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Synergistic Effects of AI-Driven Remote Respiratory Rehabilitation and Cervical Stabilization Exercises on Forward Head Posture, Neck Pain, and Respiratory Function in Older Adults: A Randomized Controlled Trial

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Conflict of interest: None declared

Background: Forward head posture in older adults is associated with cervical–thoracic misalignment, chronic tension-type headache, and impaired respiratory mechanics. This study investigated the synergistic effects of combining cervical stabilization exercises with an AI-driven remote respiratory rehabilitation program.

Material/Methods: This randomized controlled trial enrolled 50 older adults with chronic neck pain and tension-type headache, who were randomly assigned to an experimental group (n=25) or a control group (n=25). After a 12% attrition rate, data from 44 participants (22 per group) who completed a 6-week intervention were analyzed. Both groups performed cervical stabilization exercises, while the experimental group additionally received AI-based remote respiratory training using real-time pressure-threshold analysis to deliver individualized progressive overload at 50% of maximal inspiratory and expiratory pressures (MIP/MEP). In contrast, the control group received a time-matched, conventional self-managed respiratory intervention. Outcomes included pain and disability (VAS, NDI), cervical alignment (CVA), headache impact (HIT-6), pulmonary function (FVC, FEV_1, PEF), respiratory muscle strength (MIP, MEP), and ultrasonographic diaphragmatic thickness.

Results: Compared with the control group, the experimental group demonstrated significantly greater improvements in NDI (d=0.91), CVA (d=0.86), and HIT-6 (d=0.77) ($P<0.05$). Significant group-by-time interaction effects were observed for MIP (d=0.86) and diaphragmatic thickness during contraction (d=0.51). Pulmonary function parameters also improved to a greater extent in the experimental group.

Conclusions: Integrating AI-driven remote respiratory rehabilitation with cervical stabilization exercises provided a clinically meaningful and comprehensive approach for improving postural, respiratory, and headache-related outcomes in older adults with forward head posture.

Keywords: Diaphragm • Geriatrics • Neck Pain • Posture • Randomized Controlled Trial • Respiratory Muscles • Artificial Intelligence • Tele-rehabilitation

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Introduction

Aging is accompanied by sarcopenia, degenerative spinal changes, and impaired postural control, which are primary factors leading to postural misalignment. In particular, forward head posture (FHP) is a common postural abnormality frequently observed in older patients. FHP exacerbates increased cervical lordosis and the mechanical loading of the upper thoracic spine, thereby inducing musculoskeletal dysfunction [1]. These structural changes result in chronic tension of suboccipital muscles, which directly contributes to the pathophysiology of tension-type headache (TTH) [2]. Older adults are particularly susceptible to the neurophysiological consequences of FHP due to diminished efficiency of pain modulation mechanisms and the frequent presence of chronic comorbidities. These age-associated factors can ultimately contribute to functional decline and perpetuate a vicious cycle of reduced quality of life [3].

FHP induces sustained activation of the suboccipital muscles, levator scapulae, and upper trapezius, thereby increasing muscle fatigue and pain sensitivity [4]. Such age-related changes in pain processing can promote the chronicity of mechanical stress, providing a pathophysiological basis for hyperalgesia, in which exaggerated pain responses occur even in response to low-intensity stimuli [5]. FHP is also associated with alterations in respiratory mechanics in older adults.

Furthermore, FHP extends beyond simple musculoskeletal issues to negatively impact respiratory mechanics. Altered cervical and thoracic alignment restricts thoracic cage expansion/chest wall mobility [6]. Aging is associated with reduced diaphragmatic elasticity and decreased chest wall compliance. When combined with altered cervical and thoracic alignment, these changes can significantly diminish breathing efficiency [7]. The resulting upper chest-dominant compensatory breathing pattern reduces oxygen uptake efficiency and adversely affects the energy metabolic rate, acting as a key underlying mechanism that intensifies limitations in overall physical activity among older adults [8]. These findings highlight the need to address postural and respiratory dysfunction together.

Considering this multifactorial pathophysiology, an integrated intervention approach that simultaneously targets the restoration of cervical alignment and the normalization of respiratory mechanics is essential for improving FHP in older adults [9]. Cervical stabilization exercises correct cranio-cervical alignment through the reactivation of deep cervical flexor muscles and alleviate the excessive load on suboccipital muscles [10]. Concurrently, respiratory muscle strengthening exercises improve the diaphragmatic contractile force, suppressing inefficient compensatory breathing and inducing the expansion of lung volumes [11]. Such integrated management may be best delivered through accessible and individualized rehabilitation approaches. In this context, recent advances in AI-based rehabilitation systems offer opportunities to deliver individualized respiratory training with real-time physiological feedback, extending beyond the limitations of conventional tele-rehabilitation.

The restoration of cervical alignment provides a mechanical environment in which respiratory muscles can function at an optimal length–tension relationship. In addition, improved respiratory function can establish a metabolic foundation for postural stability. Therefore, the combination of these 2 interventions is expected to yield superior synergistic effects compared to single interventions, not only in improving objective pulmonary function indices but also in enhancing physical performance and achieving pain reduction [11].

Recently, remote-based respiratory muscle training programs have emerged as a non-invasive rehabilitation strategy capable of overcoming spatiotemporal constraints and enhancing the self-management capacity of older people [12]. However, given the cognitive and physical heterogeneity of the older population, real-time monitoring and feedback by clinicians combined with technology is recommended over simple technical applications to ensure the optimization of intervention effects and ensuring safety [1]. Biosignal monitoring and AI-driven feedback systems utilizing the latest ICT technologies enable personalized precision rehabilitation even in remote environments, presenting a new paradigm in geriatric rehabilitation as digital therapeutics [6].

Existing non-face-to-face interventions have been limited by their reliance on the patient's voluntary participation, making precise control of exercise intensity difficult. The AI-based platform adopted in this study possesses a distinctive feature: it performs real-time analysis of the user's maximal inspiratory and expiratory pressures to automatically set an optimized resistance level based on individual physiological thresholds. This ensures the safety of older patients while precisely applying the principle of progressive overload.

Previous studies have largely been confined to isolated components such as cervical alignment or respiratory function. Research comprehensively validating FHP, TTH, cervical function, and morphological changes of the diaphragm (thickness) in older adults remains insufficient. In particular, few studies have simultaneously examined postural alignment, headache-related disability, and diaphragmatic morphological outcomes within an integrated framework in older adults. Therefore, this study aimed to apply a combined intervention of cervical stabilization exercises and a remote respiratory muscle strengthening program to older individuals with FHP to comprehensively investigate changes in pain and functional disability, pulmonary function, and ultrasonographic assessment of diaphragmatic function. The findings of this

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study will establish evidence for an integrated rehabilitation strategy for older adults suffering from concurrent musculoskeletal and respiratory decline and provide foundational evidence for developing digital healthcare-based personalized intervention models in the future.

Based on this background, the following 2 hypotheses were formulated: (1) The experimental group, which receives AI-assisted remote respiratory rehabilitation, will demonstrate stronger interaction effects in cervical alignment and pain indices compared to the control group; and (2) The AI-driven precision feedback intervention will significantly improve diaphragmatic contraction thickness and respiratory muscle strength compared to self-directed respiratory training. Through testing these hypotheses, this study aims to present a clinical standard for personalized precision rehabilitation for older adults.

Material and Methods

Participants

This study was conducted among patients aged 60 years or older who visited C Hospital in M City for chronic neck pain and TTH. Participant recruitment was carried out from June to October 2025 through in-hospital announcements. The inclusion criteria were as follows: (1) experience of headache episodes within the last 6 weeks, (2) neck pain of 3 or higher based on the visual analog scale (VAS), (3) a Neck Disability Index (NDI) score between 5 and 24, and (4) meeting at least 2 of the clinical features of TTH (eg, bilateral location, pressing/tightening quality, not aggravated by physical activity) according to the International Headache Society classification [13]. The exclusion criteria were: (1) individuals who had taken headache-related medication within the last month (eg, analgesics, NSAIDs, or prophylactic agents), to minimize confounding effects on pain-related outcomes, (2) those with a history of spinal or thoracic surgery, (3) patients with diagnosed neurological or cardiopulmonary diseases that could limit safe participation in an exercise-based intervention (as confirmed by medical records and/or clinician screening), and (4) those with orthopedic disorders of the upper extremities that could interfere with performing the prescribed exercises. All participants provided written informed consent regarding the study's objectives and procedures. An NDI score between 5 and 24 was selected to include participants with mild to moderate neck disability. All participants completed the intervention with high adherence and without adverse events, indicating good feasibility in older adults. This study was approved by the Bioethics Committee of D University and registered in the WHO International Clinical Trials Registry Platform (no. KCT0010800).

Study Design and Procedures

This study had a randomized controlled trial design, including pre- and post-tests. The sample size was calculated using the G*Power 3.1.9.7 program. Based on the main effect size (d=0.78) for pain reported in a previous study by Park and Jung [14], with a significance level of α=0.05 and a statistical power (1-β) of 0.80, a minimum of 22 participants per group was required. Considering a dropout rate of approximately 10%, a total of 50 participants (25 per group) was established as the final study population [15].

A total of 60 participants were recruited and screened for this study. Among them, 10 individuals were excluded before allocation, including 4 who failed to meet the inclusion criteria and 6 who declined to participate for personal reasons. Ultimately, the 50 eligible participants were assigned to either the experimental group (n=25) or the control group (n=25) using a randomization program [16].

To ensure the objectivity of the study, the physical therapist in charge of the assessment performed measurements under single-blinding conditions, remaining unaware of the group assignments. Both groups performed common cervical stabilization exercises; however, the experimental group received an AI-based remote respiratory rehabilitation program, while the control group performed self-directed respiratory training. All interventions were conducted 3 times a week for 6 weeks. Changes in pain, functional disability, pulmonary function, respiratory muscle strength, and diaphragmatic thickness were precisely measured before and after the intervention (**Figure 1**).

Intervention

Common Intervention: Cervical Stabilization Exercise

The cervical stabilization exercise applied to both groups was based on the program by Joshi et al [17] and was modified and supplemented to suit the physical characteristics of older adults. This program focuses on correcting alignment through the activation of deep cervical flexor muscles and securing the dynamic stability of the scapula. The Cervical Stabilization Exercise consists of 6 movements: chin-tuck (chin-in), alignment correction accompanied by scapular retraction, isometric cervical resistance exercise, scapular stabilization using a wall, upper limb rotation including thoracic extension activation, and limb elevation in a quadruped position. Each session included 5 min of stretching (warm-up/cool-down) before and after the main exercise, which was conducted for 20 min. The maintenance time and number of repetitions were adjusted weekly according to the principle of progressive overload.

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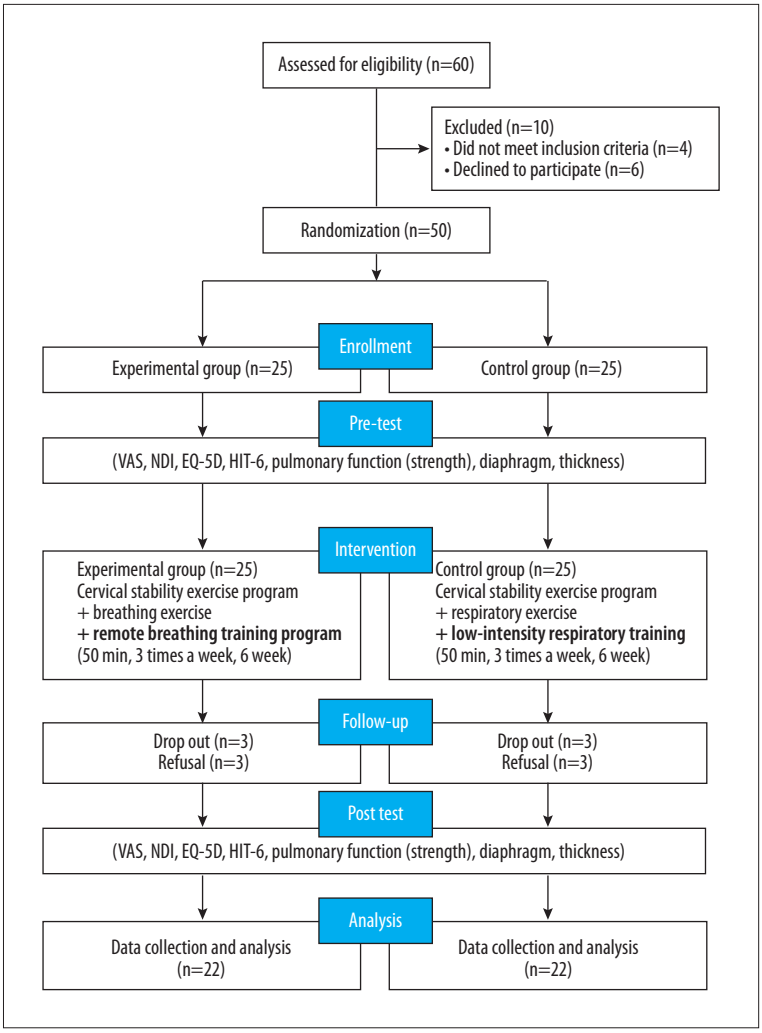

Figure 1. CONSORT flow chart.

Experimental Group: AI-Based Remote Integrated Respiratory Rehabilitation Platform

The intervention for the experimental group utilized a digital rehabilitation system based on a single platform in which Spirokit – a digital pulmonary function meter and pressure sensor module – is linked in real time with a dedicated mobile application. This program was designed to individualize the intervention by quantitatively analyzing the individual physiological indices of the subjects. To this end, the subject's baseline pulmonary capacities – FVC, FEV1, maximal inspiratory pressure (MIP), and maximal expiratory pressure (MEP) – were measured using the Spirokit before the start of the intervention.

The AI algorithm set the measured absolute values of MIP and MEP as the quantitative baseline for initial training and automatically calculated and provided an initial exercise intensity corresponding to a pressure resistance of approximately 50% of the individual's maximal physiological threshold. This is a clinical setting designed to address safety concerns regarding cardiopulmonary load in older adults while delivering targeted physiological stimulation. During the intervention, the application sensors continuously collect real-time respiratory flow and pressure data, which are integrated with the rating of perceived exertion (RPE) reported subjectively by the participant to dynamically apply the principle of progressive overload. For example, if the achievement rate of the target pressure threshold in a specific session is stable and the analyzed RPE is at a "moderate" level or below, the AI system increases the target resistance for the next session in units of 5% to 10% of the individual threshold. Conversely, if high fatigue is detected, it maintains or finely adjusts the difficulty downward, thereby simultaneously supporting the consistency and safety of the intervention.

The respiratory exercise program within the platform lasts for approximately 15 min. Considering the subject's alignment and range of motion, the AI presents an appropriate combination from over 150 exercise modules, including flexibility, strength, and aerobic elements. Specifically, through stretching that

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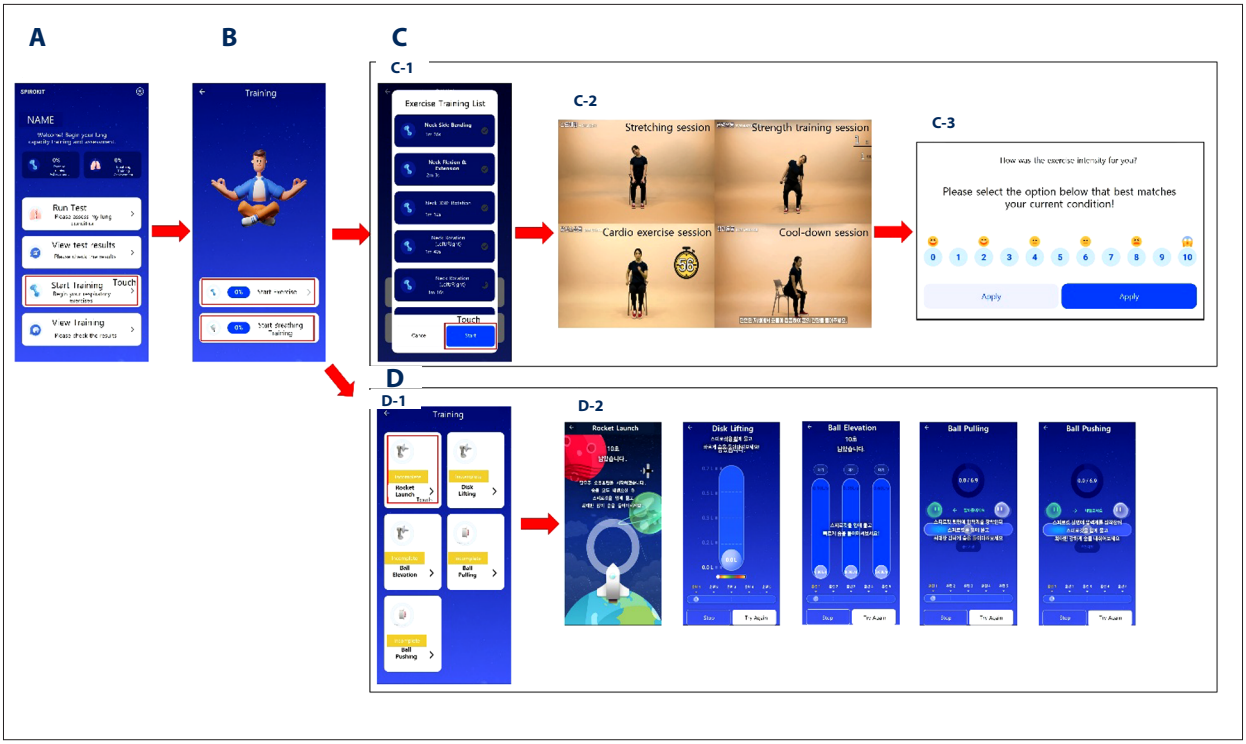

Figure 2. Overview of the mobile application interface and tele-rehabilitation intervention workflow. (**A**) Main dashboard displaying the initial user landing interface of the application. (**B**) Training selection screen for choosing between the guided breathing exercise module and the respiratory muscle training module. (**C**) Guided breathing exercise sequence: (**C-1**) exercise list and initiation screen; (**C-2**) guided instructional video interface displaying a comprehensive program of stretching, strengthening, aerobic, and cool-down exercises; (**C-3**) post-exercise rating screen for perceived exertion (RPE) used for dynamic difficulty adjustment. (**D**) Gamified respiratory muscle training sequence: (**D-1**) selection interface for various respiratory training types; (**D-2**) interactive gamified training screens providing real-time visual feedback based on Spirokit's pressure sensor data.

helps relax the muscles around the neck and thorax, the tension of the accessory respiratory muscles shortened by FHP is alleviated. Simultaneously, trunk stabilization and whole-body coordination exercises are combined to create a biomechanical environment where the diaphragm can contract efficiently. This is followed by 15 min of gamified respiratory muscle strengthening training consisting of 5 types of content (eg, rocket launch or disc lifting) utilizing visual feedback technology, which monitors real-time changes in inspiratory and expiratory hydraulic pressure through the Spirokit's pressure sensor. Each game is designed to reflect specific respiratory physiological goals, such as forced inspiration and sustained expiration. The AI regulates the target values within the game according to real-time performance, facilitating the subject's motivation and training efficiency (**Figure 2**). All intervention processes were shared in real-time with a professional physical therapist via a cloud system, who monitored the fidelity of the intervention and clinical safety by continuously managing the subjects' performance and changes in biosignals through a remote dashboard (**Figure 3**). Prior to the intervention, participants in the experimental group received a structured onboarding session conducted by a licensed physical therapist. No technology-related dropouts or adverse events were reported, and adherence exceeded 90% throughout the 6-week intervention period, indicating the feasibility of the AI-assisted intervention in older adults.

Control Group: Conventional Self-managed Respiratory Intervention

The intervention for the control group was conducted for 30 min per session, 3 times a week for a total of 6 weeks, to ensure a time-match with the experimental group. The control group's program was designed as a conventional comparative environment to identify the specific effects of the AI-based intervention by excluding real-time feedback and progressive overload principles.

In the first 15-min stage, participants performed self-directed respiratory exercises using the same video guides as the experimental group. However, these exercises were performed independently without real-time posture correction or dynamic difficulty adjustment by the AI algorithm. In the subsequent 15-min training, instead of the instrument-based high-intensity

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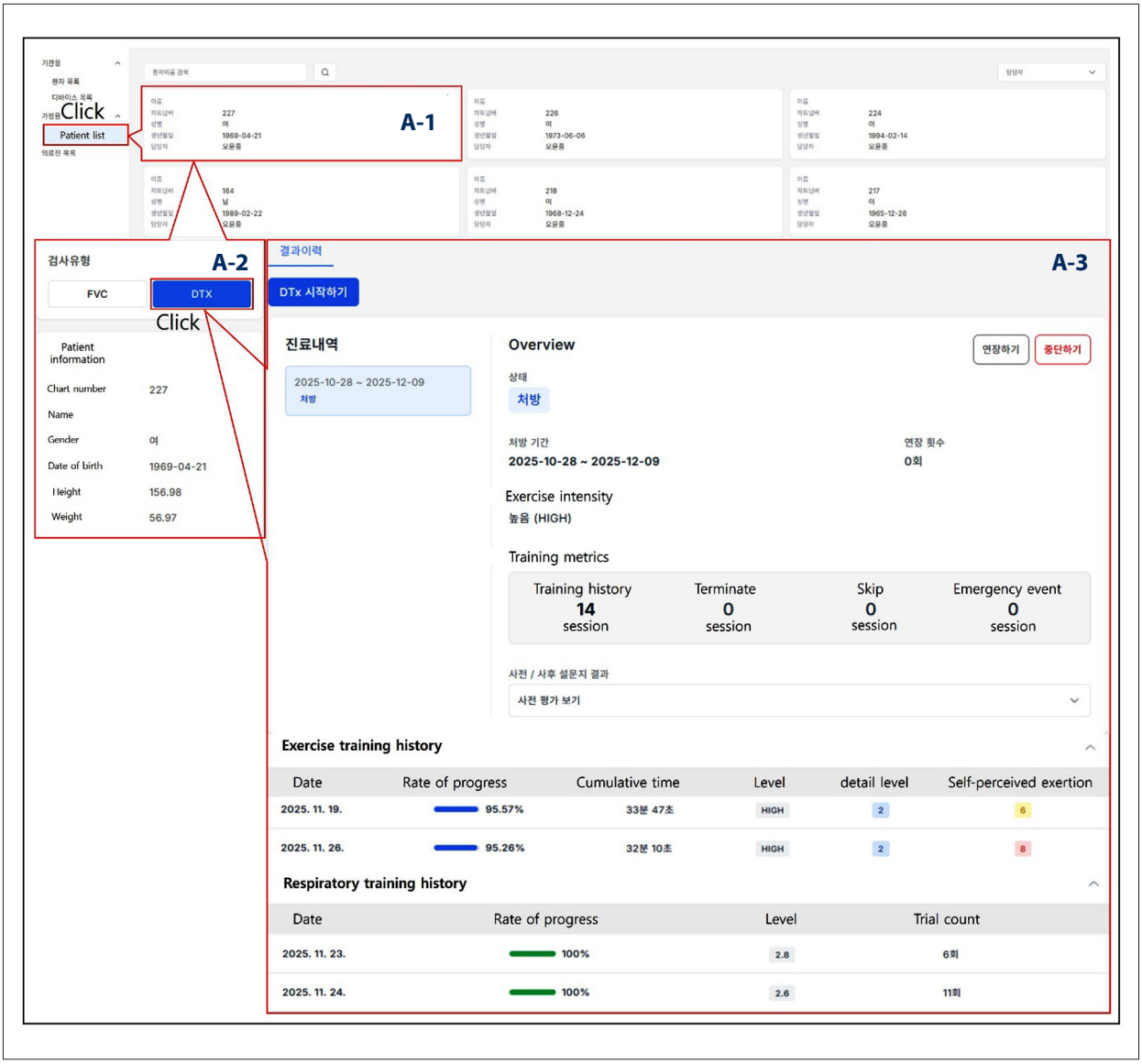

Figure 3. Overview of the patient management program workflow. (**A-1**) Central patient management dashboard providing a comprehensive list of registered participants and allowing the selection of a specific target patient. (**A-2**) Integrated intervention selection interface displayed upon patient selection, presenting available modules such as pulmonary function testing and digital-based rehabilitation programs. (**A-3**) Real-time clinical monitoring and execution interface where the selected patient's individualized training metrics – including exercise adherence, intensity levels, and real-time RPE logs – are displayed for professional supervision.

resistance training used for the experimental group, standardized breathing exercises – including diaphragmatic breathing, controlled slow inspiration/expiration, and basic thoracic expansion – were performed. This configuration was designed to focus on the cognitive control of breathing within a conventional exercise framework.

Intervention fidelity was strictly monitored by a physical therapist through session attendance records and exercise logs. To maintain the control condition, no real-time feedback, movement correction, or intensity progression was provided. This ensured that any observed differences between the groups could be attributed to the AI-driven feedback and intensity modulation rather than the amount of professional monitoring or total exercise time.

Measurements

All outcome assessments were performed by licensed physical therapists who received standardized training prior to data

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collection. To ensure measurement consistency, the same assessor evaluated each participant at baseline and post-intervention whenever possible. Standardized measurement protocols were strictly followed to minimize measurement variability across all outcome measures.

Pain and Functional Disability

To quantify the subjects' pain levels, a visual analog score (VAS) was utilized. The VAS is a method where subjects directly indicate their subjective pain intensity on a line ranging from 0 cm (no pain) to 10 cm (unbearable, extreme pain). It is a tool with high reproducibility for assessing pain severity in patients with TTH. The reliability and validity of this assessment have been reported as 0.62 and 0.75, respectively, sensitively reflecting immediate changes in pain perceived by the patient [18].

The NDI, used to identify the subjects' functional limitation status, is a survey tool consisting of 10 items, including pain intensity, reading, headache, and concentration. Each item is scored between 0 and 5 points, with higher total scores indicating more severe disability levels. Based on score ranges, 5 to 14 points are classified as mild disability, while scores of 35 or higher indicate complete disability. The intra-rater reliability of this tool has been proven to be excellent at r=0.85 to 0.95 [19].

Cervical Alignment

To measure biomechanical alignment changes in the neck due to FHP, the craniovertebral angle (CVA) was measured. A camera was installed on a tripod 1 m from the subject to photograph the lateral standing posture, followed by analysis using ImageJ software (version 1.46j, NIH, USA). The CVA is defined as the angle between a horizontal line passing through the spinous process of the seventh cervical vertebra (C7) and a line connecting the tragus of the ear. The average value of 3 photographs taken by the same measurer was recorded. The reliability of this measurement method maintains a high level at r=0.86 [20].

Headache and Quality of Life

The Headache Impact Test-6 (HIT-6) was conducted to measure the specific impact of headaches on the subjects' daily lives. For 6 items, including pain, social and role functioning, and psychological distress, weights ranging from 6 to 13 points are assigned based on frequency. Higher total scores suggest a more serious decline in quality of life due to headaches. The internal consistency (Cronbach's alpha) of the Korean version of HIT-6 was reported as 0.85, ensuring its reliability [21].

To multifacetedly evaluate health-related quality of life, the EQ-5D (EuroQol-5 Dimensions) was applied. This tool consists of 5 dimensions: mobility, self-care, usual activities, pain/discomfort, and anxiety/depression. Each dimension is classified into 3 levels to score the current health state. The EQ-5D is a highly reliable tool (r=0.87) widely used in healthcare settings and is useful for identifying changes in a patient's overall well-being following an intervention [22]

Pulmonary Function

To confirm quantitative functional changes in the respiratory system, a pulmonary function test was performed. A digital spirometer, Spirokit (TR, Daejeon, Korea), was used. After entering the subjects' personal information (age, gender, height, etc.), the test proceeded following sufficient practice. With a nose clip attached, forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), and peak expiratory flow (PEF) were measured by exhaling strongly through a mouthpiece after maximal inspiration. According to the evaluation procedures and methods suggested by the American Thoracic Society, a skilled therapist with over 9 years of clinical experience recorded 3 measurements and used the maximum value for analysis. The reliability of this test is reported as ICC ≥0.90 [23].

Respiratory Muscle Strength and Diaphragm Structure

To directly assess the contractile force and strength of the respiratory muscles, a respiratory muscle strength test was conducted to measure MIP and MEP. The pressure at which a subject inhales with maximal effort from residual volume (RV) or exhales from total lung capacity (TLC) was recorded in cmH_2O [24]. This non-invasive evaluation method is a validated tool with a reliability of ICC ≥0.85 and is extensively used in clinical practice [25].

Finally, an ultrasound device (MySonoU6, Samsung, Korea) was used to observe morphological changes in diaphragmatic thickness. A 7 to 13 MHz high-frequency linear transducer was placed at the mid-axillary line between the right 8^{th} and 10^{th} intercostal spaces to identify the diaphragm via B-mode imaging. Diaphragmatic thickness was measured in millimeters at the end of expiration and the end of inspiration. This method is highly precise, with inter-rater reliability reaching r=0.99 [26].

Statistical Analysis

The collected data were statistically processed using SPSS Win ver. 25.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were used to present the general characteristics of the participants as means and standard deviations, and data normality was examined using the Shapiro–Wilk test. Baseline

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Table 1. Baseline characteristics of the participants.

	Experimental group (n=22)	Control group (n=22)	t/χ^2	*P*
Sex (Male/Female)	3/19	4/18	0.170	0.680
Age (year)	70.09±3.18	70.05±2.85	0.050	0.960
Height (cm)	159.93±3.05	159.89±4.19	0.041	0.967
Weight (kg)	58.09±6.11	58.18±5.42	-0.052	0.959
BMI (score)	22.74±2.50	22.76±1.91	-0.030	0.977
VAS (point)	6.90±1.15	6.86±1.08	0.137	0.892
NDI (score)	17.41±3.78	18.5±3.23	-1.029	0.309
HIT-6 (score)	62.05±2.13	61.36±2.75	0.932	0.528
CVA (angle)	46.45±1.93	47.29±3.65	-0.881	0.384

Mean±standard deviation; BMI – body mass index; VAS – visual analog scale; NDI – Neck Disability Index; HIT-6 – Headache Impact Test-6; CVA – craniovertebral angle.

demographic and clinical characteristics were compared between groups using chi-square tests for categorical variables (sex) and independent *t* tests for continuous variables. Within-group changes before and after the intervention were analyzed using paired *t* tests, while independent *t* tests were conducted to compare intervention effects between groups. Repeated-measures ANOVA was performed to examine interaction effects between time and group. Post hoc analyses were performed using the Bonferroni correction to control for Type I error inflation due to multiple comparisons. Effect sizes were calculated using Cohen's d for *t* test analyses. No missing data were observed during the study period; therefore, all analyses were conducted using complete-case data, and an intention-to-treat analysis was not performed.

Results

General Characteristics of Subjects

Out of the initial 50 participants, 6 were excluded due to personal reasons and refusal to participate; thus, data from a final total of 44 participants (experimental group n=22, control group n=22) were used for the analysis. A pre-homogeneity test conducted on the general characteristics of all subjects revealed no significant differences between the 2 groups in all items, including age, sex, height, and weight, thereby ensuring baseline homogeneity (**Table 1**).

Changes in Pain, Disability, Alignment, and Quality of Life

The pre-test results for VAS, NDI, CVA, EQ-5D, and HIT-6 showed no statistically significant differences between the 2 groups ($P>0.05$). Following the intervention, the experimental group demonstrated a significant decrease in VAS, NDI, and HIT-6 scores, along with a significant increase in EQ-5D scores, compared to baseline ($P<0.05$). Although changes in EQ-5D scores were relatively modest compared to condition-specific outcomes, this finding likely reflects the limited sensitivity of this generic quality-of-life measure to short-term, region-specific functional improvements. In the comparison of change volumes between groups, the experimental group showed a greater decrease in NDI and HIT-6 scores and a greater increase in CVA than the control group ($P<0.05$). Furthermore, repeated-measures ANOVA identified a significant main effect of time across all indices. Notably, significant interaction effects between the measurement time point and group were observed for key variables such as NDI, CVA, and HIT-6, validating the efficacy of the integrated intervention program ($P<0.05$) (**Table 2**).

Changes in Pulmonary Function and Respiratory Muscle Strength

Pre-test results for pulmonary function (FVC, FEV_1, PEF) and respiratory muscle strength (MIP, MEP) indices indicated no significant differences between the 2 groups ($P>0.05$). After the 6-week intervention, both groups showed significant increases in pulmonary function (FVC, FEV_1, PEF) and respiratory muscle strength (MIP, MEP) ($P<0.05$). However, the analysis of the difference in change volumes between groups revealed the experimental group achieved significantly greater increases in FVC, FEV_1, PEF, MIP, and MEP compared with the control group ($P<0.05$). Additionally, significant interaction effects between time and group were observed for all pulmonary function and strength variables ($P<0.05$), supporting the greater

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Table 2. Intervention effects and group×time interactions on pain, disability, posture, quality of life, and headache impact.

		Experimental group (n=22)	Control group (n=22)	t(p)	Time effect F(p)	Time×group interaction F(p)
VAS (point)	Pre	6.90±1.15	6.86±1.08	.137 (.892)	159.937 (.000)	.018 (.895)
	Post	4.72±1.62	4.73±0.88			
	Post-pre	-2.18±1.40	-2.14±0.77	.146 (.886)		
	t(p)	-7.300 (.000)	-12.941 (.000)			
NDI (score)	Pre	17.41±3.78	18.5±3.23	-1.030 (.309)	513.633 (.000)	4.474 (.040)
	Post	4.36±1.26	7.68±1.49			
	Post-pre	-13.05±3.84	-10.08±3.11	2.204 (.039)		
	t(p)	-15.953 (.000)	-16.309 (.000)			
CVA (angle)	Pre	46.45±1.93	47.29±3.65	-.881 (.384)	39.573 (.000)	17.231 (.000)
	Post	52.67±1.62	48.56±3.42			
	Post-pre	6.22±2.34	1.28±5.08	-4.410 (.000)		
	t(p)	12.461 (.000)	1.178 (.252)			
EQ-5D (score)	Pre	0.68±0.13	0.71±0.15	-.637 (.528)	28.278 (.000)	2.638 (.112)
	Post	0.82±0.07	0.78±0.11			
	Post-pre	0.14±0.13	0.08±0.14	-1.904 (.071)		
	t(p)	5.238 (.000)	2.466 (.022)			
HIT-6 (score)	Pre	62.05±2.13	61.36±2.75	.932 (.357)	82.837 (.000)	7.354 (.010)
	Post	54.82±3.65	57.45±3.28			
	Post-pre	-7.23±4.00	-3.91±4.12	2.638 (.000)		
	t(p)	-8.476 (.000)	-4.454 (.000)			

Mean±standard deviation; VAS – visual analog scale; NDI – Neck Disability Index; CVA – craniovertebral angle; EQ-5D – euroqol-5 dimension; HIT-6 – Headache Impact Test-6.

effectiveness of the AI-based remote respiratory rehabilitation platform compared with self-directed respiratory training (**Table 3**).

Changes in Diaphragm Thickness

Ultrasonographic measurements of the diaphragm showed no pre-test differences between the 2 groups for both thickness at rest (relaxation) and thickness during contraction ($P>0.05$). After the intervention, the experimental group demonstrated a significantly greater increase in contractile diaphragmatic thickness compared to the control group ($P<0.05$), while no significant change was observed in thickness at rest. In the intergroup comparison, the experimental group demonstrated a statistically significant difference in the amount of change in contractile diaphragmatic thickness compared to the control group ($P<0.05$). Furthermore, a significant main effect of time and a time-by-group interaction effect were confirmed for contractile thickness ($P<0.05$), suggesting that this intervention substantially contributed to the enhancement of diaphragmatic contractile function (**Table 4**).

Discussion

This study was conducted to investigate the integrated effects of traditional cervical stabilization exercises combined with a customized AI-driven remote respiratory rehabilitation program for older individuals with chronic neck pain and TTH caused by FHP. The results demonstrated that the experimental group achieved statistically significant and substantial improvements compared to the control group, not only in musculoskeletal

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Table 3. Intervention effects and group×time interactions on pulmonary function and respiratory muscle strength.

		Experimental group (n=22)	Control group (n=22)	t(p)	Time effect F(p)	Time×group interaction F(p)
FVC (L)	Pre	2.04±0.62	2.04±0.72	.016 (.987)	295.782 (.000)	39.865 (.000)
	Post	2.49±0.59	2.25±0.72			
	Post-pre	0.45±0.16	0.21±0.09	-2.289 (.033)		
	t(p)	13.703 (.000)	10.592 (.000)			
FEV_1 (L)	Pre	1.81±0.55	1.74±0.58	.410 (.684)	87.746 (.000)	7.305 (.010)
	Post	2.21±0.57	1.96±0.57			
	Post-pre	0.40±0.20	0.22±0.23	-2.125 (.046)		
	t(p)	9.266 (.000)	4.378 (.000)			
PEF (L/s)	Pre	2.31±0.65	2.53±0.74	-1.075 (.289)	54.939 (.000)	14.902 (.000)
	Post	2.78±0.53	2.68±0.69			
	Post-pre	0.47±0.26	0.15±0.02	-2.172 (.041)		
	t(p)	8.479 (.000)	2.377 (.027)			
MIP (cmH_2O)	Pre	43.27±3.19	43.5±2.76	-.253 (.802)	375.459 (.000)	24.046 (.000)
	Post	54.86±3.40	50.41±3.75			
	Post-pre	11.59±3.69	6.91±2.54	-4.401 (.000)		
	t(p)	14.749 (.000)	12.743 (.000)			
MEP (cmH_2O)	Pre	44.00±3.22	44.55±2.86	-.594 (.556)	776.369 (.000)	61.040 (.000)
	Post	55.73±3.18	51.14±2.70			
	Post-pre	11.73±2.55	6.59±1.74	-9118 (.000)		
	t(p)	21.586 (.000)	17.803 (.000)			

Mean±standard deviation; FVC – forced vital capacity; FEV_1 – forced expiratory volume in 1 second; PEF – peak expiratory flow; MIP – maximal inspiratory pressure; MEP – maximal expiratory pressure.

indices such as the NDI, CVA, and HIT-6 but also in pulmonary function (FVC, FEV_1, PEF), respiratory muscle strength (MIP, MEP), and the change in diaphragmatic thickness during contraction measured via ultrasound. These findings suggest that an integrated intervention strategy targeting both the restoration of cervical biomechanical alignment and the normalization of respiratory mechanics is clinically beneficial for managing the complex symptoms of older patients with FHP.

The improvements in cervical alignment and functional outcomes observed in this study indicate that cervical stabilization exercises effectively facilitated the selective activation of the deep cervical flexor muscles. This activation corrected the abnormal alteration of cervical lordosis and effectively reduced the persistent mechanical overload imposed on the suboccipital muscles, levator scapulae, and upper trapezius.

Heo and Shin [27] reported a significant improvement (effect size, d=0.76) in the NDI through a remote rehabilitation program for chronic neck pain patients over 4 weeks. Similarly, Jeong and Lee [6] confirmed a marked increase (d=0.49) in the CVA through a combined remote intervention of shoulder stabilization and breathing re-education. In the present study, the significant increase in CVA (d=0.86) and the substantial reduction in NDI (d=0.91) in the experimental group align with these previous research trends. Notably, the significant reduction in the HIT-6 (d=0.77) suggests that improvements in FHP may be associated with a reduction in headache-related burden, potentially through cervicogenic mechanisms linking cervical alignment and tension-type headache symptoms. This reaffirms that active stabilization-focused exercise, rather than passive muscle relaxation therapy, is essential for functional recovery and pain modulation in older people. In particular, the

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Table 4. Intervention effects and group×time interactions on diaphragm thickness during inspiration and expiration.

		Experimental group (n=22)	Control group (n=22)	t(p)	Time effect F(p)	Time×group interaction F(p)
Inspiration (cm)	Pre	2.05±0.42	1.92±0.22	1.215 (.231)	435.605 (.000)	200.728 (.000)
	Post	2.26±0.40	2.04±0.23			
	Post-pre	0.02±0.03	0.01±0.00	14.168 (.000)		
	t(p)	-35.052 (.000)	-42.590 (.000)			
Expiration (cm)	Pre	2.31±0.38	2.39±0.22	-0.880 (.384)	1.922 (.173)	1.083 (.304)
	Post	2.34±0.37	2.40±0.23			
	Post-pre	0.03±0.08	0.00±0.09	1.041 (.304)		
	t(p)	-1.779 (.090)	-0.237 (.815)			

Mean±standard deviation.

reductions observed in NDI and HIT-6 clearly exceeded commonly reported minimal clinically important difference thresholds. Given that an MCID of approximately 5 points for NDI and 2.3 to 2.8 points for HIT-6 has been suggested in previous studies, the magnitude of improvement observed in the present study indicates not only statistical significance but also clinically meaningful benefits for older adults with FHP.

Furthermore, this study demonstrated that FHP-related impairment of respiratory function can be effectively reversed through appropriate functional intervention. FHP causes anterior displacement of the head and altered upper thoracic alignment, leading to inefficient chest wall movement, which consequently reduces the diaphragmatic excursion and elasticity of the primary respiratory muscle.

Anwar et al [11] reported an 1% to 21% improvement in pulmonary function parameters following an 8-week breathing re-education program. Similarly, Kim et al [28] demonstrated a 9% to 27% improvement in pulmonary function parameters after a 4-week breathing exercise intervention, while Kang and Jeong [29] reported a 9% improvement in pulmonary function parameters following a 4-week breathing exercise program. Consistent with these findings, the present study showed that the experimental group exhibited significantly greater increases in forced vital capacity (FVC, d=0.74), forced expiratory volume in one second (FEV_1, d=0.71), and peak expiratory flow (PEF, d=0.86) compared with the control group. These improvements reflect enhanced thoracic mobility and breathing efficiency, suggesting that respiratory intervention should be considered a core therapeutic target rather than a supplementary component in the rehabilitation of older adults with FHP.

The most distinctive finding of this study is the confirmed increase in morphological change of the diaphragm, specifically diaphragmatic thickness during contraction (d=0.51). While Balaganapathy and Kansara [30] reported that respiratory muscle strengthening training improves MIP and MEP, studies providing a precise assessment of diaphragmatic thickness are extremely rare. The enhanced diaphragmatic contractility observed in the experimental group may reflect adaptive functional changes of the diaphragm, potentially facilitated by the application of progressive overload principles within the AI-driven training program. However, this interpretation should be considered preliminary, as direct morphological confirmation or longitudinal assessment of diaphragmatic hypertrophy was beyond the scope of the present study. Nevertheless, these findings suggest that diaphragm-centered respiratory retraining can contribute to improvements in diaphragmatic function in older adults with FHP.

The digital healthcare–based remote intervention model applied in this study holds great significance regarding clinical applicability. Operating without spatiotemporal constraints, this program functioned as a robust platform supporting the long-term self-management essential for older patients. In particular, the precision rehabilitation approach – where the AI analyzed quantitative indices (eg, MIP, MEP) and the real-time rating of perceived exertion (RPE) to adjust difficulty levels – ensured higher adherence and safety than traditional, uniform exercise prescriptions. These results suggest that such digital remote interventions can serve as a practical and standardized therapeutic platform for managing chronic musculoskeletal and respiratory diseases in an aging society. Beyond technological novelty, the present findings indicate that individualized respiratory training supported by AI-based feedback can enhance patient adherence, safety, and functional

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outcomes, which are critical considerations for clinical rehabilitation in older adults. Although changes in EQ-5D were relatively modest, this finding is not unexpected, as EQ-5D is a generic quality-of-life measure that may be less sensitive to short-term, region-specific functional improvements. The observed improvements in condition-specific outcomes therefore provide a more sensitive reflection of the intervention's clinical impact.

Despite these findings, this study has several limitations. First, the sample was restricted to older adults from a single region, requiring a cautious approach to the generalizability of the results to all older adults. However, by ensuring the minimum required sample size (calculated via G*Power) was retained in the final analysis even after dropouts, the study maintained sufficient statistical power (1-\beta=0.80). Second, the lack of follow-up assessment prevented the determination of the long-term sustainability of effects. Third, there was a lack of in-depth analysis regarding qualitative satisfaction or usage behavior of the app. Nevertheless, this study delivers a strong clinical implication that the diaphragm and respiratory function must be integrated into the assessment and intervention of FHP patients. Future research should establish the validity of this model through a large-scale multicenter design and long-term follow-up, while comprehensively verifying real-world postural and behavioral changes using wearable devices.

Conclusions

The findings of this study provide preliminary evidence supporting a multidisciplinary rehabilitation approach that integrates cervical stabilization with AI-based remote respiratory rehabilitation. This integrated intervention extends beyond isolated musculoskeletal treatment by addressing the biomechanical relationship between postural misalignment and respiratory function. The superior improvements observed in the experimental group compared to the conventional control group suggest that simultaneously targeting cranio-cervical alignment and respiratory mechanics can contribute to clinically meaningful improvements in older adults with FHP.

From a clinical perspective, the present results indicate that individualized respiratory training supported by AI-based feedback can enhance accessibility and adherence to rehabilitation in older patients by overcoming spatiotemporal constraints. While broader claims regarding scalability and long-term sustainability cannot be confirmed within the scope of this trial, the current findings may inform the future development of patient-centered digital rehabilitation strategies in geriatric care. Further large-scale and longitudinal studies are warranted to establish the long-term effectiveness and system-level applicability of this integrated intervention model.

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Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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