Research Square

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Preliminary Efficacy of Combined Submental Low-Frequency Electrical Stimulation and Expiratory Resistance Exercise in Obstructive Sleep Apnea and Snoring: A Proof-of-Concept Study

Im-Pyo Cho
Korea University
Da-Been Lee
Shinhan University
Suhng-Wook Kim
Korea University
Dae-Wui Yoon
yoondw@hoseo.edu
Hoseo University

Research Article

Keywords: Obstructive sleep apnea, Low-frequency electrical stimulation, Expiratory resistance exercise, Apnea–hypopnea index, Snoring

Posted Date: November 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11541026/v1

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Additional Declarations: No competing interests reported.

Abstract

Purpose

Continuous positive airway pressure effectively treats obstructive sleep apnea (OSA). However, suboptimal adherence has prompted the investigation of alternative treatments. This single-arm pre–post proof-of-concept study examined the clinical efficacy of a 6-week program combining submental low-frequency electrical stimulation with expiratory resistance exercise to reduce apnea–hypopnea index (AHI) and snoring time percentage.

Methods

Twenty-one adults with a baseline app-estimated AHI ≥ 5 events/h started the intervention; 17 adherent completers were analyzed. Participants performed the combined intervention for 10 min daily, with submental electrical stimulation delivered only during approximately 5-s forceful expirations against resistance. SleepRoutine monitored sleep throughout the intervention period, and baseline values were compared with values from weeks 5 and 6. Primary outcomes were changes in AHI and snoring time percentage; secondary outcomes were sleep efficiency, wake ratio, subjective sleep quality, and daytime sleepiness. Changes were analyzed using paired-samples t tests or Wilcoxon signed-rank tests, with Holm adjustment for the primary outcomes.

Results

Median AHI decreased from 10.17 (interquartile range [IQR], 1.45) to 5.52 (IQR, 1.43) events/h (Holm-adjusted $p < 0.001$; rank-biserial correlation, − 0.869). Snoring time percentage decreased from 22.24 ± 15.74% to 12.75 ± 9.29% (mean change, − 9.49 percentage points [95% confidence interval (CI), − 14.05 to − 4.94]; Holm-adjusted $p < 0.001$; Cohen's d, − 1.071). No significant changes occurred in secondary outcomes.

Conclusion

These findings provide preliminary evidence supporting the combined intervention's efficacy. Randomized controlled studies using polysomnography-based outcomes are warranted.

Trial registration

Clinical Research Information Service (CRIS), KCT0012739, registered on 6 October 2026 (retrospectively registered).

Introduction

Obstructive sleep apnea (OSA) is a common sleep-related breathing disorder characterized by recurrent partial or complete upper-airway collapse during sleep, resulting in reduced or absent airflow despite ongoing respiratory effort. Repeated obstruction can cause intermittent hypoxemia and recurrent arousals, leading to fragmented sleep and symptoms including habitual snoring and excessive daytime sleepiness [1]. Globally, an estimated 936 million adults aged 30–69 years have OSA (apnea–hypopnea index [AHI] ≥ 5 events/h), including approximately 425 million with moderate-to-severe OSA (AHI ≥ 15 events/h) [2].

OSA is associated with substantial cardiovascular morbidity, including hypertension, coronary artery disease, heart failure, cardiac arrhythmias, and stroke [3]. Positive airway pressure (PAP), most commonly delivered as continuous positive airway pressure (CPAP), is an established noninvasive therapy that maintains upper-airway patency during sleep and reduces obstructive respiratory events [4]. However, inadequate adherence due to mask discomfort, air leakage, nasal symptoms, claustrophobia, and pressure intolerance often limits real-world effectiveness [4, 5], motivating investigation of alternative noninvasive approaches for OSA.

Upper airway patency during sleep depends partly on the activity of the pharyngeal dilator muscles, including the genioglossus, which counteract forces that promote airway collapse. In patients with OSA, compensatory activation of these muscles during wakefulness may decline at sleep onset, increasing susceptibility to upper airway obstruction [6]. Based on this mechanism, researchers have investigated transcutaneous electrical stimulation over the submental region as a noninvasive way to activate the upper-airway dilator muscles [7, 8]. Physiological studies have demonstrated stimulation-induced muscle contraction [8], whereas randomized trials have reported improvements in selected sleep-disordered breathing outcomes but heterogeneous responses; notably, a recent trial found that the baseline-adjusted between-group AHI effect was not statistically significant [7, 9]. Accordingly, evidence for clinical efficacy remains limited.

Researchers have investigated targeted upper-airway exercises and respiratory muscle training as noninvasive approaches for OSA. Oropharyngeal exercises involving the tongue, soft palate, and lateral pharyngeal walls have been associated with reductions in OSA severity and related symptoms [10, 11]. Respiratory muscle training studies have used heterogeneous inspiratory, expiratory, and combined protocols, with variable effects on AHI [12]. Among expiratory approaches, AHI was reduced after a 5-week expiratory muscle strength training (EMST) program in which resistance was prescribed at 75% of each participant's maximal expiratory pressure (PEmax) [13]. A preliminary before–after study also reported reduced AHI after a program comprising daytime submental neuromuscular stimulation and separate daily lingual and suprahyoid muscle exercises [14]. However, that study did not evaluate the concurrent application of the two components, and substantial attrition further limited interpretation. Collectively, these findings support evaluating OSA-related changes associated with concurrent submental low-frequency electrical stimulation and expiratory resistance exercise.

Despite growing interest in noninvasive approaches for OSA, evidence for concurrent submental low-frequency electrical stimulation and expiratory resistance exercise remains limited. Therefore, this single-arm proof-of-concept study aimed to examine within-participant changes in AHI and snoring time percentage during a 6-week home-based program combining these interventions. SleepRoutine monitored sleep throughout the intervention; baseline values were compared with those derived from recordings during weeks 5 and 6. Exploratory outcomes included sleep efficiency and wake ratio, as well as subjective sleep quality and daytime sleepiness assessed using the Korean versions of the Pittsburgh Sleep Quality Index (PSQI-K) and Epworth Sleepiness Scale (KESS), respectively [15, 16].

Materials and Methods

Participants and Recruitment

This single-arm pre–post proof-of-concept study was conducted at the Sleep Medicine Research Institute in the Republic of Korea. The Institutional Review Board of Jungwon University reviewed and approved the study protocol (approval No. 1044297-HR-202404-006-03; June 26, 2024). The study was retrospectively registered with the Clinical Research Information Service (CRIS), Republic of Korea, on 6 October 2026 (registration No. KCT0012739). All participants were informed about the study procedures and provided written informed consent before enrollment.

Figure 1 summarizes the participant recruitment and selection process. Participants were recruited from July 4 to August 2, 2024, and study procedures were conducted from July to October 2024. A total of 30 individuals were assessed for eligibility. Potential participants completed an initial screening questionnaire that collected demographic and anthropometric information, responses to the Snoring, Tiredness, Observed apnea, high blood Pressure, Body mass index (BMI), Age, Neck circumference, and Gender (STOP-BANG) questionnaire, previous awareness and treatment of OSA, and medical conditions relevant to the intervention. Adult volunteers aged 60 years or younger and with a BMI of ≤ 35 kg/m² who met the initial screening criteria underwent a baseline home sleep assessment using the SleepRoutine App. Following this assessment, individuals with an AHI < 5 events/h or a history of OSA treatment were excluded. STOP-BANG scores were used to characterize participants' risk of OSA but were not applied as an eligibility cutoff or diagnostic measure [17]. STOP-BANG scores of 0–2, 3–4, and 5–8 were categorized as low, intermediate, and high risk, respectively [18]. Individuals were also excluded if they had craniofacial abnormalities, nasal septal deviation, or previous oropharyngeal surgery; cardiac arrhythmia, pulmonary disease, diabetes, stroke, cardiovascular disease, or malignancy; pregnancy or lactation; neurologic or sensory disorders; skin allergy or an active lesion at the electrode attachment site; alcohol or drug dependence; current use of a mandibular advancement device; or an implanted electrical device. Nine individuals were excluded: three had a baseline AHI < 5 events/h, four met other exclusion criteria, and two had a history of OSA treatment. Twenty-one eligible participants initiated the intervention; two withdrew during the intervention period and 19 completed the study. Two completers were excluded for performing the intervention fewer than three times weekly, leaving 17 participants for final analysis.

Intervention Procedures

Participants performed a home-based combined intervention comprising submental low-frequency electrical stimulation and expiratory resistance exercise. In this study, expiratory resistance exercise was defined as forceful exhalation against resistance provided only during expiration by a resistance-adjustable device. Before each session, the submental area was cleaned as needed to ensure adequate pad adhesion, after which an adhesive stimulation pad was positioned beneath the mandible. The stimulation intensity was gradually increased within levels 3–8 and individually adjusted to the highest tolerable level below each participant's pain threshold. Post hoc bench characterization across a 1-kΩ resistive load indicated that the maximum estimated alternating current ranged from approximately 1.23 to 1.58 mA across stimulation levels 3–8. The expiratory resistance level was adjusted using the exercise device's resistance control. Participants performed the expiratory resistance exercise while seated comfortably with the head upright. For each expiratory effort, participants were instructed to exhale forcefully against the resistance for approximately 5 s. Low-frequency electrical stimulation was delivered only during each expiratory effort and ceased when the expiratory effort ended. The 6-week intervention period was selected based on previous evidence showing a reduction in AHI after 5 weeks of expiratory muscle strength training in patients with OSA [13]. Participants performed the combined intervention for 10 min once daily, logging each session's date and duration. Adherence was summarized as each participant's total intervention days, based on these logs. Figure 2 presents a schematic overview of the combined intervention.

Outcome Measures and Assessments

Outcome assessments were performed at baseline and at the 5–6-week follow-up. Sleep outcomes were assessed at home using the SleepRoutine App (Asleep Inc., Seoul, Republic of Korea). SleepRoutine has been evaluated earlier against polysomnography (PSG) for the accuracy of sleep-stage classification and sleep measures [19]. At the same time, Asleep Inc. has validated related breathing-sound–based models to detect apnea and hypopnea events and estimate AHI using smartphone-recorded breathing sounds in laboratory and home settings [20, 21]. All sleep outcomes were estimated using SleepRoutine App. The primary outcomes were within-participant changes in AHI, defined as the number of apnea and hypopnea events per hour, and snoring time percentage, defined as the proportion of sleep time classified as snoring. Secondary outcomes were sleep efficiency and wake ratio, both expressed as percentages.

Subjective sleep quality and daytime sleepiness were assessed at baseline and the 5–6-week follow-up using the PSQI-K and KESS, respectively [15, 16]. Total scores range from 0 to 21 (PSQI-K) and 0 to 24 (KESS), with higher scores indicating poorer subjective sleep quality and greater daytime sleepiness, respectively. Scores were treated as continuous outcomes when evaluating changes from baseline. For descriptive baseline categorization, PSQI-K scores > 5 and KESS scores > 10 indicated poor subjective

sleep quality and excessive daytime sleepiness, respectively, based on conventional PSQI and ESS thresholds [22, 23].

Statistical Analysis

Literature-based sample size and power calculations were performed for the two primary outcomes using G*Power (version 3.1.9.4). The assumed paired effect size for AHI was $d_z = 0.891$, derived from the pre- and post-intervention means and standard deviations reported by Guimarães et al. [10], assuming a correlation of zero between measurements. For snoring time percentage, an assumed $d_z = 0.974$ was derived from the mean change and its standard deviation reported by Nokes et al. [24] for a related objective snoring measure. A conservative two-sided significance level of 0.025 for each primary outcome and a target power of 80% were used. AHI calculations used Lehmann's three-moment approximation with continuity correction for the Wilcoxon signed-rank test, assuming normally distributed paired differences; snoring calculations used the paired-samples t test. The required sample sizes were 17 participants for AHI and 13 participants for snoring time percentage. Accordingly, at least 17 participants were required for the final analysis. Under these assumptions, the estimated powers for 17 participants were 83.3% for AHI and 92.6% for snoring time percentage.

Statistical analyses were performed using jamovi (version 2.7.38, The jamovi project, Sydney, Australia). The analysis population comprised participants who completed both the baseline and follow-up assessments and performed the combined intervention at least three times per week. Continuous variables were summarized as means and standard deviations or medians and interquartile ranges (IQRs), as appropriate, whereas categorical variables were summarized as frequencies and percentages. The normality of within-participant changes from baseline to follow-up was assessed using the Shapiro–Wilk test. AHI and wake ratio were analyzed using the Wilcoxon signed-rank test because their change scores were not normally distributed; within-participant changes for these outcomes were summarized using Hodges–Lehmann estimates with 95% CIs. Snoring time percentage, sleep efficiency, the PSQI-K score, and the KESS score were analyzed using paired-samples t tests because their change scores were approximately normally distributed. Effect sizes were reported as matched-pairs rank-biserial correlations for the Wilcoxon signed-rank tests and paired-samples Cohen's d values for the paired-samples t tests, with 95% CIs. Holm adjustment was applied across the two primary outcomes, whereas the secondary outcomes were regarded as exploratory and reported using unadjusted *p*-values. All tests were two-sided, and *p*-values < 0.05 were considered statistically significant. Missing values were not imputed. Individual participant changes were visualized using paired line plots.

Results

Baseline characteristics

The 17 analyzed participants had a mean age of 41.4 ± 11.3 years and a mean BMI of 26.0 ± 4.2 kg/m²; 14 (82.4%) were male (Table 1). Ten (58.8%) reported previously being told they had sleep apnea. The

mean STOP-BANG score was 3.9 ± 1.3; 14 (82.4%) were classified as having intermediate or high OSA risk. At baseline, 12 (70.6%) had PSQI-K scores > 5 and five (29.4%) had KESS scores > 10.

Table 1
Baseline characteristics of the participants included in the final analysis

Characteristic	Overall (n = 17)
Age, years	41.4 ± 11.3
Male sex, n (%)	14 (82.4)
Body mass index, kg/m²	26.0 ± 4.2
Self-reported prior awareness of sleep apnea, n (%)	10 (58.8)
STOP-BANG score	3.9 ± 1.3
STOP-BANG risk category, n (%)	
Low risk	3 (17.6)
Intermediate risk	7 (41.2)
High risk	7 (41.2)
PSQI-K score > 5, n (%)	12 (70.6)
KESS score > 10, n (%)	5 (29.4)

Note. Data are presented as mean ± standard deviation or n (%). STOP-BANG scores of 0–2, 3–4, and 5–8 were classified as low, intermediate, and high risk, respectively.

Abbreviations: STOP-BANG, Snoring, Tiredness, Observed apnea, high blood Pressure, Body mass index, Age, Neck circumference, and Gender; PSQI-K, Korean version of the Pittsburgh Sleep Quality Index; KESS, Korean version of the Epworth Sleepiness Scale.

Intervention adherence

Among the 17 participants, intervention use averaged 40.5 ± 1.5 days over the 6-week intervention period (Table 2).

Table 2. Changes in primary and secondary outcomes from baseline to the 5–6-week follow-up and intervention adherence

Outcome	Baseline	After 5–6 weeks	Change (95% CI)	*p*-value	Effect size (95% CI)
Intervention adherence					
Intervention use, days	-	40.5 ± 1.5	-	-	-
Primary outcomes					
AHI, events/h	10.17 (1.45)	5.52 (1.43)	−4.03 (−4.97 to −2.11)	< 0.001[a]	r_{rb} = −0.869 (−0.954 to −0.658)
Snoring time percentage, %	22.24 ± 15.74	12.75 ± 9.29	−9.49 (−14.05 to −4.94)	< 0.001[a]	d = −1.071 (−1.662 to −0.460)
Secondary outcomes					
Sleep efficiency, %	88.95 ± 5.15	88.45 ± 4.81	−0.51 (−2.51 to 1.49)	0.599	d = −0.130 (−0.606 to 0.349)
Wake ratio, %	5.40 (5.17)	5.00 (4.00)	−0.50 (−2.10 to 0.66)	0.394	r_{rb} = −0.242 (−0.657 to 0.286)
PSQI-K score	7.29 ± 3.29	6.53 ± 3.32	−0.76 (−2.46 to 0.93)	0.352	d = −0.233 (−0.711 to 0.253)
KESS score	6.94 ± 4.15	6.47 ± 3.57	−0.47 (−3.04 to 2.10)	0.703	d = −0.094 (−0.569 to 0.384)

Note. For outcomes analyzed using paired-samples t tests, baseline and follow-up values are presented as mean ± standard deviation (SD), and within-participant changes are presented as mean differences with 95% CIs. For outcomes analyzed using the Wilcoxon signed-rank test, baseline and follow-up values are presented as median (interquartile range [IQR]), and within-participant changes are presented as Hodges–Lehmann estimates with 95% CIs. The *p*-values are two-sided. [a]Holm-adjusted *p*-values are presented for the two prespecified primary outcomes; unadjusted *p*-values are presented for the secondary outcomes. d, paired-samples Cohen's d; r_{rb}, matched-pairs rank-biserial correlation. Negative change estimates and effect sizes indicate a reduction at follow-up. Intervention use is presented as mean ± standard deviation and represents the total number of days on which the intervention was performed during the 6-week intervention period. No inferential analysis was conducted for this variable.

Abbreviations: AHI, apnea–hypopnea index; PSQI-K, Korean version of the Pittsburgh Sleep Quality Index; KESS, Korean version of the Epworth Sleepiness Scale.

Changes in primary and secondary outcomes

AHI decreased from a median of 10.17 events/h (IQR, 1.45) at baseline to 5.52 events/h (IQR, 1.43) at the 5–6-week follow-up, with a Hodges–Lehmann estimated change of −4.03 events/h (95% CI, −4.97 to −2.11; Wilcoxon W = 10.0; Holm-adjusted $p < 0.001$; rank-biserial correlation = −0.869, 95% CI, −0.954 to −0.658). Snoring time percentage also decreased from 22.24 ± 15.74% to 12.75 ± 9.29%, with a mean within-participant change of −9.49 percentage points (95% CI, −14.05 to −4.94; t(16) = −4.417; Holm-adjusted $p < 0.001$; Cohen's d = −1.071, 95% CI, −1.662 to −0.460) (Table 2). Fig. 3 shows individual trajectories for the two primary outcomes and complements the group-level statistics in Table 2.

No statistically significant changes were observed in sleep efficiency ($p = 0.599$), wake ratio ($p = 0.394$), PSQI-K score ($p = 0.352$), or KESS score ($p = 0.703$) after the intervention (Table 2).

Discussion

In this single-arm proof-of-concept study, a 6-week home-based program combining submental low-frequency electrical stimulation with expiratory resistance exercise was associated with significant reductions in both prespecified primary outcomes, AHI and snoring time percentage. In contrast, sleep efficiency, wake ratio, PSQI-K score, and KESS score did not change significantly. The discordance between the significant improvements in respiratory outcomes and the lack of significant changes in subjective measures may reflect several factors. Only 29.4% of participants had KESS scores >10 at baseline, which may have limited the potential for measurable improvement in daytime sleepiness. In addition, PSQI-K captures multiple dimensions of perceived sleep quality that may not change in parallel with reductions in respiratory events or snoring. The relatively short 6-week intervention period may have been insufficient for the respiratory improvements to translate into detectable improvements in subjective sleep quality or daytime sleepiness. Overall, these findings provide preliminary evidence supporting the clinical efficacy of the combined intervention.

Previous studies of noninvasive upper-airway electrical stimulation have reported heterogeneous findings, possibly reflecting differences in stimulation timing and parameters, intervention duration, and participant characteristics [7-9, 25]. A 4-week daytime study reported an improvement in PSQI scores but no significant changes in AHI or ESS scores [25]. In contrast, Lequeux et al. reported a decrease in mean PSG-derived AHI from 32.9 to 20.6 events/h following 30 sessions of submental transcutaneous neuromuscular stimulation combined with lingual and suprahyoid muscle exercises [14]. More recently, an open-label randomized trial of domiciliary transcutaneous electrical stimulation found an unadjusted between-group difference favoring stimulation. However, the baseline-adjusted between-group difference in AHI was not statistically significant [9]. Baptista et al. reported a substantial reduction in objective snoring after 6 weeks of transoral tongue stimulation in individuals with primary snoring or mild OSA [26], while a subsequent analysis limited to participants with mild OSA found significant improvements in AHI, objective snoring, ESS, and PSQI [24]. In a randomized, double-masked, sham-controlled trial, exploratory analyses also showed a significant reduction in respiratory event index with active but not sham stimulation [27]. Although these studies employed transoral tongue stimulation rather than transcutaneous submental stimulation and did not combine electrical stimulation with

expiratory resistance exercise, their findings support the broader concept that repeated awake neuromuscular stimulation of upper-airway musculature may improve sleep-disordered breathing outcomes. Respiratory exercise studies have likewise employed heterogeneous training protocols.

In contrast to the PEmax-based pressure-threshold expiratory muscle strength training (EMST) protocol used by Kuo et al. [13], the present intervention applied resistance only during expiration without a PEmax-based load prescription. It combined this exercise with synchronized submental electrical stimulation. Thus, although the observed reduction in AHI is directionally consistent with previous findings from expiratory muscle training, the present protocol represents a distinct combined intervention rather than a conventional EMST regimen. Systematic reviews and a recent meta-analysis have reported improvements in OSA-related outcomes, including reduced AHI. Still, the evidence remains limited by small sample sizes, heterogeneous interventions, and risk of bias, and improvements in daytime sleepiness have been inconsistent [11, 12, 28]. Comparisons of effect magnitude should be interpreted cautiously because the present outcomes were estimated using a smartphone application, whereas the cited studies generally used polysomnography or other sleep-study methods.

Several mechanisms could underlie the association. Submental stimulation may activate upper-airway muscles, while expiratory resistance exercise may train expiratory musculature [8, 13]. However, this study did not identify activated muscles or measure genioglossus activity, respiratory muscle strength, or upper-airway collapsibility. Concurrent application prevents separation of the components' independent or additive contributions. These mechanisms remain hypothetical and require controlled studies with physiological measurements.

Strengths include home-based implementation, paired analyses of within-participant changes in two prespecified primary outcomes, effect sizes with 95% CIs, and Holm adjustment for multiple testing.

Several limitations should be considered: First, the single-arm pre–post design does not allow the observed changes to be attributed exclusively to the intervention, because natural night-to-night variability, regression to the mean, expectancy effects, and concurrent behavioral changes cannot be excluded. Second, the small sample size limited the precision and generalizability of the findings, and the completer- and adherence-based analysis of 17 of 21 participants may have introduced attrition and selection bias and limited representativeness. Third, eligibility and outcome assessment were based on smartphone application–derived estimates rather than PSG. Although the application and related breathing-sound models have been evaluated against PSG [19-21], app-derived changes should not be considered equivalent to PSG-derived AHI, and the study did not assess oxygen desaturation. Fourth, the study did not record or control sleep position, and differences in positional distribution between assessments may have influenced AHI and snoring. Fifth, adherence was assessed using participant-recorded logs rather than objective device records, precluding objective verification of the intervention dose and dose–response relationship. Sixth, stimulation intensity was individualized according to participant tolerance and was not fully standardized, while concurrent delivery prevented isolation of

each component's contribution. Finally, no post-intervention follow-up was conducted; therefore, the durability of the observed changes remains unknown.

The observed within-participant reductions in AHI and snoring time percentage support randomized, sham-controlled, multi-arm trials with blinded PSG-based assessment comparing the combined intervention, each component alone, and an appropriate control. Dosing should be prospectively standardized by specifying measurable electrical output, expiratory resistance or training load, session duration, treatment frequency, and progression criteria. Objective time-stamped device logs should capture adherence; adverse events and tolerability should be assessed prospectively. Submental electromyography, respiratory muscle strength, and upper-airway imaging could clarify mechanisms. Repeated PSG or validated multi-night monitoring with longer follow-up could assess night-to-night variability and durability. Smartphone-derived measures should be validated for longitudinal treatment-related changes before use as primary efficacy outcomes.

Conclusion

In this single-arm pre–post proof-of-concept study, a 6-week home-based program combining submental low-frequency electrical stimulation with expiratory resistance exercise was associated with statistically significant within-participant reductions in AHI and snoring time percentage. These findings provide preliminary evidence supporting the clinical efficacy of the combined intervention in reducing AHI and snoring time percentage. Randomized controlled studies incorporating PSG-based outcome assessment, standardized intervention dosing, objective adherence monitoring, and sleep-position assessment are warranted to confirm these findings.

Declarations

Funding

This research was supported by the Regional Innovation Strategy (RIS) through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (MOE) (grant No. 2021RIS-001).

Competing interests

The authors declare no competing interests.

Ethics approval

This study was approved by the Institutional Review Board of Jungwon University (approval No. 1044297-HR-202404-006-03; June 26, 2024). The study was conducted in accordance with the Declaration of Helsinki and its later amendments.

Consent to participate

Written informed consent was obtained from all participants before enrollment.

Consent to publish

Not applicable. No identifying information about individual participants is included in this manuscript.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available because of participant privacy and ethical restrictions. However, they are available from the corresponding authors on reasonable request, subject to applicable institutional and ethical approvals.

Author contributions

I.P.C. and D.B.L. contributed equally to this work. I.P.C. performed the statistical analyses, interpreted the data, and drafted the manuscript. D.B.L. recruited participants, conducted the study, collected the data, and contributed to drafting the manuscript. S.W.K. supervised the study and reviewed and revised the manuscript. D.W.Y. conceived and designed the study, supervised the project, acquired funding, and reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Figures

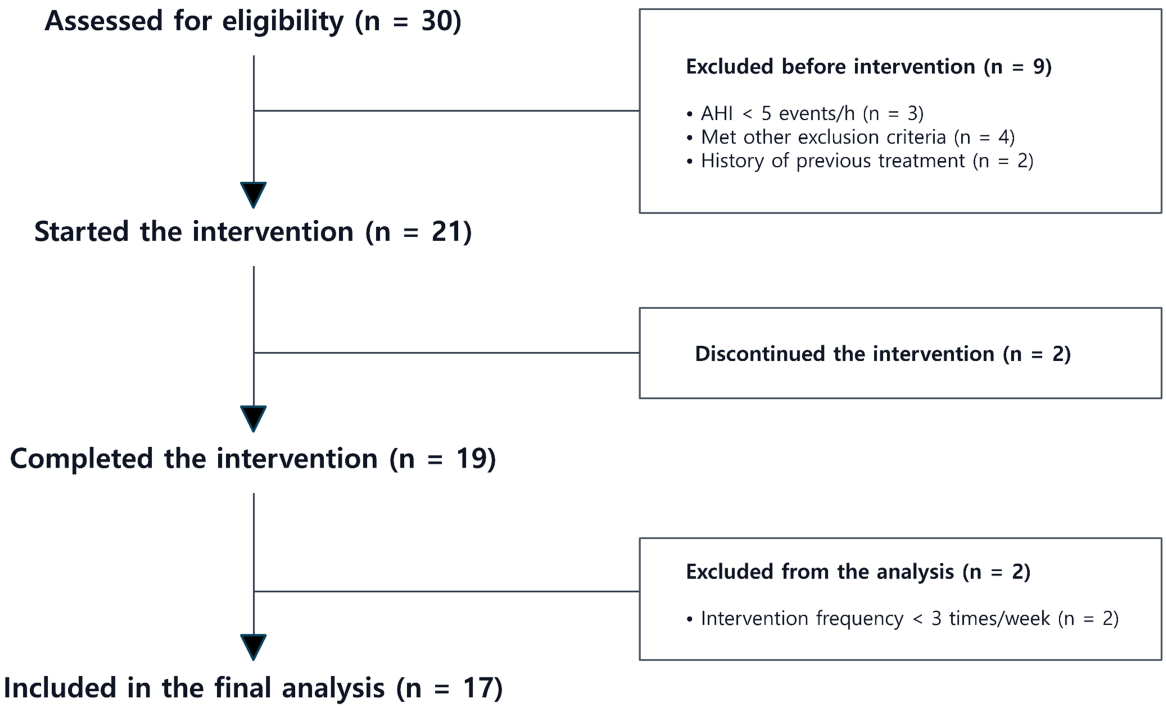


Figure 1

Flow diagram of participant screening, intervention completion, and analysis

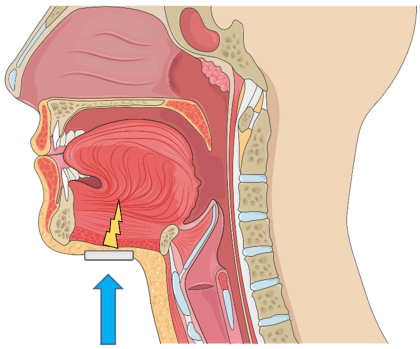
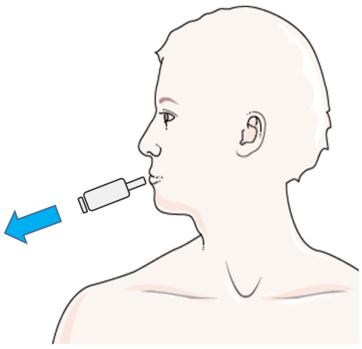
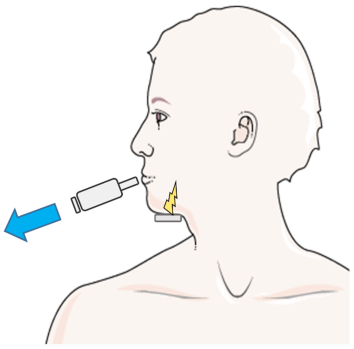
a Submental low-frequency electrical stimulation	b Expiratory resistance exercise	c Combined intervention
		
Submental stimulation site	Forceful expiration against resistance (~5 s per effort) Resistance applied during expiration only	10 min once daily for 6 weeks

Figure 2

Schematic overview of the combined intervention. a) Submental low-frequency electrical stimulation applied beneath the mandible. b) Expiratory resistance exercise performed against resistance during expiration, with each expiratory effort lasting approximately 5 s. c) Combined application of expiratory

resistance exercise and synchronized submental electrical stimulation during each expiratory effort, performed for 10 min once daily over 6 weeks. Anatomical illustrations were adapted from Servier Medical Art (https://smart.servier.com/) and are licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

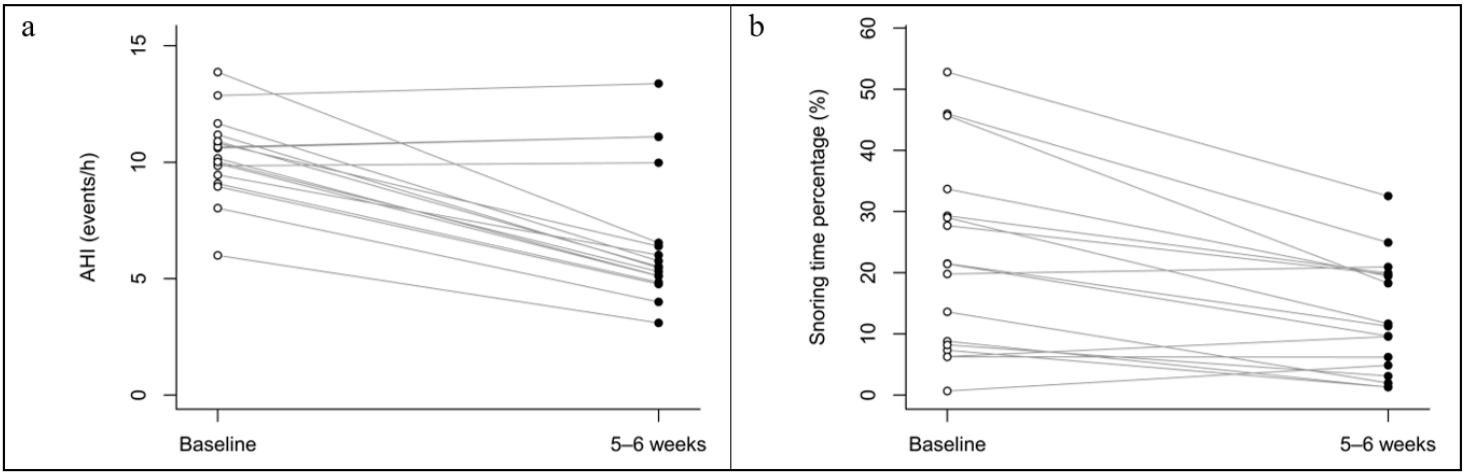


Figure 3

Individual changes in the two primary outcomes from baseline to the 5–6-week follow-up. a) Apnea–hypopnea index (AHI). b) Snoring time percentage. Each line represents an individual participant