Original Paper

A mHealth-Based Vestibular Rehabilitation Program for Postoperative Vestibular Dysfunction in Patients With Vestibular Schwannoma: Randomized Controlled Trial

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Abstract

Background: Patients with vestibular schwannoma often experience postoperative vestibular dysfunction, including vertigo, dizziness, and imbalance, which severely impair daily functioning and quality of life. Effective and accessible rehabilitation strategies are needed to improve recovery after surgery.

Objective: This study aimed to evaluate the effectiveness of a mobile health–based vestibular rehabilitation program in improving postoperative vestibular outcomes after unilateral vestibular schwannoma surgery.

Methods: A prospective randomized controlled trial comparing a customized mobile app–based vestibular rehabilitation program with standard face-to-face vestibular rehabilitation was conducted at the Otology Center, Eye & ENT Hospital, Fudan University, from October 2023 to May 2025. A total of 60 patients undergoing unilateral vestibular schwannoma surgery were enrolled and randomly assigned to either an intervention group (n=30) or a control group (n=30). Both groups received a 90-day vestibular rehabilitation program. The intervention group received guidance, symptom recording, and adherence monitoring through a customized mobile app, whereas the control group received face-to-face guidance. The primary outcome was the between-group difference in the change in Dizziness Handicap Inventory (DHI) score from baseline (preoperative) to postoperative day 90. Secondary outcomes included visual analog scale scores for vestibular symptoms and the incidence of vertigo, dizziness, vestibulo-visual symptoms, and postural symptoms.

Results: Of the 60 randomized participants, 52 (86.7%) had DHI scores available at postoperative day 90, and 49 (81.7%) had paired baseline and day-90 DHI scores available to calculate the primary outcome. The adjusted between-group difference in DHI change from baseline to postoperative day 90 was not significant (adjusted mean difference −0.83, 95% CI −8.79 to 7.13; *P*=.84). No significant differences were observed in visual analog scale scores at postoperative days 7, 30, or 90 (all *P*>.05). Among the assessed vestibular symptoms, postural symptoms on postoperative day 7 were reported by 53.3% (16/30) of the intervention group and 83.3% (25/30) of the control group; the difference was not significant after Holm adjustment (unadjusted *P*=.03; Holm-adjusted *P*=.30).

Conclusions: In conclusion, mobile health–based rehabilitation did not demonstrate greater improvement in postoperative vestibular outcomes than face-to-face rehabilitation following unilateral vestibular schwannoma surgery. The lower proportion of patients reporting postural symptoms on postoperative day 7 remains an exploratory finding requiring confirmation in future studies.

Trial Registration: Chinese Clinical Trial Registry ChiCTR2200056123; https://www.chictr.org.cn/showproj.html?proj=150939

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KEYWORDS

vestibular schwannoma; mobile health; vestibular rehabilitation; randomized controlled trial; artificial intelligence; AI

Introduction

Vestibular schwannoma (VS), previously termed acoustic neuroma, is a benign intracranial tumor arising from Schwann cells on the vestibulocochlear nerve [1], accounting for 6% to 7% of intracranial tumors [2,3]. Most cases are idiopathic and unilateral, with prominent clinical manifestations, including vertigo, defined as a false sensation of self-motion or environmental motion, imbalance, unilateral sensorineural hearing loss, and tinnitus [4,5]. Due to its slow progression, surveillance is the primary initial strategy [6], with radiotherapy or surgery reserved for cases with tumor growth [7]. Following VS surgery, patients may develop acute vestibular dysfunction. Postoperatively, 21% to 28% of patients report vertigo and 58% to 75% experience imbalance [4,8], with symptoms persisting for more than 1 month in up to 30% of cases [9]. Vestibular dysfunction, particularly vertigo, has been identified as the primary factor affecting quality of life [7]. These symptoms severely compromise patients' daily activities and mobility, frequently leading to difficulties with driving and work and limitations in social interactions, and they may precipitate psychological distress [4]. In severe instances, debilitating vertigo may result in job loss or fall-related injuries, imposing substantial economic burdens on both families and society [10-13].

Vestibular rehabilitation has been proven to effectively alleviate symptoms of vestibular dysfunction [14,15]. Previous studies have demonstrated that vestibular rehabilitation provides additional benefits compared with no intervention or usual care, improving vestibular symptoms and functional outcomes [14]. However, its efficacy in patients after VS surgery, particularly in facilitating recovery after acute unilateral vestibular loss, remains unclear [16]. Current vestibular rehabilitation programs include gaze stabilization, habituation exercises, balance and gait training, and endurance walking [14,17], with multimodal approaches potentially offering superior outcomes [18]. Despite its established efficacy, traditional face-to-face delivery of vestibular rehabilitation remains limited by multiple systemic barriers. The uneven distribution of specialized facilities and trained therapists limits access to vestibular rehabilitation [18], with only 25.5% of eligible patients receiving any rehabilitation session and merely 15.2% completing the full course of treatment [19,20]. Exercise-induced dizziness may hinder adherence to vestibular rehabilitation [21]. Mobile health (mHealth) interventions may help overcome these barriers by providing video-based exercise instructions and remote guidance, thereby improving access to rehabilitation and supporting patient engagement [22,23].

mHealth technologies enable the transmission of health-related data via smartphones or tablets to clinical teams for remote home monitoring, thereby enhancing health care delivery [22]. A 2018 report estimated that more than 325,000 health-related apps were available in app stores [24], covering areas such as health promotion [25,26], disease prevention [27], and chronic disease management [28,29]. Many studies have demonstrated the positive impact of mHealth apps on health outcomes for patients with chronic diseases [24]. Previous studies have demonstrated that mobile app reminder notifications effectively improve treatment adherence [28]. Bao et al [29] found that mHealth-based health education and treatment supervision enhanced disease understanding and self-management initiatives of patients with tuberculosis. Zhu et al [30] demonstrated that a mobile app–based intervention incorporating video-based guidance and automated compliance monitoring improved adherence among patients with obstructive sleep apnea compared with traditional treatment. In addition, mHealth apps have demonstrated potential in remotely monitoring disease activity and supporting personalized management for patients with urticaria [31]. A systematic review of postoperative remote monitoring technologies demonstrated that mHealth-based remote monitoring enhances postoperative care and accelerates quality of life improvements [23]. Although previous studies suggest that mHealth interventions may benefit patients with other chronic conditions, evidence for interventions tailored to patients with VS remains limited. A preliminary study in Singapore confirmed the feasibility of mobile-based rehabilitation but was limited to English-speaking older adults and an Android-only platform, with a primary focus on exercise delivery rather than comprehensive patient management [32]. Another study demonstrated the feasibility and acceptability of a mobile health app, but evidence regarding its effectiveness in a broader vestibular rehabilitation population remains limited [33].

This study aimed to assess the effectiveness of an mHealth-based vestibular rehabilitation intervention designed for patients with vestibular dysfunction following VS surgery. The effectiveness of the intervention measure is determined by improvement in the Dizziness Handicap Inventory (DHI) score and the incidence and severity of vestibular symptoms. We hypothesized that the mHealth-based vestibular rehabilitation intervention could effectively improve health outcomes in patients after VS surgery.

Methods

Study Design

This study was conducted from October 2023 to May 2025 in Shanghai, China. During the 90-day intervention period, patients in the intervention group used the Vertigo Station app, jointly developed by the Eye & ENT Hospital of Fudan University and The Second People's Hospital of Shenzhen, Shenzhen, China, for vestibular rehabilitation, symptom self-reporting, and exercise logging. The control group received face-to-face guidance, used paper diaries to record training data, and was provided with a handbook containing information on vestibular rehabilitation. Assessments were conducted at baseline (preoperatively) and on postoperative days 7, 30, and 90 by trained raters blinded to group allocation. At admission,

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demographic and clinical data were collected from medical records and through patient and family interviews. Vestibular symptoms and visual analog scale (VAS) scores were recorded on postoperative day 7 (in the ward) and on days 30 and 90 (at the vertigo clinic). DHI was measured preoperatively and on postoperative days 30 and 90. The CONSORT-EHEALTH (Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth) checklist is provided in Multimedia Appendix 1.

Ethical Considerations

This study was conducted in accordance with Good Clinical Practice and the Declaration of Helsinki. The trial protocol (2021-2021071-1) was approved by the Ethics Committee of the Eye & ENT Hospital of Fudan University in April 2021, and subsequent amendments were approved by the same committee and registered on the Chinese Clinical Trial Registry (ChiCTR2200056123). Informed consent was obtained from all study participants.

Participants and Procedure

The patients were recruited from the Eye & ENT Hospital of Fudan University (Shanghai, China). All participants underwent tumor resection via the retrosigmoid approach by the same lead surgeon. Eligible participants were aged 18 to 70 years, diagnosed with unilateral VS confirmed by contrast-enhanced magnetic resonance imaging, scheduled to undergo tumor resection surgery, and had provided written informed consent. Participants were excluded if they met any of the following: neuromuscular diseases affecting motor function or balance disorders due to other causes, head or neck movement restrictions or required immobilization, history of radiotherapy or surgery for intracranial lesions, or severe organ dysfunction. Eligible patients were sent recruitment invitations directly by the researchers upon admission. Eligible participants were randomly assigned to the intervention group (Vertigo Station app; n=30) or the control group (face-to-face guidance; n=30) in an equal ratio of 1:1 according to a software-generated random number sequence.

Sample Size Calculation

The sample size was calculated based on the between-group difference in change in DHI score from baseline to postoperative day 90. An expected between-group difference of 18 points was assumed based on previously reported minimal clinically important differences for the DHI [34]. The SD of the change in DHI score from baseline to postoperative day 90 was estimated from a previous randomized vestibular rehabilitation study using the reported mean changes and CIs, yielding an estimated SD of 20.1 points [35]. Assuming a 2-sided α level of .05, 80% power, and a 1:1 allocation ratio using a 2-sample comparison of means framework, 20 participants per group were required. To account for potential attrition and improve the precision of treatment effect estimates, the target sample size was increased to 30 participants per group (total N=60).

Randomization and Masking

Before surgery, participants were randomly assigned in a 1:1 ratio to the intervention or control group using a computer-generated sequence prepared by a researcher independent of recruitment and clinical management. Allocation was concealed using sequentially numbered, opaque, sealed envelopes, opened in order after enrollment. Outcome assessors were not involved in intervention delivery and were blinded to group allocation. Participants were instructed not to disclose their allocation during assessments.

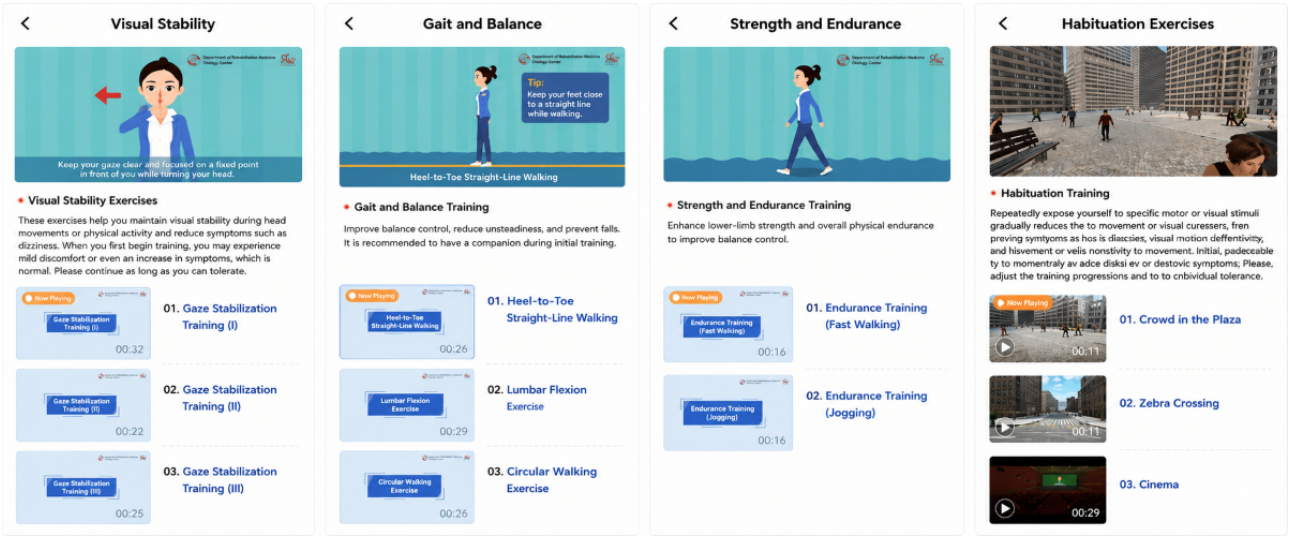
Intervention

Intervention Group

Patients in the intervention group received a 90-day mHealth-based vestibular rehabilitation program through the Vertigo Station app (version 1.3.0; Eye & ENT Hospital of Fudan University and Shenzhen Second People's Hospital), with daily 10- to 20-minute sessions. In addition to exercise guidance, the program included reminders, symptom tracking, physician consultation, a patient community, and a points-based reward system. The initial session was supervised by a trained therapist (PW). Following current vestibular rehabilitation guidelines, the protocol comprised 4 components: visual stability exercises, gait and balance training, strength and endurance exercises, and habituation exercises (Figure 1).

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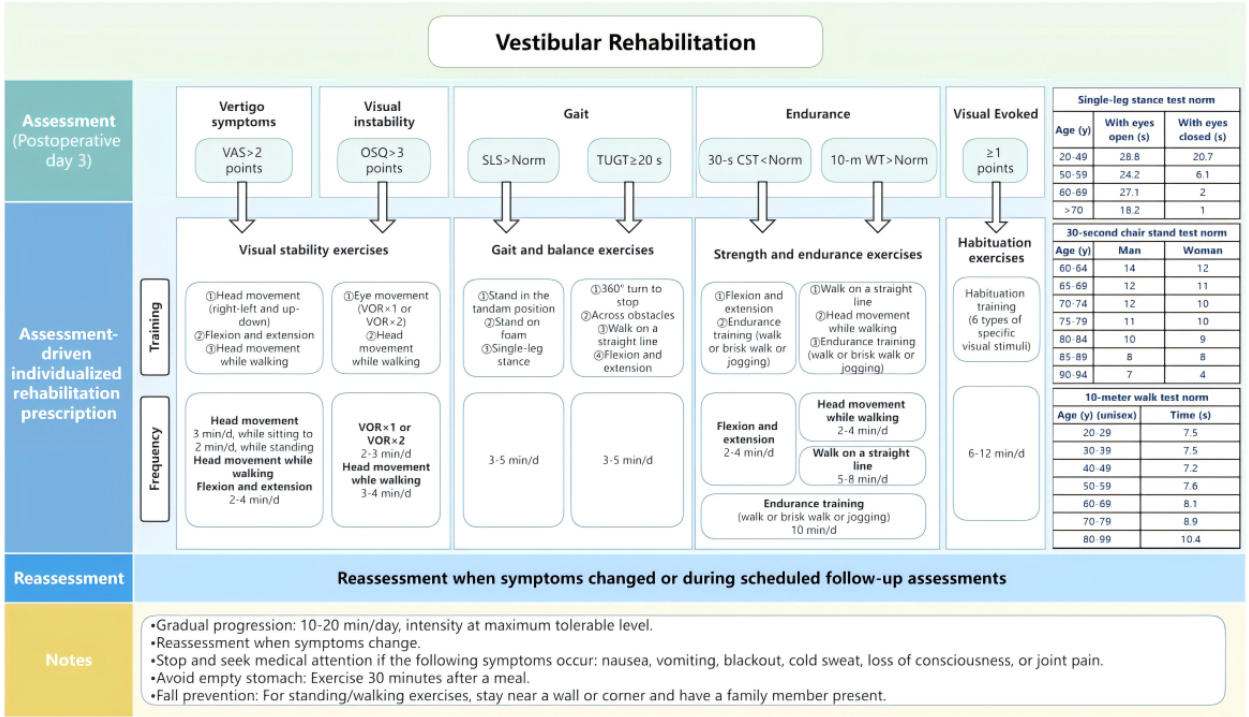
Figure 1. Screenshots of the Vertigo Station app. The app includes 4 rehabilitation modules: Visual Stability, Gait and Balance, Strength and Endurance, and Habituation Exercises. The app interface shown in the figure was translated into English for publication. The original-language interface is provided in Multimedia Appendix 2.



Intervention Workflow

Vestibular rehabilitation was initiated on postoperative day 3 when clinically appropriate and followed four steps (Figure 2): (1) assessment, in which vestibular symptoms and functional performance were evaluated through the app; (2) individualized planning, in which the app automatically generated an individualized rehabilitation plan using predefined rules based on symptom scores, functional test results, and age-specific reference values, and exercise duration and difficulty followed a predefined progression schedule; (3) exercise execution, in which patients performed the prescribed exercises and recorded completion through daily app check-ins; and (4) monitoring and reassessment, in which symptoms and rehabilitation progress were recorded. Reassessments were conducted at scheduled follow-up visits, including postoperative days 30 and 90, or when symptoms changed, and the app regenerated the individualized plan using the updated assessment results. Details of the individualized exercise program are provided in Multimedia Appendix 3.

Figure 2. Workflow of the mobile health–based individualized vestibular rehabilitation intervention. 10m WT: 10-m walk test; 30s CST: 30-second chair stand test; OSQ: Oscillopsia Severity Questionnaire; SLS: single-leg stance; TUGT: timed up and go test; VAS: visual analog scale; VOR: vestibulo-ocular reflex.

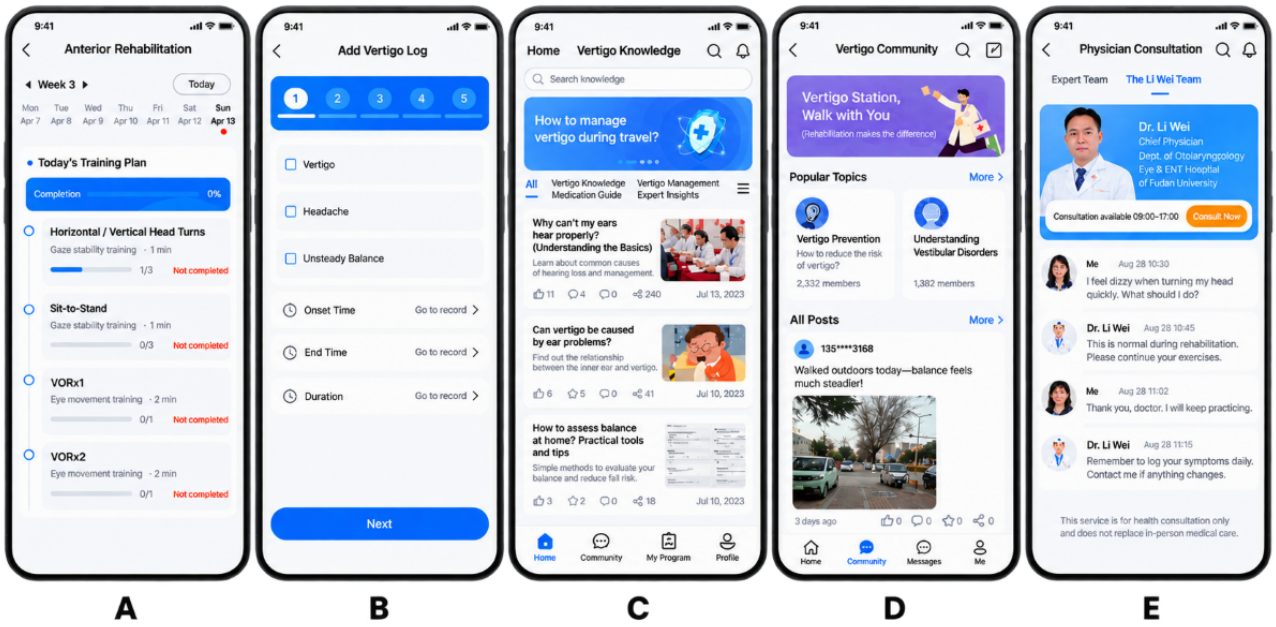


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App Functional Modules

The Vertigo Station app comprised five modules (Figure 3): (1) Vestibular Rehabilitation (Figure 3A), providing assessments, exercise instructions, individualized rehabilitation plans, and reassessment; (2) Vertigo Log (Figure 3B), for symptom recording; (3) Vertigo Knowledge (Figure 3C), providing educational materials; (4) Vertigo Community (Figure 3D), supporting patient interaction; and (5) Physician Consultation (Figure 3E), enabling remote communication with clinicians. The original-language user interface of the mobile app is presented in Multimedia Appendix 2.

Figure 3. Main functional modules of the Vertigo Station app: (A) Vestibular Rehabilitation, (B) Vertigo Log, (C) Vertigo Knowledge, (D) Vertigo Community, and (E) Physician Consultation.



Control Group

The control group also initiated the same vestibular rehabilitation protocol on postoperative day 3. Participants received face-to-face assessments and guidance from trained therapists and nurses. After discharge, participants received face-to-face guidance on postoperative days 30 and 90, with rehabilitation plans reviewed and adjusted as needed. The exercise components, training frequency, and duration were identical to those of the intervention group. Participants recorded training data using paper diaries and received a standardized vestibular rehabilitation handbook. Follow-up schedules and outcome assessments were the same between groups.

Quality Control

Quality control strategies included standardized vestibular rehabilitation training for all researchers, administration of assessments by trained staff with at least 5 years of experience, intelligent reminders via the app, scheduled visits to minimize loss to follow-up, and regular team meetings to review progress.

Outcome Measures

Primary Outcome

The DHI is a 25-item questionnaire assessing self-perceived dizziness-related handicap across physical, functional, and emotional domains [34]. Responses are scored as yes (4), sometimes (2), or no (0), yielding a total score of 0 to 100. Higher scores indicate greater dizziness-related handicap.

The primary end point was the between-group difference in DHI change from preoperative baseline to postoperative day 90, calculated as day-90 minus baseline score. Positive values indicate worsening, and negative values indicate improvement.

Secondary Outcomes

Secondary outcomes were overall vestibular symptom severity and the proportions of patients reporting vertigo, dizziness, vestibulo-visual symptoms, and postural symptoms on postoperative days 7, 30, and 90. Each symptom was rated separately using a 10-cm VAS, with scores ranging from 0 to 10. The 4 ratings were averaged to obtain a composite VAS score for each participant at each assessment, with higher scores indicating greater overall symptom severity.

Adherence Assessment

Adherence was monitored over the 90-day intervention period. A day was considered adherent if greater than or equal to 80% of the prescribed exercise duration was completed, based on app logs in the intervention group and paper diaries in the control group.

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Safety

Safety outcomes were monitored throughout the 90-day intervention period. Adverse events related to vestibular rehabilitation were recorded.

Statistical Analyses

Analyses followed the intention-to-treat principle using R (version 4.5.2; R Foundation for Statistical Computing) [36]. Continuous variables were summarized as mean (SD) or median (IQR), and categorical variables were summarized as n/N (%). Missing data were multiply imputed using chained equations (*mice*; version 3.19.0) [37], generating 20 datasets with 50 iterations under a missing-at-random assumption. Predictive mean matching with 5 donors was used for continuous outcomes and logistic regression for binary symptoms. The DHI model included treatment group; age; continuous tumor size (mm); and baseline, day-30, and day-90 DHI scores; other models included treatment group and repeated measurements of the corresponding outcome. DHI changes were derived after imputation. Day-90 DHI change was analyzed using a post hoc analysis of covariance (ANCOVA) adjusted for baseline DHI, age, and tumor size, including all 60 participants. Estimates were pooled using the Rubin rules with Barnard-Rubin degrees of freedom. The same model fitted to complete cases served as a sensitivity analysis. Supplementary DHI and VAS comparisons used tie-corrected asymptotic Mann-Whitney *U* tests without covariate adjustment or continuity correction. For incomplete outcomes, squared standardized statistics were combined using the D_2 rule. Supplementary VAS mean differences and 95% CIs were obtained from separate unadjusted linear models and pooled using the Rubin rules. Fully observed binary outcomes used Fisher exact tests and log-risk ratio (RR) CIs; incomplete outcomes used Rubin-pooled log RRs and variances. Day-90 vertigo was descriptive only. Holm correction covered 3 additional DHI comparisons (day-30 DHI, day-90 DHI, and day-30 change), 3 VAS comparisons, and 12 symptom comparisons as separate families. The supplementary day-90 DHI-change comparison and all CIs were unadjusted for multiplicity. Tests were 2-sided, with $P<.05$ assessed after multiplicity adjustment where applicable.

Results

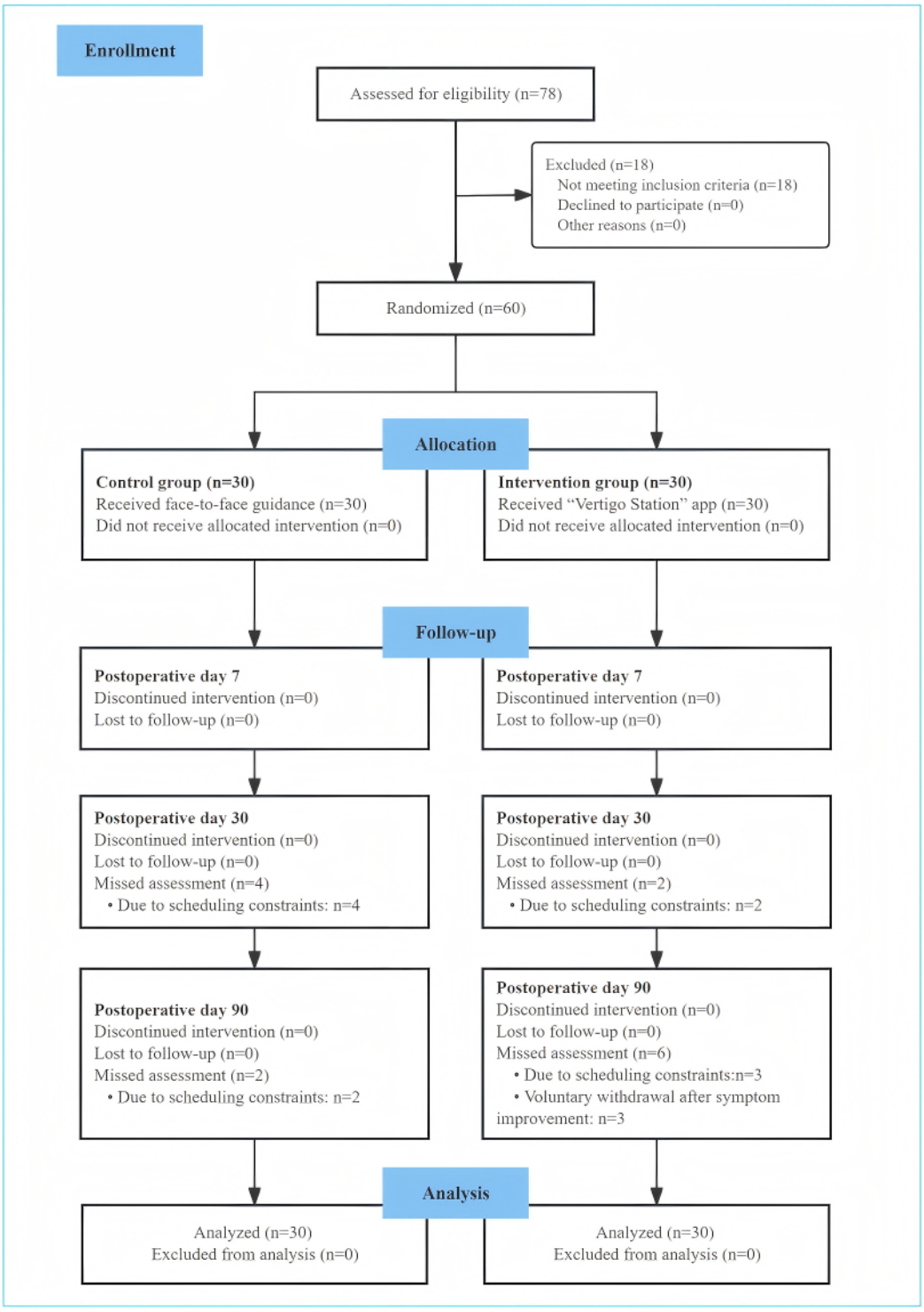
Participant Characteristics

A total of 78 patients were screened for eligibility, of whom 60 were enrolled and randomly assigned to the intervention group (n=30) or control group (n=30). The CONSORT (Consolidated Standards of Reporting Trials) flow diagram is presented in Figure 4. In the intervention group, 2 participants missed the 30-day assessment but completed the 90-day follow-up; 3 were unavailable at 90 days, and 3 withdrew after reporting symptom improvement. In the control group, 4 missed the 30-day assessment but completed the 90-day follow-up, and 2 were unable to attend the 90-day assessment due to scheduling conflicts. Of the 60 participants, 49 (81.7%) completed DHI assessments at both baseline and postoperative day 90, allowing calculation of the primary outcome. Outcome-specific observed and missing counts are provided in Multimedia Appendix 4.

Baseline demographic and clinical characteristics are summarized in Table 1. No significant differences were observed between groups in demographic characteristics or other clinical variables. However, tumor size showed a baseline imbalance between groups ($z=-2.629$; $P=.01$), with larger tumors observed in the control group. Therefore, tumor size, together with baseline DHI score and age, was included as a covariate in the adjusted primary analysis.

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Figure 4. CONSORT (Consolidated Standards of Reporting Trials) flowchart.



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Table 1. Basic participant characteristics of the 2 groups.

Characteristics	Control group (n=30)	Intervention group (n=30)	Test statistic	*P* value
Gender, n (%)			χ^2_1=2.424	.12
Female	17 (56.7)	10 (33.3)		
Male	13 (43.3)	20 (66.7)		
Age (years), mean (SD)	47.77 (11.06)	47.03 (9.97)	t_{58}=−0.27	.79
Education, n (%)			*z*=0.121	.90
Primary school or lower	1 (3.3)	0 (0.0)		
Junior high school	6 (20.0)	8 (26.7)		
High school	8 (26.7)	6 (20.0)		
College or higher	15 (50.0)	16 (53.3)		
Affected side, n (%)			χ^2_1=0.000	>.99
Left	15 (50.0)	14 (46.7)		
Right	15 (50.0)	16 (53.3)		
Pre-SOT[a], median (IQR)	75 (70-79)	77 (75-81)	*z*=1.503	.13
Pre-DHI[b], median (IQR)	4 (0-11)	2 (0-8)	*z*=−0.463	.64
Tumor size, n (%)			*z*=−2.629	.01
Small (≤15 mm)	7 (23.3)	17 (56.7)		
Middle (>15 to ≤30 mm)	20 (66.7)	12 (40.0)		
Large (>30 mm)	3 (10.0)	1 (3.3)		

[a]Pre-SOT: Preoperative Sensory Organization Test composite score.

[b]Pre-DHI: Preoperative Dizziness Handicap Inventory.

Primary Outcome

Exploratory Mann-Whitney *U* tests showed no significant between-group differences in DHI scores or changes from baseline at any assessment time point (all *P*>.05). The specific results are included in Multimedia Appendix 5.

Given the baseline imbalance in tumor size, a post hoc ANCOVA was conducted to adjust for baseline DHI score, age, and tumor size. The adjusted mean change in DHI score from baseline to postoperative day 90 was 8.19 (SE 2.79) in the control group and 7.37 (SE 2.87) in the intervention group. The adjusted analysis revealed no statistically significant between-group difference The adjusted mean difference, calculated as the intervention group minus the control group, was −0.83 (95% CI −8.79 to 7.13; *P*=.84). The complete-case sensitivity analysis yielded consistent results (adjusted mean difference −1.39, 95% CI −10.03 to 7.24; *P*=.75; n=49). The specific results are included in Multimedia Appendix 6.

Secondary Outcomes

No vestibular symptom comparison remained statistically significant after Holm correction (Table 2). The numbers of participants reporting postoperative vestibular-related symptoms during follow-up are shown in Figure 5. At postoperative day 7, postural symptoms were reported by 53.3% (16/30) of intervention participants and 83.3% (n=25) of control participants (RR 0.64, 95% CI 0.44-0.93; unadjusted *P*=.03; Holm-adjusted *P*=.30). No significant between-group differences were observed for other vestibular symptoms or assessment time points (all *P*>.05). VAS scores for vestibular symptoms are presented in Table 3. No significant between-group differences were observed at any postoperative assessment time point (all *P*>.05).

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Table 2. Comparison of vestibular symptom prevalence between 2 groups at postoperative time points.

Outcomes	Control group, n/N[a] (%)	Intervention group, n/N (%)	RR[b] (95% CI)[c]	*P* value	Holm-adjusted *P* value[d]
Vertigo					
T1[e]	2/30 (6.67)	2/30 (6.67)	1.00 (0.15-6.64)	>.99	>.99
T2[f]	0/30 (0.00)	1/30 (3.33)	—[g]	>.99	>.99
T3[h]	0/27 (0.00)	0/22 (0.00)	—	—[i]	—
Dizziness					
T1	22/30 (73.33)	22/30 (73.33)	1.00 (0.74-1.36)	>.99	>.99
T2	18/30 (60.00)	22/30 (73.33)	1.22 (0.85-1.76)	.41	>.99
T3	12/27 (44.44)	15/22 (68.18)	1.46 (0.87-2.46)	.15	>.99
Vestibulo-visual symptoms					
T1	19/30 (63.33)	14/30 (46.67)	0.74 (0.46-1.18)	.30	>.99
T2	13/30 (43.33)	13/30 (43.33)	1.00 (0.56-1.78)	>.99	>.99
T3	5/27 (18.52)	7/22 (31.82)	1.75 (0.62-4.97)	.28	>.99
Postural symptoms					
T1	25/30 (83.33)	16/30 (53.33)	0.64 (0.44-0.93)	.03[j]	.30
T2	14/29 (48.28)	17/29 (58.62)	1.23 (0.74-2.03)	.42	>.99
T3	15/26 (57.69)	10/22 (45.45)	0.74 (0.41-1.33)	.31	>.99

[a]Data are observed n/N (%), where n is the number reporting the symptom and N is the number assessed.

[b]RR: risk ratio.

[c]Analyses included 30 participants per group following multiple imputation, where applicable. RRs compare intervention with control. For outcomes with missing data, log RRs and their variances were pooled across 20 imputed datasets using the Rubin rules. Fully observed outcomes were analyzed using Fisher exact tests, with CIs calculated on the log-RR scale. All CIs are unadjusted for multiple comparisons.

[d]Holm adjustment covered 12 symptom comparisons.

[e]T1: postoperative day 7.

[f]T2: postoperative day 30.

[g]Not applicable. The data are not estimable because of 0 events in one or both groups.

[h]T3: postoperative day 90.

[i]Not estimated. Day-90 vertigo was reported descriptively and was neither imputed nor tested; $P>.99$ was used only to retain this comparison within the multiplicity correction family.

[j]$P<.05$ before multiplicity adjustment.

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Figure 5. Number of participants reporting postoperative vestibular-related symptoms during the follow-up period. *P<.05, unadjusted for multiple comparisons.

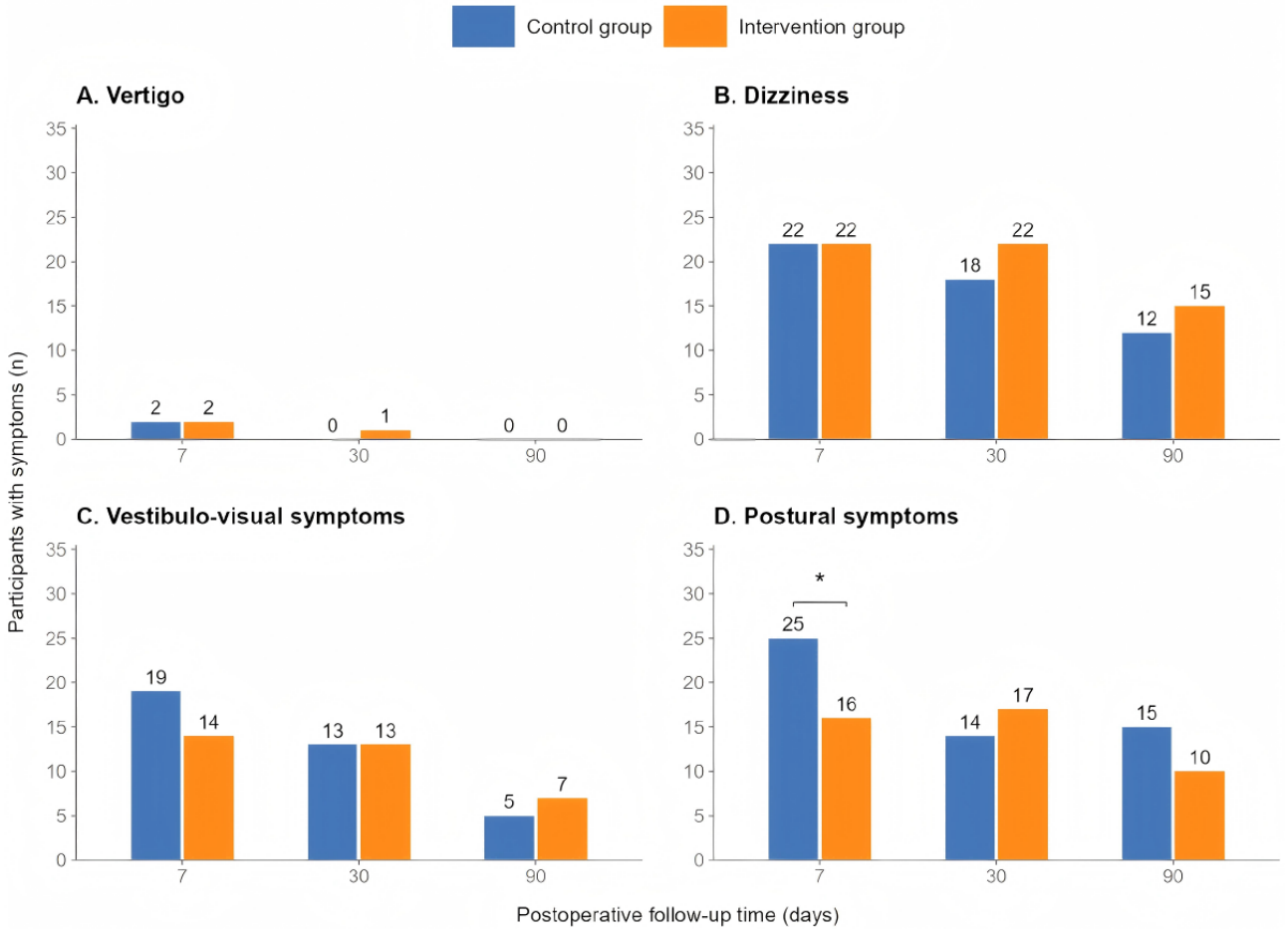


Table 3. Comparison of VAS[a] scores averaged across 4 vestibular symptoms between the 2 groups at different time points.

Postoperative day	Control (n=30), median (IQR)[b]	Intervention (n=30), median (IQR)[b]	Supplementary unadjusted mean difference (95% CI)[c]	Unadjusted P value[c]	Holm-adjusted P value[d]
7	3.00 (2.00-3.00)	3.00 (2.00-3.00)	−0.33 (−0.95 to 0.28)	.44	>.99
30	2.00 (0.00-3.00)	2.92 (2.00-3.00)	0.20 (−0.55 to 0.96)	.59	>.99
90	1.57 (0.00-3.00)	2.00 (0.00-2.64)	0.10 (−0.72 to 0.92)	.82	>.99

[a]VAS: visual analog scale.

[b]VAS scores are the average of 4 symptom-specific ratings. Each group included 30 participants in each of 20 imputed datasets. Descriptive values are the arithmetic averages of the within-dataset medians and first and third quartiles across imputations.

[c]Supplementary mean differences (intervention minus control) and 95% CIs were estimated using separate unadjusted linear models within each dataset and pooled using the Rubin rules with Barnard-Rubin degrees of freedom. CIs are unadjusted for multiple comparisons.

[d]P values are from separate 2-sided, tie-corrected asymptotic Mann-Whitney U tests without continuity correction. Day-7 data were complete; for days 30 and 90, squared standardized test statistics were combined using the D_2 rule. Holm adjustment covered the 3 time points.

Adherence

During the 90-day rehabilitation period, adherence was monitored using app logs in the intervention group and paper diaries in the control group. In the intervention group, median adherence rates were 70% (IQR 50%-85%), 60% (IQR 45%-75%), and 50% (IQR 40%-65%) during days 1 to 30, 31 to 60, and 61 to 90, respectively. The corresponding adherence rates in the control group were 85% (IQR 70%-95%), 80% (IQR 65%-90%), and 75% (IQR 60%-85%), respectively.

Safety

No adverse events related to the rehabilitation program were reported in either group during the 90-day follow-up period.

Discussion

Main Findings

This randomized controlled trial did not demonstrate superiority of mHealth-based vestibular rehabilitation over conventional face-to-face rehabilitation for the primary outcome of DHI

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change from baseline to postoperative day 90 following unilateral VS surgery. Although a lower proportion of intervention participants reported postural symptoms on day 7, this difference was not significant after Holm adjustment.

Several factors may have contributed to the absence of a significant between-group difference in the primary outcome at postoperative day 90. Functional recovery after unilateral vestibular loss is influenced by multiple factors, including central vestibular compensation, vestibular rehabilitation, and other contributing factors [38,39]. Importantly, randomized evidence has demonstrated that vestibular rehabilitation can improve dizziness-related symptoms and functional outcomes [35], suggesting that recovery during rehabilitation may not be attributable solely to spontaneous recovery over time. mHealth- and technology-assisted approaches have further been investigated as alternative modes of delivering vestibular rehabilitation [32,40,41]. In the present study, both groups received structured vestibular rehabilitation, including gaze stability exercises, habituation exercises, gait and balance training, and muscle strengthening and endurance exercises. Rehabilitation was initiated on postoperative day 3 in both groups, which may have facilitated early vestibular adaptation [42,43].

Because conventional face-to-face rehabilitation can promote functional recovery [14,20], the active control condition and early initiation of rehabilitation in both groups may have limited the observable additional benefit of the mHealth program on patient-reported functional outcomes at 90 days. Previous randomized studies have evaluated mHealth and other technology-assisted approaches as potential alternatives to conventional vestibular rehabilitation [38,44,45]. However, the mHealth intervention did not demonstrate superiority over face-to-face rehabilitation in the present study, and its effectiveness warrants further evaluation.

Although tumor size differed between groups at baseline, it was adjusted for, together with age and baseline DHI, in the ANCOVA model. The adjusted analysis showed no significant between-group difference in the primary outcome, suggesting that baseline tumor size imbalance was unlikely to fully account for the observed findings. The complete-case sensitivity analysis yielded results consistent with the primary analysis. Although baseline tumor size was smaller in the intervention group, a study of patients following VS resection found no significant association between tumor size and DHI scores [46]. In addition, measured baseline postural control performance, assessed using the Sensory Organization Test, was comparable between groups, suggesting that baseline functional status was broadly similar. Nevertheless, residual confounding from unmeasured factors, including individual variability in vestibular compensation and recovery capacity, cannot be completely excluded [38].

Regarding secondary outcomes, postural symptoms on postoperative day 7 were reported by 53.3% (16/30) of the intervention group and 83.3% (n=25) of the control group; the difference was not significant after Holm adjustment (unadjusted P=.03; Holm-adjusted P=.30). This exploratory finding should therefore be interpreted cautiously. In addition, vestibular symptom incidence was based on participant self-report, and differences in reporting patterns between groups cannot be excluded. Thus, it remains uncertain whether the observed day-7 difference reflects a true difference in symptom incidence. Early postoperative vestibular symptoms are common after VS surgery, and early participation in vestibular rehabilitation may facilitate vestibular compensation and functional recovery during this period [42,43]. Although mHealth-based rehabilitation may facilitate access to rehabilitation resources and provide timely rehabilitation support [28-30], the present study cannot determine whether these features contributed to the observed day-7 difference. Given the absence of superiority in the primary outcome, this exploratory finding requires confirmation in future adequately powered studies. No rehabilitation-related adverse events were reported during the 90-day study period, although the small sample limits conclusions about safety. The Vertigo Station app may facilitate home-based vestibular rehabilitation through personalized exercise guidance, video-based instruction, symptom monitoring, and rehabilitation tracking. These functions may support the delivery of more accessible and standardized rehabilitation programs, as suggested by previous mHealth-based rehabilitation studies [20,21,41,47]. Recorded adherence declined over time in both groups and was numerically lower in the mHealth group across all 3 periods, despite its reminders and rewards. These findings highlight the challenge of sustaining rehabilitation engagement and the need to identify barriers to participation and improve digital support.

Limitations

This study has several limitations. First, the small sample size and single-center design may limit generalizability, warranting larger multicenter studies. Second, low preoperative DHI scores may have introduced a floor effect. Changes from the preoperative baseline reflect net postoperative handicap rather than recovery from acute postoperative dysfunction; an assessment before rehabilitation may better capture recovery. Third, although the primary analysis adjusted for baseline tumor size and the complete-case sensitivity analysis yielded consistent results, residual confounding cannot be excluded. The extent of tumor resection was not accounted for and may have influenced postoperative recovery. Fourth, objective vestibular function assessments were not included, limiting investigation of recovery mechanisms. Fifth, detailed app engagement metrics, including login frequency, session duration, and module-specific use, were not collected, limiting assessment of their relationships with clinical outcomes. Adherence was measured using app logs and paper diaries in the intervention and control groups, respectively. Paper diaries may overestimate exercise adherence [48], limiting between-group comparability. Sixth, participants and therapists could not be blinded, potentially introducing performance bias. Finally, the 90-day follow-up limits conclusions about longer-term outcomes.

Conclusions

In conclusion, the mHealth-based rehabilitation program did not demonstrate greater improvement in postoperative vestibular outcomes than conventional face-to-face rehabilitation following unilateral VS surgery. A lower proportion of patients in the intervention group reported postural symptoms on postoperative day 7, but this difference was not significant after correction

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for multiple comparisons. This exploratory finding warrants confirmation in future studies.

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Data Availability

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Generative AI Use

The authors declare the use of generative AI (GenAI) in the research and writing process. According to the Generative AI Delegation Taxonomy (2025), the following tasks were delegated to GenAI tools under full human supervision: translation, grammar correction, sentence structure refinement, and vocabulary improvement. The GenAI tool used was DeepSeek (version 1.8.0). The original prompts and responses for AI-assisted translation and language editing are provided in Multimedia Appendix 7 [1-34]. Responsibility for the final manuscript lies entirely with the authors. GenAI tools are not listed as authors and do not bear responsibility for the final outcomes. The declaration was submitted by FZ.

Authors' Contributions

Conceptualization: DZ (lead), PW (equal)
Data curation: FZ (lead)
Formal analysis: FZ (lead)
Funding acquisition: DZ (lead), FZ (support)
Investigation: GC (equal), XY (equal), YL (equal), XG (equal), ZM (equal)
Methodology: DZ (lead), PW (equal)
Project administration: DZ (lead), PW (equal)
Resources: DZ (lead), PW (equal)
Supervision: DZ (lead), PW (equal)
Validation: FZ (lead)
Visualization: FZ (lead)
Writing—original draft: FZ (lead), DZ (support)
Writing—review & editing: All authors contributed equally to the review and editing of the manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

CONSORT-EHEALTH (Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth) checklist (version 1.6.1).
[PDF File (Adobe PDF File), 12499 KB-Multimedia Appendix 1]

Multimedia Appendix 2

Original-language user interface of the mobile app.
[DOCX File , 631 KB-Multimedia Appendix 2]

Multimedia Appendix 3

Individualized vestibular rehabilitation assessment and exercise program.
[DOCX File , 10 KB-Multimedia Appendix 3]

Multimedia Appendix 4

Numbers of participants with missing data by outcome and treatment group.
[DOCX File , 18 KB-Multimedia Appendix 4]

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Multimedia Appendix 5

Results of exploratory Mann-Whitney U tests.
[DOCX File , 15 KB-Multimedia Appendix 5]

Multimedia Appendix 6

Results of complete-case sensitivity analysis.
[DOCX File , 13 KB-Multimedia Appendix 6]

Multimedia Appendix 7

AI conversation. During the preparation of this manuscript, we used AI for language translation and grammar polishing.
[DOCX File , 23 KB-Multimedia Appendix 7]

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Abbreviations

ANCOVA: analysis of covariance
CONSORT: Consolidated Standards of Reporting Trials
CONSORT-EHEALTH: Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth
DHI: Dizziness Handicap Inventory
mHealth: mobile health
VAS: visual analog scale
VS: vestibular schwannoma

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