	3.569	0.314	0.756
Height	-0.783	0.697	-1.124	0.271
Weight	0.873	0.584	1.495	0.147
Course of the disease	0.122	0.259	0.470	0.642
Affected side	-6.764	4.395	-1.539	0.136
Brain disease type	1.948	1.826	1.067	0.296

Table 3 Multiple linear regression analysis for the dependent variable of IE-treatment (%)

Constant and variable	B (Unstandardized coefficient)	Standard error	*t*-statistic	Significance (*p*-value)
(Constant)	-1483.229	111.536	-1.329	0.195
Group	9.750	4.542	2.147	0.041
Age	1.269	5.341	0.238	0.814
Gender	0.629	4.813	0.131	0.897
Height	1.426	0.940	1.517	0.141
Weight	-0.889	0.788	-1.129	0.269
Course of the disease	0.072	0.349	0.207	0.838
Affected side	2.932	5.926	0.495	0.625
Brain disease type	-2.046	2.462	-0.831	0.413

and training frequency, which can affect outcomes. Furthermore, differences in study design, including the size and diversity of the sample population and the length of follow-up periods, can influence the evaluation of WBV's effects on balance recovery. Lastly, other factors. Stroke patients may show significant individual differences when receiving WBV training, depending on their age, stroke severity, and other comorbidities.

Specifically, meta-analyses conducted by Yang et al. [27] and Lu et al. [52] have similarly reported that WBV training does not substantially enhance balance or walking functions in stroke patients. Furthermore, Park et al. [53] observed only small effect sizes for balance and gait functions in stroke patients following WBV interventions, indicating limited benefits. Yang and Butler [54] suggested that any improvements in balance and mobility from controlled WBV training are temporary, highlighting the necessity for extended follow-up periods to ascertain lasting effects. Conversely, other studies have identified positive contributions of WBV to the recovery of balance and walking functions in stroke patients [25, 55]. This apparent contradiction in findings may stem from methodological differences, such as the types and severity of stroke among study participants, as well as variations in the WBV protocols employed. To resolve these discrepancies, further research with larger, more diverse samples and standardized WBV protocols is imperative. Such studies should aim to clarify the conditions under which WBV is most beneficial and explore the longevity of its therapeutic effects.

In our investigation of ankle joint proprioception, significant improvements in DP and IE were observed in the WBV group post-treatment, confirming part of our hypothesis that WBV can enhance ankle proprioception. These findings are in alignment with previous research by authors in references [56, 57], which also reported enhancements in proprioceptive capabilities following WBV. Conversely, Martínez et al. [58] found that six weeks of WBV training did not improve the reflex response of the ankle's lateral stabilizing muscles, suggesting that the effects of WBV might be specific to certain aspects of proprioceptive function. Additionally, Lu et al. [59] reported that although WBV and conventional training both benefitted patients with unilateral functional ankle instability (FAI), WBV did not provide superior results. This discrepancy highlights the need for further exploration into the variable impacts of WBV on different elements of ankle proprioception, necessitating more comprehensive studies to discern the precise modalities and mechanisms through which WBV training can be most beneficial.

WBV training employs an innovative neuromuscular technique that leverages vibrations from a platform to induce muscle contractions and enhance motor neuron activation through the stimulation of muscle spindles [50, 51]. The effectiveness of WBV training is largely determined by variables such as vibration frequency, amplitude, pattern, posture, and training frequency, yet there is currently no standardized guideline for these parameters [60]. In this study, vibration frequencies were set between 10–20 Hz with amplitudes of 4.00 to 6.00 mm, considering patient safety and existing literature that suggests frequencies of 20–45 Hz are optimal for enhancing muscle activity, while lower frequencies are more suited for muscle relaxation [21, 61, 62].

The chosen horizontal vibration mode is particularly effective for weight-shifting exercises and sensory stimulation, aligning with findings from Lee et al. [63] on the benefits of this mode. WBV training enhances proprioception through several mechanisms: direct stimulation of plantar proprioceptors increases sensory input and nerve excitability; repetitive joint movements enhance ligament and tendon excitability; and vibrations transmitted to the brain potentially stimulate central nervous system remodeling and nerve regeneration [64–66].

Proprioceptive deficits post-stroke can severely impact ADL and prognosis, yet research often overlooks proprioception in favor of motor function [67–69]. The ankle joint, crucial for balance and proprioceptive feedback, is particularly affected in stroke survivors who commonly exhibit stiffness and sensory loss [70]. WBV stimulates the tonic vibration reflex, enhancing proprioceptive acuity through increased motor neuron excitability and improved synchronization of motor units [71].

The clinical implications of our findings indicate that incorporating WBV therapy into routine stroke rehabilitation protocols could be advantageous, especially for enhancing proprioceptive functions without requiring additional or specialized equipment. Although WBV does not outperform conventional therapies in improving balance recovery, its equivalent effectiveness provides a valuable alternative, particularly in situations where traditional balance training methods are limited or require supplementation. For instance, WBV could be integrated into early-stage rehabilitation programs to exploit its proprioceptive benefits, which are crucial during the initial recovery phases when patients are regaining basic motor functions and sensory feedback mechanisms. Moreover, the ease of implementing WBV sessions and the minimal training required to operate such systems make it a practical choice for rehabilitation centers aiming to enhance therapeutic outcomes efficiently. Given the safety profile and overall efficacy demonstrated in our study, routine application of WBV in clinical settings could potentially expedite recovery times, enhance patient outcomes, and lessen the long-term care burdens commonly associated with stroke rehabilitation.

Future research should focus on elucidating the specific conditions under which WBV training yields the most significant benefits for stroke rehabilitation. Considering the variability in responses observed in this and previous studies, further research is necessary to identify the optimal vibration frequencies, amplitudes, and session durations for different stages of stroke recovery. Comparative studies that evaluate WBV against emerging neurorehabilitation technologies, such as robotic-assisted therapy and virtual reality, could also offer deeper insights into the relative effectiveness of these modalities. Additionally, longitudinal studies with larger, more diverse randomized controlled trials (RCTs) are essential to assess the long-term effects of WBV on functional recovery and quality of life in stroke survivors. Such studies should incorporate detailed analyses of patient-specific variables, including age, stroke severity, and pre-existing comorbidities, to better understand how these factors influence the efficacy of WBV training. Ultimately, this research will aid in developing personalized rehabilitation protocols that optimize recovery trajectories and functional outcomes for stroke patients.

Conclusions

This study demonstrates that while WBV therapy is as effective as conventional treatments in enhancing general proprioception and balance in stroke patients, it does not show superior efficacy in specifically improving balance recovery. Our findings confirmed that WBV is equally effective in promoting proprioceptive enhancements, as evidenced by significant improvements in DP and IE parameters in the WBV group compared to the control group. However, for balance recovery, measured through BBS, FRT, RTL, and RTA, WBV did not outperform traditional rehabilitation methods. These results underscore the potential of WBV as a valuable component of comprehensive stroke rehabilitation protocols, particularly for enhancing proprioceptive functions. Future research should explore the optimal conditions and protocols for WBV application to ensure maximum recovery outcomes across diverse patient demographics and stroke severities. Larger, methodologically robust studies will be crucial in defining WBV's role in stroke rehabilitation and potentially extending its application to other areas of neurological recovery.

Abbreviations

WBV	Whole-body vibration
BBS	Berg balance scale
FRT	Functional reach test
RTL	Romberg test length
RTA	Romberg test area
DP	Dorsiflexion-plantar flexion
IE	Inversion-eversion
MMSE	Mini-mental state examination
MAS	Modified Ashworth scale
IPC	Intermittent pneumatic compression
ADL	Activities of daily living
ICC	Intraclass correlation coefficient
COP	Center of pressure
SD	Standard deviation
CG	Control group
FAI	Functional ankle instability
RCT	Randomized controlled trial

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
All authors contributed to the study conception and design. PX, JS, WF, YZ, and YG: Material preparation, data collection and analysis. PX, CN, MW, and JM: Initial draft. All authors commented on previous versions of the manuscript. All authors read and approved the final version of the manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the First Affiliated Hospital of the University of Science and Technology of China (IRB, Institutional Review Board, 2022-ky403). Informed consent was obtained from all subjects involved in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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