



Effects of exercise and a lifestyle app on sleep disordered breathing, physical health and quality of life

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Shareable abstract (@ERSpublications)

A 12-week exercise programme is sufficient to reduce sleep disordered breathing (SDB) severity and generate relevant health improvements. In contrast, the improvements from a lifestyle app intervention were more modest and did not affect SDB severity. <https://bit.ly/4f4CkE2>

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Abstract

Background Sleep disordered breathing (SDB) is a growing public health problem, and noninvasive treatments may be a valid option. The objective of this randomised controlled trial was to assess the effects of a 12-week exercise programme and a lifestyle app on SDB severity, physical health (anthropometry, body composition, physical fitness) and health-related quality of life (HRQoL) in 18- to 50-year-old adults with mild-to-moderate SDB.

Methods 192 participants (age 37.4±6.3 years, body mass index (BMI) 33.3±4.2 kg·m⁻², 52.6% males) with mild-to-moderate SDB (apnoea-hypopnea index (AHI) ≥5<30.0, objective snore ≥10%) were randomised into: exercise (three times/week, 60 min), app and control groups. The assessments included a 3-night self-applied polysomnography, anthropometry, body composition, physical fitness and HRQoL. Repeated ANOVA, Wilcoxon signed-rank and Kruskal–Wallis test were used to evaluate the changes.

Results Time effect was observed in AHI (F=6.290, p=0.014), neck circumference (F=5.253, p=0.024), hand dynamometry (F=7.102, p=0.009), and 6-min walking test (F=8.340, p=0.005). Group × time interactions were observed in weight (F=9.318, p≤0.001), BMI (F=9.302, p≤0.001), body fat percentage (F=4.756, p=0.01), body fat mass (F=5.916, p=0.004) and skeletal muscle mass (F=9.380, p≤0.001). Intragroup changes were observed in physical functioning, vitality and general health in both the exercise and app groups, in addition to role limitations due to physical health in the exercise group.

Conclusions The 12-week exercise programme reduced AHI and increased skeletal muscle mass, physical fitness and HRQoL in four domains. The lifestyle app programme reduced weight, BMI, neck circumference, body fat, visceral adiposity and skeletal muscle mass while increased three HRQoL domains in participants with mild-to-moderate SDB.

Introduction

Sleep disordered breathing (SDB) is a growing public health problem [1], which encompasses breathing difficulties during sleep [2]. The symptoms can range from loud and frequent snoring to partial (hypopnea) or complete (apnoea) airway obstruction and respiratory-related arousals from sleep, known as obstructive sleep apnoea (OSA) [3]. OSA is the most common SDB, affecting about one billion people worldwide between 30 and 69 years old [4]. The first-line OSA treatment is positive airway pressure (PAP) therapy [5, 6]. However, longitudinal studies report low adherence, especially among patients with milder disease [7, 8]. While some studies recommend exercise as a non-PAP treatment [9, 10], others report exercise only in relation to weight reduction [6]. Notably, a systematic review by the European Research Society task



force did not mention physical exercise as a non-PAP treatment option [11]. Also, a limited number of studies have evaluated the effects of exercise on snoring, but findings suggest that physically active OSA patients tend to snore less than inactive OSA patients [12]. Decreased snoring has been reported following a 16-week intervention of a very low-energy diet and a combination of aerobic exercises and resistance training [13].

The primary risk factors for OSA are overweight and obesity [14], with over 70% of OSA patients being obese (body mass index (BMI) $>30 \text{ kg}\cdot\text{m}^{-2}$) [15]. Lifestyle modifications, including exercise and diet, have been recommended for weight loss in obese OSA patients [16], as even a small weight reduction can reduce OSA severity [17]. However, studies have shown conflicting results on whether exercise programmes alone generate changes in anthropometry in OSA patients [18–22]. A limited number of randomised controlled trials (RCTs) with small sample sizes have studied the changes in body composition following an exercise programme and also shown mixed results [19, 21, 23]. In regard to mobile applications (hereinafter referred to as apps) studies, only one previous study has assessed the effects of a lifestyle app accessible through a smartphone as a treatment option for obese OSA patients [24]. This study reported weight reduction in 24 app users following a 4-week lifestyle modification (physical activity and diet) using a lifestyle app [24].

On the other hand, overweight and obesity influence physical fitness. Thus, poor hand dynamometry is associated with an increased risk of chronic conditions often coexisting with OSA, such as cardiovascular disease, type 2 diabetes [25] and hypertension [26]. However, only two RCTs evaluating the effects of exercise in OSA patients have used hand dynamometry to measure muscular strength [23, 27]. Both studies (one with elderly OSA patients) reported no change in hand dynamometry following an exercise intervention in OSA patients [23, 27]. Further, OSA is associated with impaired cardiorespiratory fitness [28], but exercise has been shown to improve cardiorespiratory fitness in OSA patients [21, 22, 29]. Despite using different types of exercises, high-intensity interval training [21], aerobic exercises [22], and a combination of aerobic and resistance training [29], all studies showed improvement in cardiorespiratory fitness following an exercise intervention for OSA patients [21, 22, 29]. Lastly, exercise has been shown to effectively improve health-related quality of life (HRQoL) in OSA patients [19, 22, 30]. On the other hand, with rapidly advancing digital technology, readily available via smartphones, there is a growing literature on digital therapeutic apps. Evidence-based apps are often rooted in self-care or self-help that guide patients to treat, prevent or manage diseases or conditions that have proven clinical benefits (*e.g.*, the Sidekick Health app) [31]. Lifestyle apps that encourage physical activity and healthy lifestyle behaviours can potentially be used as an accessible and flexible treatment option for obese OSA patients to achieve lifestyle modification [24].

Thus, despite the RCTs conducted so far, the studies on the effects of physical exercise programmes and app interventions are limited, both in sample size and in the number of variables studied. It should also be noted that the studies conducted so far have focused on moderate-to-severe OSA in middle-aged or older adult populations. In this context, the objective of this study was to assess the effects of a 12-week exercise programme and a lifestyle app compared to controls on SDB severity (as indicated by the apnoea–hypopnea index (AHI), and snore percentage), physical health (anthropometry, body composition, physical fitness) and HRQoL in 18- to 50-year-old adults with mild-to-moderate SDB.

Methods

Design

This was a RCT with three groups (exercise, app and control) performed for 12 weeks with a parallel design. The study was registered in ISRCTN16974764. The independent variable was the type of intervention (exercise programme, lifestyle app programme or no intervention). The dependent variables were SDB severity parameters (AHI and snore percentage) (primary outcomes), physical health parameters (anthropometry, body composition, physical fitness) and HRQoL (secondary outcomes). All the dependent variables were evaluated immediately before and after the interventions.

Participants

1299 subjects responded to the advertisements to participate in this study. The inclusion criteria were: 1) adults aged 18–50 years; 2) overweight or obese (BMI $\geq 25 < 42 \text{ kg}\cdot\text{m}^{-2}$); 3) inactive (not participating in an exercise programme at baseline); and 4) diagnosed with mild-to-moderate SDB (AHI $\geq 5 < 30.0$; objective snore $\geq 10\%$). 422 participants met the inclusion criteria of 1, 2 and 3. Subsequently, these subjects were invited to the laboratory at Reykjavík University Sleep Institute (RUSI) for a preliminary type 3 sleep study for one night (T3 device, Nox Medical, Reykjavík, Iceland) to confirm SDB (AHI $\geq 5 < 30.0$; objective snore $\geq 10\%$) scored from a minimum of 4 h of wearable O_2 measures and other

sleep study signals according to the current American Academy of Sleep Medicine (AASM) and the International Classification of Sleep Disorders (ICSD) criteria [32]. The following exclusion criteria were also considered: current OSA treatment, pregnancy, shift workers and inability to exercise. Out of the 357 that completed the preliminary studies, 222 were eligible for participation in the study. Finally, 192 subjects (age 37.4 ± 6.3 years, BMI 33.3 ± 4.2 kg·m⁻², 52.6% males) fulfilled the inclusion criteria, accepted participation in the study, and were randomised into exercise, app and control groups. The statistical power was calculated a posteriori ($n=192$, effect size=0.13, three groups and two measurements), with G*Power 3 [33] resulting in a power of 0.88. The randomisation was stratified by age, sex, BMI and AHI from the preliminary studies due to their potential confounding effects on the study outcomes using Python (version 3.10.6.) programming language and the A* Pathfinding algorithm. This artificial intelligence-based method ensures that individuals are grouped based on similarity, aiming for the stratified variables to be as alike as possible in each group. Difference was used to avoid any variable exceeding limits. Artificial intelligence method for randomisation was chosen due to small population (study country, Iceland), which increased the risk of bias in groups selection, making the algorithmic option more robust. In this way, using a hierarchical structure, the algorithm prioritised balancing the female and male count across each of the three groups (exercise, app, control). The algorithm then calculated a “score” for each group. The “score” reflected the difference between the mean value and standard deviation of key variables in each group to the total sample, total female sample and total male sample. When sex distribution was not a determining factor, the algorithm used the “score” to balance each group with regard to the overall sample characteristics (total, females, males).

111 participants were analysed, which represented a dropout rate of 42.2%. The flowchart is shown in figure 1. The recruitment of participants occurred in two phases: from June to August 2022 and from September 2022 to January 2023. Additionally, table 1 displays the characteristics of the sample before the interventions (baseline) and the results of Levene’s test, showing that the homogeneity assumption of the variance between the three groups was met.

Interventions

Two interventions were carried out: the exercise programme and the lifestyle app.

Exercise programme

The exercise programme was done three times per week for 60 min throughout the 12-week intervention period. The programme duration is the most common in this type of study [20–22, 27, 34, 35]. The programme was designed based on previous studies and recommendations [36–38]. Each session consisted of a 5- to 10-min warm-up (mobility and activation), 15–22 min of circuit training, 8–14 min of brisk walking and a 5- to 10-min cooldown period. To limit the risk of injuries, the dose of exercise gradually increased throughout the intervention period. Weeks 1–2: The circuit training consisted of 10 different exercises; the working time was 60 s, with a 30-s rest between exercises followed by an 8-min brisk walk. Weeks 3–4: The circuit training consisted of 12 different exercises; the working time was 60 s, with a 30-s rest between exercises followed by a 10-min brisk walk. Weeks 5–8: The circuit training consisted of 14 different exercises; the working time was 60 s, with a 30-s rest between exercises followed by a 12-min brisk walk. Weeks 9–12: The circuit training consisted of 16 exercises; the working time was 60 s, with a 20-s rest between exercises followed by a 14-min brisk walk. The circuit training consisted of upper body push (*i.e.* bench press and shoulder press), upper body pull (*i.e.* resistance band face pull and bicep curl), knee-dominant (*i.e.* squats and forward lunges), hip-dominant (*i.e.* deadlift and glute bridge), core-specific (*i.e.* modified plank and alternating superman), medicine ball throw (medicine ball wall throw and slam ball) and aerobic-specific exercises (*i.e.* jump rope and box toe taps). The exercise intensity was considered moderate intensity, evaluated after each part (warm-up, circuit training, brisk walking and cool down) of every session using the Borg Rating of Perceived Exertion [39]. The intensity of the warm-up was 8–9 (very light), circuit training ranged from 14 (somewhat hard) to 17 (very hard), brisk walking was 12 (moderate) to 13 (somewhat hard) and the cool down was 7 (extremely light).

Lifestyle app

Participants assigned to the app group were asked to complete daily tasks within the app (Sidekick Health, Reykjavík, Iceland) during the 12-week intervention period. The tasks encouraged healthy behaviours through goal setting, self-monitoring and completing health-related tasks in four categories: diet, physical activity, sleep and stress control. The lifestyle app had gamification elements embedded within it. Gamification elements are used within apps in order to nudge users towards healthy behaviours [40]. The physical exercises were divided into three categories: walking, home exercises and stress management exercises. Walking was presented as a challenge where participants were challenged to reach a specific number of daily steps, using the phone’s pedometer for tracking. The home exercises mainly consisted

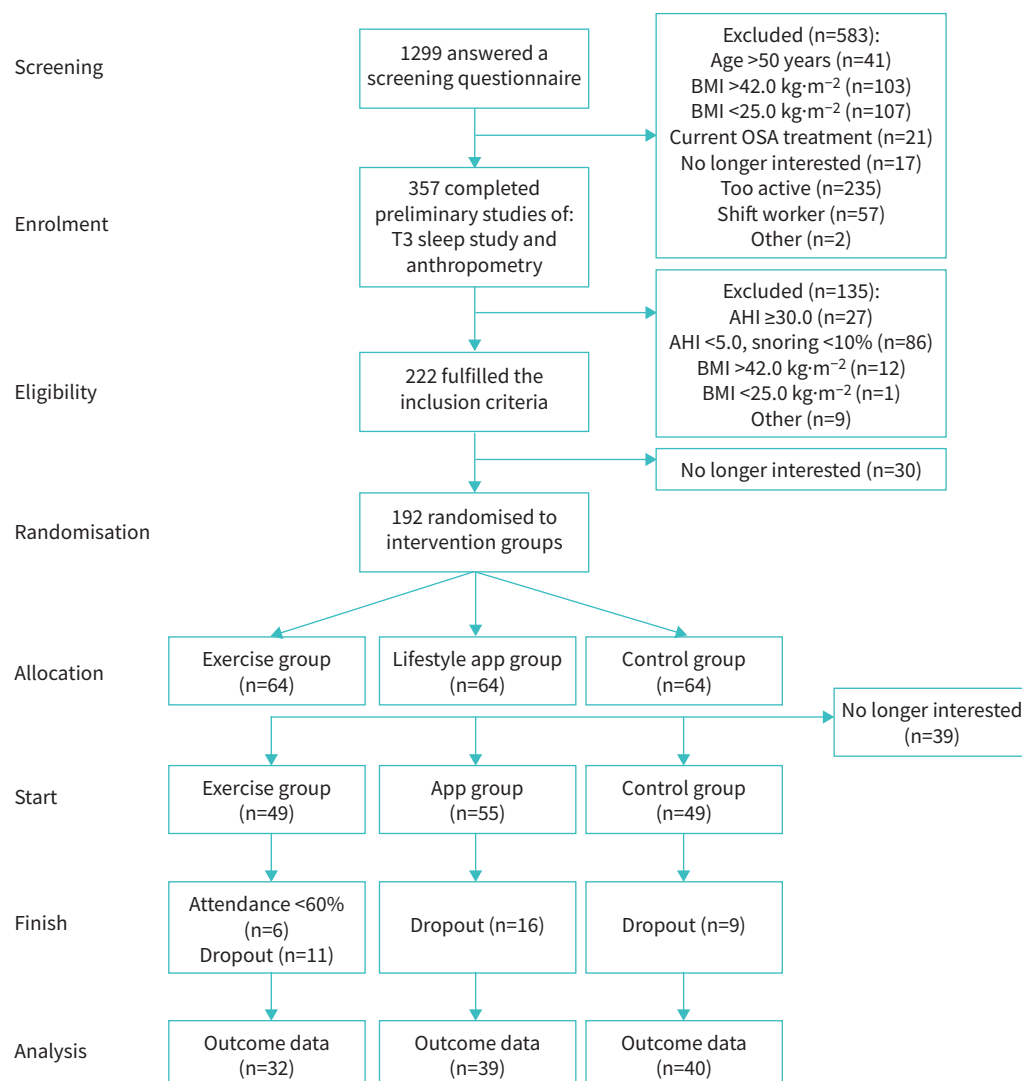


FIGURE 1 Summary of participant flow through the study. AHI: apnoea-hypopnea index; BMI: body mass index; OSA: obstructive sleep apnoea.

of routines offered by the app, based on classic exercises such as squats, push-ups and sit-ups, with instructions and demonstration videos. Finally, the stress management exercises were primarily focused on breathing control exercises, meditation and mindfulness. The users accumulated points that provided virtual and altruistic rewards such as badges and charitable water donations by completing a task for motivation and engagement. In addition, the participants in the lifestyle app programme received support and feedback from a live coach, delivered through text messages within the app. This app has been shown to be effective in weight loss for patients that are overweight or obese [41], as well as in glycemic control and improvement of psychological well-being in obese patients diagnosed with type 2 diabetes [42], and in improving metabolic health in patients with multiple diseases (obese individuals with metabolic syndrome or type 2 diabetes and non-alcoholic fatty liver disease) [43].

Measurements

All the participants underwent several evaluations: 1) SDB severity, 2) physical health (2a) anthropometry and body composition, and 2b) physical fitness), and (3) HRQoL assessments.

- 1) SDB severity. All participants had a 3-night sleep study using self-applied polysomnography (A1s, Nox Medical, Reykjavík, Iceland). A 3-night sleep study was performed to assess night-to-night variability in SDB severity [44]. The setup included frontal electroencephalogram (AF4, AF3, AF8 and AF7) and

TABLE 1 Baseline characteristics of each group and Levene's test results (n=153 participants)

Variable	Exercise group	App group	Control group	F	p-value
Participants n	49	55	49		
General information					
Age years	37.0±6.4	37.1±6.8	37.0±5.6	1.294	0.277
Males %	55.1	50.9	51.0		
SDB parameters					
AHI events·h ⁻¹	17.7±14.6	12.1±9.7	14.9±11.4	2.302	0.104
Snore %	36.2±21.9	35.6±20.1	30.1±19.9	0.395	0.674
Anthropometry					
Weight kg	101.0±14.8	101.8±18.1	96.6±14.3	2.373	0.097
BMI kg·m ⁻²	33.7±4.1	32.9±4.1	32.4±4.1	0.013	0.987
Neck circumference cm	40.2±4.0	40.4±3.4	39.9±4.0	1.385	0.253
Waist-to-hip ratio	0.95±0.09	0.96±0.09	0.94±0.08	0.954	0.388
Body composition					
Body fat %	35.4±7.2	34.8±7.3	34.6±7.1	0.100	0.905
Body fat mass kg	36.0±10.0	35.7±10.5	33.5±8.3	1.296	0.277
Skeletal muscle %	61.4±6.8	62.0±7.0	62.0±6.8	0.155	0.856
Skeletal muscle mass kg	61.8±9.9	62.9±12.0	60.0 ±10.8	1.201	0.304
Visceral adiposity index	11.5±3.5	10.8±3.8	10.4±3.0	2.297	0.104
Physical fitness					
Hand dynamometry N	286.6±83.5	317.5±87.9	297.8±84.4	0.785	0.458
6-min walking test m	619.6±61.7	632.7±63.1	625.4±66.2	0.362	0.697

Data are presented as mean±sd unless indicated otherwise. SDB: sleep disordered breathing; AHI: apnoea-hypopnea index; BMI: body mass index.

electrooculography (E1, E2, E3 and E4) recordings [45]. Nasal airflow was detected with a cannula measurement, oxygen saturation with oximetry, heart rate with electrocardiography and oximetry, respiratory movements with respiratory inductance plethysmography, thorax and abdominal belts, activity and body position with an accelerometer, and leg movements with left and right anterior tibialis electromyography. In addition, an audio recording was performed to detect snoring. Expert sleep technologists manually scored all sleep studies according to the AASM manual, version 2.6 [32]. The mean AHI from valid nights was used to determine OSA severity. The AHI was calculated as the total number of apnoea and hypopnea events per hour of sleep [32]. Snore ≥10% was used as the cut-off to confirm habitual snoring without OSA (no official cut-offs exist). Automatic scoring of snoring was done with manual validation (listening). Events above 65 dB with at least three snores in a series were scored. The snoring rate was defined as the percentage of snoring time during total sleep time.

- 2a) Anthropometry and body composition. The anthropometric and body composition measurements included height, weight (to calculate BMI) [46], neck circumference and waist-to-hip ratio, measured and calculated following the International Society for the Advancement of Kinapometry recommendations [47]. Height and weight were measured using a wall-mounted stadiometer (Soehnle Professional 5002.01, Backnang, Germany) and a digital scale (TANITA MC-780, Tokyo, Japan). Neck circumference and waist-to-hip ratio were measured with a flexible but non-stretchable tape measure with an accuracy of 0.1 cm. Body composition was measured using a bioelectrical impedance device (TANITA MC-780MA, Tokyo, Japan) that calculates body fat percentage, body fat mass, skeletal muscle percentage, skeletal muscle mass and visceral adiposity index (from 1 to 59).
- 2b) Physical fitness. Hand dynamometry of the dominant hand was evaluated using a Vernier hand dynamometer (Vernier, Orlando, FL, USA) [48]. Hand dynamometry is a frequently used method to determine muscular strength and is considered a feasible way to detect changes in physical function [49]. Each participant received three attempts with a 20-s rest between. The mean Newtons (N) for the three attempts was reported. Cardiorespiratory fitness was evaluated with a 6-min walking test [50]. This sub-maximal, self-paced test measures an individual's sub-maximal capacity to perform activities by walking as fast as possible for 6 min on a flat, hard surface. The total distance (m) was reported for further analysis.
- 3) HRQoL. The HRQoL was evaluated with the SF-36 questionnaire (short-form survey) [51]. SF-36 is a self-administered instrument frequently used concerning exercise programmes in OSA patients to evaluate HRQoL [13, 19, 22, 34, 52] and has good reliability (Cronbach's $\alpha > 0.85$) [53]. SF-36 measures HRQoL through eight health domains: physical functioning, role limitations due to physical health, role limitations due to emotional problems, vitality, emotional well-being, social functioning,

pain and general health [51]. Each domain is scored from 0 to 100, with higher scores indicating more favourable HRQoL. The SF-36 questionnaire data were collected and managed using REDCap (Research Electronic Data Capture) electronic data capture tools hosted at Reykjavík University, Reykjavík, Iceland. REDCap is a secure, web-based software platform designed to support data capture for research studies [54].

Procedure

Participants were recruited from the general population through media advertisements, where they answered a screening questionnaire, including general information about sex, height, weight, shiftwork, previous OSA diagnosis, current OSA treatment and physical activity. Participants who fulfilled the inclusion criteria from the screening questionnaire were invited to a preliminary type 3 sleep study and anthropometric measurements to further assess inclusion–exclusion criteria. Eligible participants were randomised into the three groups. Participants assigned to the exercise group were asked about the most suitable time to exercise to adapt the programme schedule to their needs. Only participants with at least 60% attendance in the exercise programme were analysed. As this was an RCT with random group assignments, participants could be assigned to the exercise group without initial interest. Since the participants were inactive, overweight or obese, and the programme was relatively demanding, an adherence goal of attending approximately two of the weekly sessions was set. Participants assigned to the app group were instructed to install the lifestyle app (Sidekick Health, Reykjavík, Iceland) on their smartphones. The exercise programme was conducted at the Sports Science Laboratory of Reykjavík University, designed by the leader of the work package (J.M. Saavedra), supervised by the PhD student (K.Y. Fridgeirsdottir), and delivered by MSc and third-year BSc students in Sports Science. After the initial phases of the study, the postdoc researcher (C.J. Murphy) joined the research team, performing coordinator functions under the responsibility of the principal investigator (E.S. Arnardottir) and the work package leader (J.M. Saavedra). All participants were informed about the purpose of this study, and written consent was a prerequisite for participation. The study was approved by the Icelandic Data Protection Authority and the National Bioethics Committee of Iceland (ref. no. 22–082) and respected the Declaration of Helsinki.

Statistical analysis

All the variables were checked for the test of homoscedasticity (Levene's variance homogeneity test) and normality (the Kolmogorov–Smirnov test) of their distribution. Basic descriptive statistics (mean and standard deviations) were calculated. In the case of nonnormal distribution, a logarithmic transformation was performed. Repeated measures ANOVA using Bonferroni *post hoc* test was performed to summarise changes in the dependent variables (SDB severity and physical health) concerning the independent variable (interventions exercise programme, lifestyle app programme and no intervention). The main effects of the time, group and time×group interaction were also calculated. A Wilcoxon signed-rank test assessed the difference in pre- and post-intervention HRQoL scores within each group. A Kruskal–Wallis H test was used to compare the post-intervention HRQoL scores across the three groups. All missing data were excluded from the analysis. For all analyses, the statistical significance was set at $p < 0.05$. IBM SPSS Statistics 28 was used for all statistical analysis.

Results

Table 2 shows the basic descriptive statistics, repeated measures ANOVA values, intragroup comparison, and SDB severity and physical health variables' studied time, group and time × group interaction effects. Regarding the primary outcomes, only AHI showed a time effect ($F = 6.290$, $p = 0.014$). In terms of secondary outcomes, there was a time effect on physical health: neck circumference ($F = 5.253$, $p = 0.024$), hand dynamometry ($F = 7.102$, $p = 0.009$) and 6-min walking test ($F = 8.340$, $p = 0.005$). There were time × group interactions in weight ($F = 9.318$, $p \leq 0.001$), BMI ($F = 9.302$, $p \leq 0.001$), body fat percentage ($F = 4.756$, $p = 0.01$), body fat mass ($F = 5.916$, $p = 0.004$) and skeletal muscle mass ($F = 9.3601$, $p \leq 0.001$). Figure 2 displays the intragroup comparison of SDB severity and physical health parameters.

Table 3 presents the results from nonparametric tests for the HRQoL parameters (secondary outcomes): the exercise programme improved physical functioning ($p = 0.036$), role limitations due to physical health ($p = 0.039$), vitality ($p = 0.005$) and general health ($p = 0.040$). The app programme improved physical functioning ($p < 0.001$), vitality ($p = 0.002$) and general health ($p = 0.010$). The HRQoL parameters did not differ between the groups prior to the interventions ($p > 0.058$) or after the interventions ($p > 0.073$). Figure 3 highlights the intragroup comparison of HRQoL domains.

Discussion

This RCT assessed the effects of a 12-week exercise programme and a lifestyle app programme on SDB severity (primary outcomes), physical health (anthropometry, body composition, physical fitness) and

TABLE 2 Mean±sd and repeated measures ANOVA results for sleep disordered breathing severity and physical health parameters corresponding to the exercise programme (EG), lifestyle app (AG), and control (CG) groups pre- and post-intervention, and main effects and interaction

Variable	Group	Time			Time effect		Group effect		Time×Group effect	
		Pre-intervention	Post-intervention	Δ%	F	p-value	F	p-value	F	p-value
Sleep parameters										
AHI [#] events·h ⁻¹	EG	16.6±11.1	13.5±9.2	-19.11*	6.290	0.014	0.988	0.376	1.714	0.185
	AG	12.1±10.4	12.2±12.7	1.01						
	CG	13.2±8.3	11.9±10.0	-9.86						
Snoring %	EG	36.7±21.7	36.7±19.3	0.14	3.375	0.069	0.543	0.583	0.799	0.453
	AG	31.9±20.6	35.4±19.7	11.20						
	CG	30.1±21.8	33.2±22.0	10.10						
Anthropometry										
Weight [#] kg	EG	101.3±16.3	102.1±16.4	0.86	2.038	0.156	1.148	0.321	9.318	<0.001
	AG	98.1±17.5	96.3±17.1	-1.79**						
	CG	96.3±13.6	96.2±14.3	-0.04						
BMI [#] kg·m ⁻²	EG	33.4±4.3	33.7±4.4	0.89	1.987	0.161	1.542	0.219	9.302	<0.001
	AG	32.1±3.8	31.5±3.7	-1.83**						
	CG	32.8±4.0	32.7±4.0	-0.15						
NC cm	EG	40.5±4.3	40.3±4.0	-0.54	5.253	0.024	0.431	0.651	1.474	0.233
	AG	40.1±3.4	39.7±3.5	-0.95*						
	CG	39.7±3.9	39.6±3.9	-0.05						
WHR	EG	0.95±0.10	0.95±0.09	0.15	0.114	0.736	0.219	0.804	0.185	0.831
	AG	0.94±0.08	0.94±0.08	-0.46						
	CG	0.94±0.07	0.94±0.09	-0.10						
Body composition										
BF %	EG	34.7±7.0	34.5±7.2	-0.69	0.387	0.535	0.540	0.584	4.756	0.010
	AG	34.3±7.2	33.9±7.1	-1.16*						
	CG	35.5±6.9	35.9±6.7	1.18*						
BFM kg	EG	35.5±10.4	35.6±10.8	0.26	1.125	0.291	0.498	0.609	5.916	0.004
	AG	33.9±9.9	32.8±9.6	-2.99**						
	CG	34.1±7.9	34.5±7.9	1.04						
SM %	EG	62.0±6.7	62.3±6.8	0.40	0.986	0.323	0.584	0.559	2.946	0.057
	AG	62.5±6.8	62.8±6.8	0.58						
	CG	61.2±6.7	60.9±6.4	-0.43						
SMM [#] kg	EG	62.5±10.1	63.2±10.1	1.08*	1.593	0.210	1.351	0.263	9.360	<0.001
	AG	61.0±11.8	60.3±11.6	-1.17*						
	CG	59.1±10.5	58.7±10.9	-0.69*						
Visceral adiposity index [#]	EG	11.5±3.8	11.4±3.7	-0.87	3.343	0.070	1.780	0.174	0.914	0.404
	AG	10.1±3.6	9.9±3.7	-2.28*						
	CG	10.4±3.1	10.4±3.4	0.00						
Physical fitness										
Hand dynamometry [#] N	EG	297.2±84.6	320.5±91.1	7.81*	7.102	0.009	0.456	0.635	2.850	0.062
	AG	309.7±88.4	310.2±91.5	0.18						
	CG	291.0±87.8	298.9±90.1	2.70						
6-min walking test m	EG	631.7±55.1	647.7±51.4	2.54*	8.340	0.005	0.558	0.574	0.772	0.465
	AG	632.9±58.5	640.9±63.5	1.26						
	CG	623.4±68.5	629.2±62.8	0.93						

p-values in bold type denotes statistical significance. Δ%: percentages change from pre to post-intervention; AHI: apnoea-hypopnea index; BMI: body mass index; NC: neck circumference; WHR: waist-to-hip ratio; BF %: body fat percentage; BFM: body fat mass; SM %: skeletal muscle percentage; SMM: skeletal muscle mass. #: a logarithmic transformation. *p<0.05; **p<0.001.

HRQoL (secondary outcomes) in 18- to 50-year-old adults with mild-to-moderate SDB. To the best of our knowledge, this is the largest RCT assessing exercise effects in SDB currently available and the first RCT that compares the effects of two interventions: an exercise programme and a lifestyle app programme, in participants with mild-to-moderate SDB. In general, the main findings of this study were that the 12-week exercise intervention promoted a reduction in AHI, increased skeletal muscle mass, physical fitness (muscular strength and cardiorespiratory fitness) and HRQoL in four domains. The lifestyle app programme generated changes in anthropometry and body composition and improvements in three HRQoL domains in participants with mild-to-moderate SDB but did not generate changes in AHI. No changes

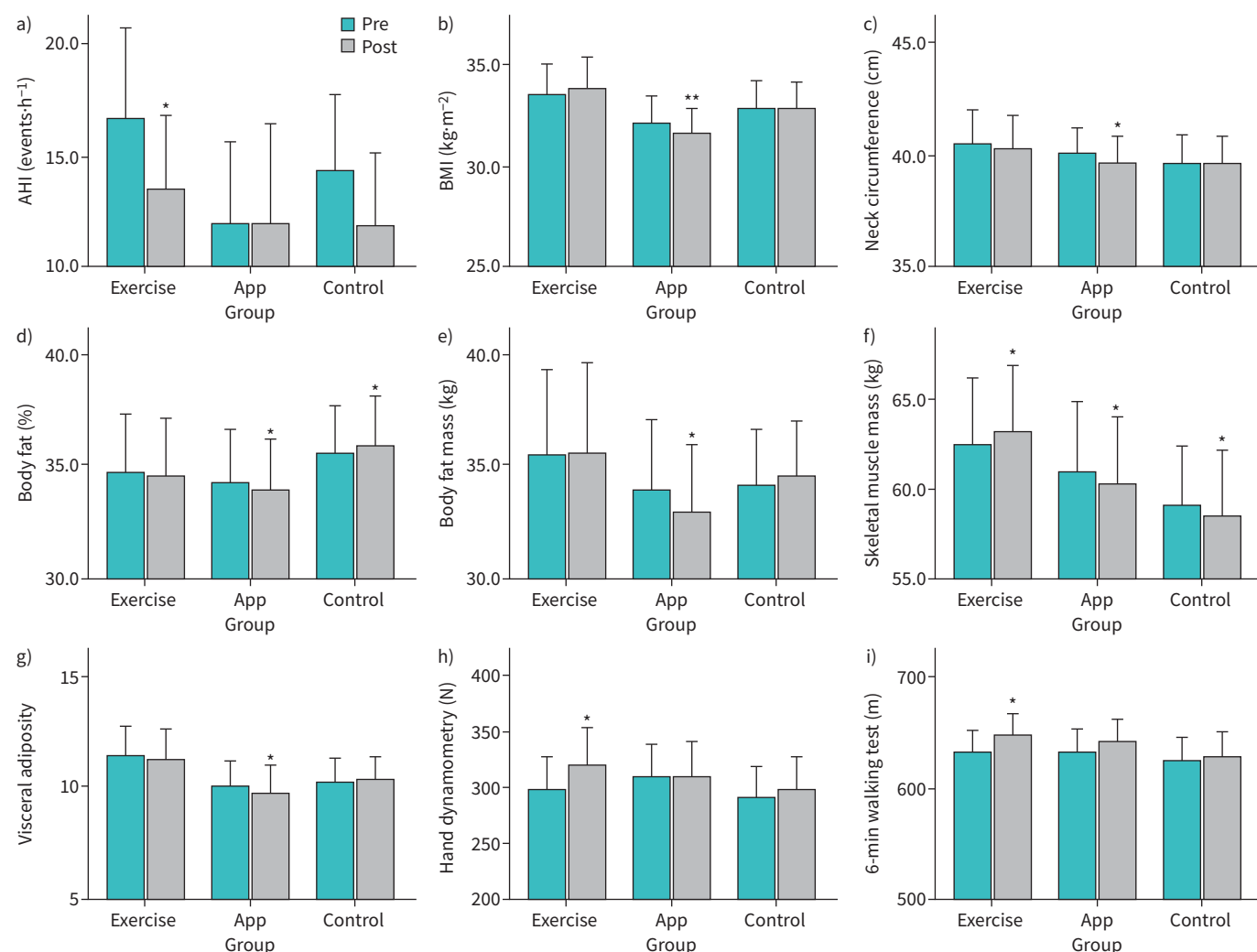


FIGURE 2 Intragroup differences between pre- and post-measures of sleep disordered breathing severity, and physical health: a) apnoea-hypopnea index (AHI), b) body mass index (BMI), c) neck circumference, d) body fat percentage, e) body fat mass, f) skeletal muscle mass, g) visceral adiposity, h) hand dynamometry and i) 6-min walking test. * $p<0.05$; ** $p<0.001$.

were found in the snore percentage in any of the groups. A time $\times$ group interactions were only present in weight, BMI, body fat (percentage and mass) and skeletal muscle mass.

Regarding the primary outcomes, the current study results showed a 19% reduction in AHI (pre-test: 16.6 ± 11.1 , post-test: 13.5 ± 9.2 , $p=0.014$) in the exercise group (figure 2a), with a time effect (table 2). Studies conducted with the same type of aerobic exercise (but on a bicycle) and resistance training but in people with moderate-to-severe OSA have obtained similar reductions in AHI: 19% [55], or higher: 29% [18], 31% [20] and 45% [19]. The difference between these studies and the current study are smaller exercise intervention samples ($n=11$ and 18 respectively *versus* 32) [19, 55], and control groups were active [20], or received education about diet [18]. However, reductions in AHI are achieved with programmes involving a different number of sessions/week: four [20] or six [19], or longer sessions (120 min) [18, 19]. It should be noted that the characteristics of the programmes are not exactly the same since the current study consisted of 12 weeks with three 60-min sessions per week, 15–22 min of circuit training and 8–14 min of brisk walking. In contrast, the previous studies used more time in both aerobic exercise 37.5 [20] and 45 min [18, 19] and resistance training 30 min [18, 19]. This indicates that it is unnecessary for people with mild-to-moderate OSA to adhere to long sessions (>60 min) or high weekly frequency ($>three$ sessions) to significantly reduce AHI. This is an important finding as this less intense programme is likely easier to adhere to than the more intense programmes. No reduction was found in AHI for the app group, despite their significant weight loss, highlighting the importance of OSA patients

TABLE 3 Mean±SD and Wilcoxon signed-rank test for the health-related quality of life pre- and post-intervention

Variable/Group	Time		Δ%	Wilcoxon signed-rank test p-value	Kruskal–Wallis H p-value
	Pre-intervention	Post-intervention			
PF					
EG	85.8±11.2	90.7±10.2	5.64	0.036*	0.335
AG	87.2±9.4	92.8±9.2	6.33	<0.001**	
CG	89.1±13.6	88.9±11.4	−0.15	0.422	
RPH					
EG	67.5±32.9	83.3±28.9	23.45	0.039*	0.196
AG	71.6±33.2	82.8±30.0	15.67	0.072	
CG	70.3±32.2	68.9±38.4	−1.92	0.742	
REP					
EG	85.5±27.2	77.8±35.4	−9.09	0.191	0.479
AG	70.1±34.9	75.9±37.7	8.20	0.511	
CG	69.4±35.5	67.6±40.4	−2.60	0.844	
VI					
EG	36.7±18.1	45.0±17.4	22.72	0.005*	0.073
AG	38.6±18.2	51.6±18.3	33.48	0.002*	
CG	36.4±18.2	40.4±18.7	11.17	0.164	
EWB					
EG	71.9±16.4	70.5±15.7	−1.86	0.536	0.203
AG	71.7±11.3	73.5±13.5	2.51	0.290	
CG	67.5±16.0	66.5±16.3	−1.44	0.605	
SF					
EG	76.3±19.5	81.3±20.7	6.56	0.098	0.746
AG	76.3±21.0	79.3±20.7	3.95	0.554	
CG	72.6±19.3	78.0±20.3	7.44	0.116	
P					
EG	70.8±23.3	77.9±21.4	10.13	0.078	0.693
AG	71.1±19.8	76.1±17.4	7.03	0.364	
CG	72.4±21.4	73.9±21.6	2.15	0.658	
GH					
EG	59.8±12.1	65.2±9.6	8.93	0.040*	0.874
AG	59.5±11.7	65.0±12.2	9.28	0.010*	
CG	66.8±13.5	65.8±13.9	−1.42	0.729	
Kruskal–Wallis H for the difference between the exercise programme (EG), lifestyle app (AG), and control (CG) groups post-intervention. p-values in bold type denotes statistical significance. Δ%: percentage change from pre- to post-intervention; PF: physical functioning; RPH: role limitations due to physical health; REP: role limitations due to emotional problems; VI: vitality; EWB: emotional well-being; SF: social functioning; P: pain; GH: general health. *p<0.05; **p<0.001.					

following a structured exercise programme, preferably aerobic and resistance training programme, to reduce their OSA severity, coherent with a recent systematic review and meta-analysis [10].

With respect to the secondary outcomes, the results showed changes in anthropometry in the app group measured as weight, BMI (figure 2b) and neck circumference (figure 2c). These results partly align with a previous study, indicating reduced weight and BMI in OSA patients following a 4-week lifestyle app intervention [24]. The difference between that study and the current one is that it has a smaller lifestyle app sample (n=24 *versus* 39), no measures of neck circumference or waist-to-hip ratio, and daily goals focused on physical activity and diet, compared to diet, physical activity, sleep and stress control in the current study. No changes were observed in anthropometry in the exercise group, evaluated as weight, BMI, neck circumference (figure 2b,c), and waist-to-hip ratio. The results are consistent with a previous study reporting no change in weight, BMI and neck circumference following a 12-week exercise intervention, yet it achieves significant reductions in AHI [20]. Another type of exercise intervention (high-intensity interval training) has shown no change in BMI but reduced neck circumference [21]. However, the results contradict previous studies reporting changes in weight [18], BMI, neck circumference and waist-to-hip ratio [19] following an exercise intervention in OSA patients. These studies included dietary management as a part of the intervention [18, 19], which may explain the difference in the results. In the current study, there was a time × group effect in weight and BMI (reduced in the app group) and a time effect in neck circumference (table 2). This indicates that the app-based programme effectively reduced weight and BMI,

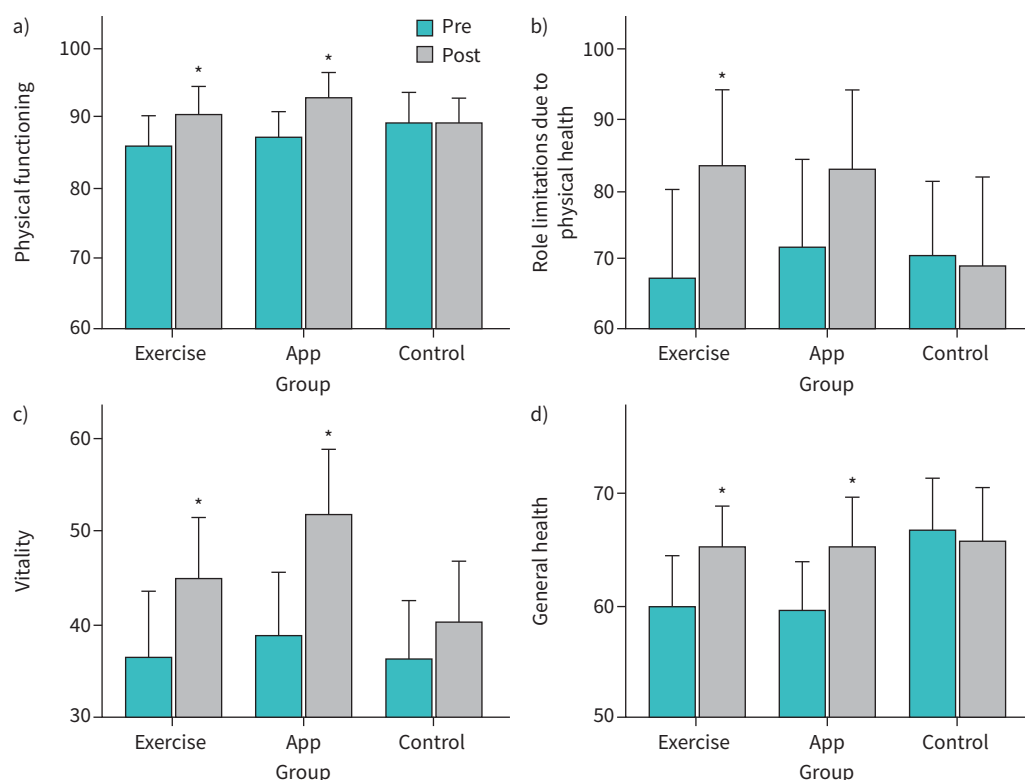


FIGURE 3 Intragroup differences between pre- and post-measures of health-related quality of life: **a)** physical functioning, **b)** role limitation due to physical health, **c)** vitality and **d)** general health. * $p < 0.05$.

not achieved by the other groups. This is significant for igniting future research into the use of lifestyle apps and other digital therapeutics for weight reduction.

The current study results showed changes in body composition (secondary outcomes), where participants in the exercise group gained skeletal muscle mass (figure 2f). The results contradict a previous study that reported decreased body fat mass (kg) but no change in fat-free or skeletal muscle mass in the exercise group following a 4-week individualised exercise training programme [19]. This suggests that the intervention programme was more intense over a shorter period than the current one, and the diet management as a part of the intervention may explain the difference in the results. However, that study was limited by the intervention group sample size ($n=11$). Furthermore, the lifestyle modification delivered through a smartphone app promoted a reduction in body fat percentage and body fat mass, and a significant loss of skeletal muscle mass (figure 2d,e,f). Visceral adiposity also decreased significantly (figure 2g). Weight loss should ideally be derived from fat mass [56], but the loss of skeletal muscle mass in the lifestyle app group may partly explain the subsequent drop in BMI of $\sim 3\text{--}8\%$ per decade [57], resulting in loss of strength and function, referred to as age-related sarcopenia. This indicates the importance of resistance training to improve muscle strength and function, which is coherent with a previous study [56]. Also, in the current study, there was a time $\times$ group effect on body fat percentage (decrease in the app group and increase in the control group), body fat mass (decrease in the app group) and skeletal muscle mass (increase in the exercise group and decrease in app group) (table 2). The results indicate that the lifestyle app intervention is more effective in reducing body fat. However, the exercise intervention is more effective in increasing skeletal muscle mass.

Regarding physical fitness (secondary outcomes), the results showed that only the exercise group improved in hand dynamometry (muscular strength) and 6-min walking test (cardiorespiratory fitness) (figure 2h,i) with a time effect (table 2). The hand dynamometry results do not agree with a previous study, which showed no change in isometric hand dynamometry following a 6-month aerobic and resistance training intervention [23]. This study had a smaller intervention sample ($n=20$ versus 32) than the current study and lasted 72 sessions, initially three times/week for 6 months, but ended up lasting 11.65 ± 0.85 months. Further, the difference in the results may be explained by the fact that in the previous study, 10 min of

each session were dedicated to resistance training; in comparison, 15–22 min of circuit training in each session in the current study. The length of the previous study and the low weekly frequency (≤ 3 times per week) may also explain the difference in the results. Concerning the improvements in cardiorespiratory fitness, the results of the current study align with a previous study reporting improvements in peak oxygen uptake ($\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) (pre-test: 24.4 ± 6.0 , post-test: 26.7 ± 6.1 , $p=0.003$) in 36 exercise group participants after a 9-month aerobic and resistance training intervention [29]. Further, the current study results also align with other studies reporting improved cardiorespiratory fitness following other types of exercise interventions: high-intensity interval training [21] and aerobic exercise [22] in people with moderate-to-severe OSA. It is noteworthy that both low hand dynamometry and cardiorespiratory fitness are related to numerous comorbidities often coexisting with SDB, including obesity, type 2 diabetes, cardiovascular disease and impaired HRQoL [25, 58]. The results indicate favourable changes regarding physical fitness parameters connected to comorbidities often coexisting with SDB following a 12-week aerobic and resistance training intervention.

Finally, regarding HRQoL (secondary outcomes), the result of the present study showed improvements in four domains (physical functioning, role limitations due to physical health, vitality and general health) of the SF-36 questionnaire in the exercise group (figure 3a–d) (table 3). Improvements in three domains (physical functioning, vitality and general health) were also observed in the app group (figure 3a,c,d). The results of the present study are mostly consistent with a previous study that reported improvements in physical functioning, role limitations due to physical health, vitality, social functioning, pain and general health following a 4-week aerobic and resistance training exercise programme [19]. However, the current study did not find significant intragroup changes in pain and social functioning (table 3). Further, another study observed the largest improvement in HRQoL in the exercise group out of the four groups studied (exercise, PAP, exercise+PAP and control groups) [35]. This indicates that exercise alone can effectively improve HRQoL in OSA patients, coherent with a recent systematic review and meta-analysis [30]. However, the results of the current study contradict a study that did not show significant improvement in HRQoL following a 12-week (5 sessions/week, 60 min) exercise intervention of T'ai Chi and Qigong [34]. The difference in the results may be explained by the different types of exercise interventions used in the studies, and the previous study included an active control group (home exercises). The results of the current study indicate that both exercise- and app-based programmes can effectively improve physical functioning, vitality and general health in 18- to 50-year-old adults with mild-to-moderate SDB, with the exercise programme also reducing role limitations due to physical health.

The strengths of this study include the fact that this is the largest RCT assessing exercise effects in individuals with mild-to-moderate SDB. It is also the first study to compare the effects of a structured exercise programme and a lifestyle app on individuals with SDB, with extensive objective and subjective measurements of their sleep and physical health. Also, the exercise programme was designed for sedentary individuals with structured aerobic and resistance training, and participants' perceived exertion was measured in all exercise sessions. The state-of-the-art 3-night polysomnography (PSG) performed at baseline and follow-up allowed us to assess night-to-night variability, which is known to be higher for mild-to-moderate OSA than for severe OSA and healthy individuals [59]. This study has some limitations. First, the 3-night PSG was performed at home, and there were no recommendations about sleeping or not sleeping with a partner in the same bed to keep the sleep routine as close to normal as possible. However, this means that if the participant had a snoring partner, it could have falsely inflated the number of snore events. Second, one participant in the control group had a pre-test AHI of 51.8 and a post-test AHI of 15.9. This participant was considered an outlier and was excluded from this variable's analysis. Third, the study was conducted on 18- to 50-year-old adults (mean age of 37.4 years), so the conclusions of the present study cannot be generalised to older populations with SDB, or at the very least, should be interpreted with caution. Fourth, the dropout rate was high (44.2%), although the range of dropout rates from the studies cited in this current work varies from 7.1% [35] to 44.4% [52], with a mean of 15.7%. This could indicate that, despite the effectiveness of the interventions, they are demanding and require a high level of commitment from the participants in order to complete the intervention. Finally, it would have been interesting to include a group that combined both the physical exercise and the app intervention; however, since the app already included physical exercise in its programme, it was decided not to include it in this study.

Conclusions

The conclusions of this study were five-fold: 1) the 12-week aerobic and resistance training programme reduced AHI, increased skeletal muscle mass, physical fitness and four HRQoL domains in participants with mild-to-moderate SDB; 2) the 12-week lifestyle app focusing on diet, physical activity, sleep and stress control reduced weight, BMI, neck circumference, body fat and visceral adiposity, while improving

in three HRQoL domains in participants with mild-to-moderate SDB, but it negatively affected skeletal muscle mass; 3) both interventions produced benefits for people with mild-to-moderate SDB, but only the exercise programme reduced AHI, highlighting the need for a structured exercise programme to reduce OSA severity; 4) the exercise-based intervention had a greater impact on HRQoL; and 5) these results suggest that a 12-week exercise programme conducted three times a week for 60 min is sufficient to reduce SDB severity and generate relevant health improvements. In contrast, the improvements from the lifestyle app-based intervention were more modest and did not affect SDB severity.

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Data availability: Data will not be shared.

Provenance: Submitted article, peer reviewed.

This clinical trial is prospectively registered with the ISRCTN Registry as 16974764

Ethics statement: The study was approved by the Icelandic Data Protection Authority and the National Bioethics Committee of Iceland (reference number 22-082).

Conflict of interest: All the authors have nothing to disclose.

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