The Role of Physical Activity and Exercise in Sleep-Disordered Breathing

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Abstract

Introduction: Sleep-disordered breathing (SDB), particularly obstructive sleep apnea (OSA), is a major public health concern, affecting around one billion adults globally, with obesity as a key risk factor. Fat distribution in the neck and abdomen, in addition to physical inactivity and sedentary behavior, contribute to its severity. OSA disrupts sleep, reduces sleep quality, causes daytime sleepiness, and significantly impacts physical health and well-being. While positive airway pressure therapy is the gold-standard treatment for moderate-to-severe OSA, limited options exist for milder cases. Exercise interventions have shown promise in reducing OSA symptoms, especially in moderate-to-severe cases, while lifestyle mobile applications (apps) have been shown to promote weight loss.

Objectives: The overall objectives of this doctoral thesis were: (i) To explore the differences in the role of physical activity (PA) in individuals with OSA by examining both subjectively and objectively measured PA, and to study PA as a predictor of OSA severity; and (ii) to evaluate the effects of two distinct interventions, a structured exercise program and a lifestyle app, on various SDB-related and health parameters including SDB severity, anthropometry, body composition, physical fitness, health-related quality of life (HRQoL), and sleep health in 18-50-year old individuals with mild to moderate SDB.

Methods: In Paper I, 65 participants (49.2% males) were assessed to determine the relationship between OSA severity and daily PA. Participants were categorized into three OSA severity groups: no, mild, and moderate-to-severe OSA. Participants completed anthropometric measurements, body composition, apnea-hypopnea index (AHI), and a desaturation parameter (DesSev+RecSev), wore a smartwatch for one week, and completed a PA questionnaire and daily exercise logs in a sleep diary. In Papers II and III, 192 participants (52.6% male) were enrolled in a 12-week randomized controlled trial evaluating the effects of exercise and lifestyle app interventions. Participants underwent comprehensive measurements pre- and post-intervention. The measurements included AHI and snoring, anthropometry, body composition, physical fitness, HRQoL questionnaire, and sleep health (subjective and objective measurements). The exercise intervention involved supervised 60-

minute circuit training and brisk walking sessions three times per week, while the lifestyle app intervention included daily tasks focused on diet, PA, stress management, and sleep.

Results: Participants with moderate-to-severe OSA underestimated their sitting time compared to objectively measured PA, a discrepancy not observed in participants with no or mild OSA. PA was not a predicting factor for OSA severity, whereas age, body mass index (BMI), and body composition were significant predictors. A no-to-weak correlation was found between objective and subjective PA measures. The 12-week exercise intervention reduced AHI and increased skeletal muscle mass, physical fitness, and HRQoL in four domains. In addition to improvement in subjective sleep health, reflected in the Pittsburgh Sleep Quality Index (PSQI) global score and three PSQI subscales. The lifestyle app program reduced weight, BMI, neck circumference, body fat, visceral adiposity, and skeletal muscle mass while improving three HRQoL domains. Further, subjective sleep health was enhanced, particularly in the daytime dysfunction subscale of the PSQI, in addition to changes in objective sleep health, reflected in reduced wake after sleep onset (WASO), increased light sleep (N2), and decreased deep sleep (N3).

Conclusions: The overall conclusions were: (i) Individuals with moderate-to-severe OSA tended to underestimate their sedentary time, with subjective PA assessments misaligning with objective measurements. PA was not a predictor of OSA severity after accounting for age, BMI, and body composition. (ii) Both structured exercise and lifestyle app interventions benefited but had distinct effects. The 12-week exercise program reduced AHI, increased skeletal muscle mass, and improved physical fitness, HRQoL, and subjective sleep health, without changes in anthropometry. In contrast, the lifestyle app intervention promoted improvements in anthropometry, body composition, and HRQoL and influenced both subjective and objective sleep health parameters, but did not lower AHI and led to muscle mass reduction.

Keywords: Apnea-hypopnea index, snoring, obstructive sleep apnea, aerobic exercise, concurrent training,

Ágrip

Inngangur: Öndunarháðar svefntruflanir, sérstaklega kæfisvefn, eru alvarlegt lýðheilsuvandamál sem hefur áhrif á um það bil einn milljarð fullorðinna á heimsvísu, þar sem offita er lykiláhættuþáttur. Fitudreifing á hálsi og kvið, auk hreyfingarleysis og kyrrsetu auka alvarleika ástandsins. Kæfisvefn truflar svefn, dregur úr svefngæðum, veldur dagsyfju og hefur veruleg áhrif á líkamlega og andlega heilsu. Þrátt fyrir að svefnöndunartæki sé aðalmeðferðarúrræðið við miðlungs til alvarlegum OSA, eru fá úrræði í boði fyrir vægari tilfelli sjúkdómsins. Rannsóknir hafa sýnt fram á að æfingaíhlutanir geti dregið úr einkennum kæfisvefns, sérstaklega meðal einstaklinga með miðlungs til alvarleg einkenni, á meðan lífstíls forrit í snjallsímum hafa sýnt árangur í að stuðla að þyngdartapi.

Tilgangur: Markmið þessarar doktorsritgerðar voru (i) að rannsaka hlutverk daglegrar hreyfingar hjá einstaklingum með kæfisvefn með því að bera saman hlutlægar og huglægar mælingar á hreyfingu og meta hvort hreyfing spái fyrir um alvarleika kæfisvefns; og (ii) að meta áhrif tveggja mismunandi íhlutana, skipulagðrar æfingaáætlunnar og lífsstílsforrits, á mismunandi þætti tengda kæfisvefni og heilsu, þar á meðal alvarleika kæfisvefns, líkamsmælingar, líkamssamsetningu, líkamlegt hreysti, heilsutengd lífsgæði og svefnheilsu hjá einstaklingum á aldrinum 18-50 ára með vægan til miðlungsháan kæfisvefn.

Aðferðir: Í fyrstu rannsókninni (Grein I), voru 65 þátttakendur (49.2% karlar) metnir til að rannsaka tengslin milli alvarleika kæfisvefns og daglegar hreyfingar. Þátttakendum var skipt í þrjá hópa eftir alvarleika kæfisvefns: enginn, vægur og miðlungs-til-alvarlegur kæfisvefn. Þátttakendur gengust undir líkamsmælingar, líkamssamsetningargreiningu, mælingar á fjölda öndunarhléa á klukkustund (AHI) og súrefnismettunar breytu (DesSev+RecSev), báru snjallúr í eina viku og svöruðu spurningalista um hreyfingu auk daglegrar spurningar um skipulagða æfingu í rafrænni svefndagbók. Í annarri rannsókn (Grein II og III), voru 192 einstaklingar (karlar 52.6%) sem tóku þátt í 12 vikna slembaðari samanburðarrannsókn með íhlutun. Þátttakendur undirgengust yfirgripsmiklar mælingar fyrir og eftir íhlutun, þar á meðal AHI og hrotur, líkamsmælingar, líkamssamsetningargreiningu, mat á líkamlegu hreysti, svöruðu spurningalistum um HRQoL auk huglægra og hlutlægra

mælinga á svefnheilsu. Æfingaíhlutunin samanstóð af þol- og styrktarþjálfun þrisvar í viku 60 mínútur í senn undir handleiðslu þjálfara. Íhlutun með lífstíls forriti í gegnum snjallsíma fól í sér dagleg verkefni, með áherslu á mataræði, hreyfingu, streitustjórnun og svefn.

Niðurstöður: Þátttakendur með miðlungs til alvarlegan kæfisvefn vanmátu kyrrsetutíma sinn miðað við hlutlægar mælingar, þetta misræmi sást ekki hjá þátttakendum með vægan eða engan kæfisvefn. Hreyfing var ekki marktækur spáþáttur fyrir alvarleika kæfisvefns, aldur, líkamsþyngdarstuðull (BMI) og líkamssamsetning voru hins vegar marktækir spáþættir. Veik eða engin fylgni fannst milli hlutlægra og huglægra mælinga á hreyfingu. Hjá þátttakendum með vægan til miðlungsháan kæfisvefn leiddi 12 vikna æfingaáætlunin til lækkunar á AHI, auknins vöðvamassa, bætinga á líkamlegu hreysti og fjórum þáttum HRQoL. Að auki urðu bætingar á huglægri svefnheilsu samkvæmt heildarskori spurningalista um svefngæði (PSQI) og þremur undirþáttum hans, án breytinga á hlutlægri svefnheilsu. Lífsstílsforritið leiddi til þyngdartaps, lækkaði BMI, og minnkaði hálsummál, líkamsfitu, innri fitu og vöðvamassa. Einnig urðu bætingar í þremur þáttum HRQoL og huglægri svefnheilsu, sérstaklega í "dagsyfju" undirþætti PSQI. Auk þess urðu breytinga á hlutlægri svefnheilsu, þar sem vökutími eftir svefnbyrjun styttist, aukinn léttur svefn (N2) og styttri djúpsvefn (N3). Einungis N3 svefnstigið sýndi mun milli apphópsins og samanburðarhóps.

Ályktanir: (i) Einstaklingar með miðlungs til alvarlegan kæfisvefn vanmátu setutíma sinn, þar sem huglægar mælingar á hreyfingu reyndust ónákvæmar miðað við hlutlægar mælingar. Hreyfing var ekki marktækur spáþáttur fyrir alvarleika kæfisvefns, en aldur, BMI og líkamsamsetning reyndust mikilvægustu spáþættirnir. (ii) Bæði skipulagða æfingaáætlunin og lífsstílsforritið veittu heilsufarslegan ávinning fyrir einstaklinga á aldrinum 18-50 ára með vægan til miðlungsháan kæfisvefn, en með ólíkum áhrifum. Æfingaáætlunin lækkaði AHI, jók beinagrindarvöðvamassa og bætti líkamlegt hreysti, HRQoL og huglæga svefnheilsu, án breytinga á líkamsmælingum. Aftur á móti stuðlaði lífsstílsforritið að jákvæðum breytingum á líkamsmælingum, líkamsamsetningu og HRQoL, auk þess að hafa áhrif á bæði huglægar og hlutlægar svefnmælingar, en það lækkaði ekki AHI og

leiddi til rýrnunar á vöðvamassa.

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III. Fridgeirsdottir, K. Y., Murphy, C. J., Islind, A. S., Hrubos-Strøm, H., Saavedra, J. M., & Arnardottir, E. S. (2025). The effects of an exercise program and a lifestyle app on sleep health in people with mild to moderate sleep-disordered breathing: ISRCTN 16974764. *Submitted for publication.*

Declaration of Contribution

Paper I: *Katrin Y. Fridgeirsdottir:* Conceptualization; data curation; formal analysis; methodology; writing – original draft; writing – review and editing. *Kristín A. Ólafsdóttir:* Data curation; funding acquisition; project administration; writing – review and editing. *Anna Sigridur Islind:* Data curation; funding acquisition; writing – review and editing. *Timo Leppänen:* Funding acquisition; data curation; writing – review and editing. *Erna S. Arnardottir:* Conceptualization; methodology; funding acquisition; project administration; supervision; writing – original draft; writing – review and editing. *Jose M. Saavedra:* Conceptualization; formal analysis; methodology; funding acquisition; supervision; writing – original draft; writing – review and editing

Paper II: *Katrin Y. Fridgeirsdottir:* Data curation; formal analysis; methodology; writing – original draft; writing – review and editing. *Conor Jordan Murphy:* Data curation; methodology; writing – review and editing. *Anna Sigridur Islind:* Funding acquisition; methodology; writing – review and editing. *Birta S. Árnadóttir:* Data curation; writing – review and editing. *Harald Hrubos-Strøm*: Funding acquisition; methodology; writing – review and editing. *Erna S. Arnardottir:* Conceptualization; methodology; funding acquisition; project administration; supervision; writing – original draft; writing – review and editing. *Jose M. Saavedra:* Conceptualization; formal analysis; methodology; funding acquisition; supervision; writing – original draft; writing – review and editing.

Paper III: *Katrin Y. Fridgeirsdottir:* Data curation; formal analysis; methodology; writing – original draft; writing – review and editing. *Conor Jordan Murphy:* Data curation; methodology; writing – review and editing. *Anna Sigridur Islind:* Funding acquisition; methodology; writing – review and editing. *Harald Hrubos-Strøm*: Funding acquisition; methodology; writing – review and editing. *Jose M. Saavedra:* Conceptualization; formal analysis; methodology; funding acquisition; supervision; writing – original draft; writing – review and editing. *Erna S. Arnardottir:* Conceptualization; methodology; funding acquisition; project administration; supervision; writing – original draft; writing – review and editing.

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List of Abbreviations

AASM	American Academy of Sleep Medicine
ABOSA	Automatic Blood Oxygen Saturation Signal Analysis Software
AI	Apnea Index
AHI	Apnea-Hypopnea Index
ATP	Adenosine Triphosphate
BMI	Body Mass Index
CVD	Cardiovascular Disease
DesSev	Desaturation Severity
ECG	Electrocardiography
EDS	Excessive Daytime Sleepiness
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
ESS	Epworth Sleepiness Scale
HI	Hypopnea Index
HIIT	High-Intensity Interval Training
HRQoL	Health-Related Quality of Life
MS	Metabolic Syndrome
N1	Non-Rapid Eye Movement Sleep Stage 1
N2	Non-Rapid Eye Movement Sleep Stage 2
N3	Non-Rapid Eye Movement Sleep Stage 3
NREM	Non-Rapid Eye Movement Sleep
ODI	Oxygen Desaturation Index
OSA	Obstructive Sleep Apnea
PA	Physical Activity
PCr	Phosphocreatine
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
RecSev	Recovery Severity

RCT	Randomized Controlled Trial
RedCap	Research Electronic Data Capture data management platform
REM	Rapid Eye Movement Sleep
SDB	Sleep-Disordered Breathing
SE	Sleep Efficiency
SOL	Sleep Onset Latency
SpO_2	Oxygen Saturation
SQ	Sleep Quality
TST	Total Sleep Time
WASO	Wake After Sleep Onset
WHO	World Health Organization

1 INTRODUCTION

1.1 Sleep

Sleep is a natural, recurring neurobehavioural state of unconsciousness during which the body and brain undergo rest and restoration, primarily responding to internal stimuli (Brinkman et al., 2024). In humans, sleep is typically characterized by a reclined posture, behavioral inactivity, and closed eyes (Carskadon & Dement, 2005). Sleep also involves psychological changes, including shifts in muscle tone, breathing patterns, body temperature, heart rate, and brain activity (Institute of Medicine (US) Committee on Sleep Medicine and Research, 2006). The recommended sleep duration for adults aged 18 to 64 is seven to nine hours per day (Hirshkowitz et al., 2015), which amounts to approximately one-third of a person's life (Jacobson & Hoyer, 2022).

Beyond its role in daily restoration, sleep is one of the fundamental pillars of overall health and well-being, alongside regular exercise, a nutritious diet, and effective stress management (Abe & Abe, 2019). These four interconnected behaviors are essential for maintaining physical and mental health, as well as preventing a range of chronic conditions, including obesity, type II diabetes, hypertension, cardiovascular disease (CVD), certain cancers, cognitive decline, depression, and anxiety (Abe & Abe, 2019; Sadiq, 2023).

1.2 Sleep Health

The concept of "sleep health" was defined as a multidimensional pattern of sleep and wakefulness, adapted to individual, social, and environmental demands, that promotes physical and mental health and well-being (Buysse, 2014). Sleep health encompasses six subjective domains: regularity, sleep satisfaction, appropriate timing, adequate duration, high efficiency, and sustained daytime alertness (Buysse, 2014; Vorster et al., 2024). This approach reframes sleep from merely avoiding sleep disorders and disturbances to recognizing it as a positive health attribute (Meltzer et al., 2021).

Sleep health can be assessed using either subjective or objective methods or both (Meltzer et al., 2021). Whereas multidimensional tools are recommended for comprehensive sleep health evaluation (Chung et al., 2021, 2023). Subjective assessments of sleep health are typically derived from questionnaires and sleep diaries (Monk et al., 2000). The regularity satisfaction, alertness, timing, efficiency, and duration (RU-SATED) questionnaire, a validated self-reported scale, measures all five dimensions of sleep health (Buysse, 2014; Ravyts et al., 2021). Additional questionnaires, more frequently used in the field of sleep science, include the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989), Epworth Sleepiness Scale (ESS) (Johns, 1991), Medical Outcome Surway (MOS) sleep measure (Hays & Stewart, 1992) and PROMIS sleep disturbance and sleep-related impairment scale (Buysse et al., 2010), can further enhance the evaluation of sleep health (Buysse, 2014). Subjective assessments rely on an individual's perception of sleep, while objective measures often provide more accurate data. However, studies have shown a poor (Schokman et al., 2018) to a modest correlation between self-reported and objective measures (Jackson et al., 2018; Lauderdale et al., 2008). Objective sleep measures, such as those obtained through polysomnography (PSG), provide valuable insight into sleep health parameters (Zhou et al., 2025). PSG data includes total sleep time (TST), sleep efficiency (SE), sleep onset latency (SOL), wake after sleep onset (WASO), and the number of awakenings, which can correspond to subjective measures like sleep diaries or PSQI (Krystal & Edinger, 2008). TST is the total amount of sleep time scored from sleep onset to sleep offset. SOL is defined as the time between when the lights are out and when the individual attempts to sleep until the time he falls asleep. WASO refers to wakefulness after a defined sleep onset (Shrivastava et al., 2014). Objective measures also reflect sleep architecture, detailing the proportions of each sleep stage and offering insight not captured by subjective assessments (Krystal & Edinger, 2008).

Although good sleep health is not merely the absence of sleep disorders, it is essential to recognize that sleep disorders, such as sleep-disordered breathing (SDB), can affect sleep health. Studies have shown that SDB patients frequently report poor sleep quality (SQ), as assessed with the PSQI questionnaire (Lusic Kalcina et al., 2017). The prevalence of excessive daytime sleepiness (EDS) has been shown to increase with SDB severity, with a prevalence reported between 40.5 and 58% (Bjorvatn et al., 2015). This indicates that many SDB patients do not experience sleepiness (Roure et al., 2008), especially those with milder disease (Kapur et al., 2005). Furthermore, severe SDB is associated with worse SE, SOL, and WASO (Gasa et al., 2023) along with alterations in sleep duration, suggesting that individuals with moderate-to-severe SDB often experience worse and shorter sleep (Chen et al., 2015).

1.3 Sleep Stages

Sleep architecture refers to the structural organization of sleep (Institute of Medicine (US) Committee on Sleep Medicine and Research, 2006), typically inferred from PSG, which includes electroencephalography (EEG). Sleep is divided into two distinct types: non-rapid eye movement sleep (NREM) and rapid eye movement sleep (REM) (Burman & Muzumdar, 2020).

NREM sleep is further categorized into three stages, N1, N2, and N3, representing a continuum of increasing depth. Each sleep stage has a unique characteristic, including variations in brain waves, eye movement, and muscle tone (Patel et al., 2024). According to the American Academy of Sleep Medicine (AASM) (2020) scoring rules, sleep stages are assessed in 30-second intervals, known as epochs. During a typical night, individuals process through all sleep stages approximately four to six times, completing what is known as the sleep cycle. Each cycle typically lasts between 90 and 110 minutes, reflecting a consistent and organized pattern of sleep stages (Patel et al., 2024).

A sleep episode typically begins with NREM stage N1, which serves as a transitional stage from wakefulness to sleep. As the lightest sleep stage, N1 is highly susceptible to disturbances; even minor noises can easily awaken an individual. Upon waking from N1, individuals often do not perceive that they are asleep (Burman & Muzumdar, 2020). This stage typically lasts between one to seven minutes during the initial sleep cycle, accounting for 2-5% of TST (Patel et al., 2024). N1 begins when more than 50% of alpha waves, associated with a wakeful relaxation state, are replaced with low-amplitude, mixed-frequency activity, known as theta waves (4-7Hz) (American Academy of Sleep Medicine., 2020; Patel et al., 2024).

N1 is further characterized by slow rolling eye movements, the presence of muscle tone in skeletal muscles, and regular breathing (Burman & Muzumdar, 2020; Patel et al., 2024).

After N1, individuals transition into a deeper NREM sleep stage, N2 (Burman & Muzumdar, 2020). Awakening from N2 requires more stimuli compared to N1. In the initial sleep cycle, N2 lasts approximately 10-25 minutes and extends with each subsequent cycle (Institute of Medicine (US) Committee on Sleep Medicine and Research, 2006; Patel et al., 2024). This stage accounts for the largest proportion of TST in the average adult, comprising 45-55%. N2 is characterized by physiological changes, including a drop in heart rate and body temperature, as well as the presence of sleep spindles and K-complexes (Patel et al., 2024). Sleep spindles are trains of distinct sinusoidal waves with a frequency of 11-16Hz, most commonly 12-14Hz, lasting at least 0.5 seconds (American Academy of Sleep Medicine, 2020). These sleep spindles are considered crucial in memory consolidation (Fogel & Smith, 2011). K-complexes are distinctive brain wave patterns characterized by a sharp negative deflection immediately followed by a high-amplitude positive component (American Academy of Sleep Medicine, 2020), known to be the longest and most prominent brain waves observed during sleep (Burman & Muzumdar, 2020; Patel et al., 2024).

From N2, individuals progress to the deepest NREM stage, N3, also known as slow wave or deep sleep (Burman & Muzumdar, 2020; Patel et al., 2024). This stage is considered the most restorative and difficult to awaken from. When awakened from N3, individuals experience mental fogginess, known as sleep inertia, with moderately impaired cognitive performance lasting 30 minutes to an hour (Hilditch & McHill, 2019). Deep sleep typically constitutes about 25% of TST, with the majority occurring during the early part of the night (Patel et al., 2024). This stage is characterized by EEG signals of lower frequency (0.5-2Hz) and higher amplitude (>75 microvolts) occurring in more than 20% of the epoch (American Academy of Sleep Medicine, 2020), known as delta waves (Burman & Muzumdar, 2020). During N3, the body engages in critical repair and recovery processes, including tissue repair, bone and muscle growth, and immune system strengthening (Patel et al., 2024). This stage is also associated with parasomnias, such as sleepwalking, night terrors, and bedwetting (Shakankiry, 2011).

REM sleep typically begins about 80-100 minutes after falling asleep (Burman & Muzumdar, 2020). During the first sleep cycle, the REM period is brief, lasting only between one and ten minutes, but lengthens with each subsequent sleep cycle, with the final REM period potentially lasting up to an hour (Institute of Medicine (US) Committee on Sleep Medicine and Research, 2006). REM sleep is strongly associated with dreaming, and nightmares are more likely to occur (Dement & Kleitman, 1957). REM is not considered a restful sleep stage, as brain activity is heightened (Patel et al., 2024). EEG during REM sleep is characterized by low voltage and mixed frequency, including beta waves and sawtooth waves, sharp, contoured, or triangular (2-6Hz) patterns that often precede bursts of rapid eye movements (American Academy of Sleep Medicine, 2020). A defining feature of REM sleep is atonia, characterized by the near-complete loss of muscle tone in skeletal muscles, except for the eye and diaphragmatic muscles (Patel et al., 2024). This atonia is believed to be essential in preventing individuals from physically enacting their dreams (Institute of Medicine (US) Committee on Sleep Medicine and Research, 2006). Furthermore, REM sleep is considered essential for cognitive processes, including memory consolidation (Boyce et al., 2016), emotional regulation (Tempesta et al., 2018), and learning of new motor skills (Li et al., 2017).

The sleep stages described represent the typical patterns observed in healthy adults. However, it is important to note that sleep disorders such as SDB can disrupt normal sleep patterns. For example, these conditions can lead to increased light sleep (N1) (Gasa et al., 2023; Shahveisi et al., 2018) and reductions in both N3 sleep (Gasa et al., 2023) and REM sleep (Basunia et al., 2016; Patel et al., 2024).

1.4 Sleep-Disordered Breathing

SDB encompasses various conditions characterized by breathing irregularities during sleep, including obstructive sleep apnea (OSA), central apnea, sleep-related hypoventilation, and hypoxemia disorder (Foldvary-Schaefer & Waters, 2017; Panossian & Daley, 2013). The symptoms range from loud, frequent snoring to partial or complete airway obstruction, causing respiratory-related arousals from sleep, known as OSA (Panossian & Daley, 2013). SDB is a growing health concern, with previous studies indicating that the prevalence of SDB has risen substantially in recent decades, especially among middle-aged adults (Peppard et al., 2013).

1.4.1 Obstructive Sleep Apnea

OSA is the most prevalent form of SDB, with approximately one billion people worldwide between the ages of 30 and 69 having OSA (Benjafield et al., 2019). In Iceland, the prevalence of OSA is estimated to be 15.6%, with 11.8% of the population affected by moderate-to-severe OSA (Benjafield et al., 2019). OSA events occur when the upper airway muscles relax and collapse, leading to airway obstruction (Jordan et al., 2014). This obstruction restricts airflow, resulting in breathing cessations, known as obstructive respiratory events. A full obstruction that completely blocks the airflow is classified as apnea, while a partial obstruction that limits the airflow without entirely blocking it is termed hypopnea (Jordan et al., 2014; Punjabi, 2008). These apnea and hypopnea events can cause intermittent hypoxemia, where the blood oxygen saturation (SpO_2) levels drop (Dewan et al., 2015).

The breathing cessations during sleep often end with arousal, which is a brief intrusion of wakefulness or a sudden, transient increase in vigilance (Phillipson & Sullivan, 1978). These arousals play a critical role by activating the upper airway muscles, allowing airflow to resume (Huang et al., 2022). However, these frequent arousals can fragment sleep by reducing the time spent in the deeper, restorative sleep stage (N3) and REM (Eckert & Younes, 2014). Therefore, these sleep fragmentations often lead to poor SQ and EDS (Roure et al., 2008).

1.4.2 Diagnosis

The diagnosis of OSA is based on the number of apnea and hypopnea events during the night and daytime symptoms (American Academy of Sleep Medicine, 2014), first introduced in the 1970s as a measure of OSA severity (Block et al., 1979; Guilleminault et al., 1978). According to the AASM guidelines (2020), an apnea event is defined as a ≥90% drop from the pre-event baseline in nasal flow for ≥10 seconds, accompanied by a respiratory effort. A hypopnea event is defined as a ≥30% decrease in nasal flow for ≥10 seconds, followed by a ≥3% desaturation or arousal. The apnea-hypopnea index (AHI) is the standard parameter to assess OSA severity, calculated by dividing the total number of apnea and hypopnea events by TST, simply representing the total number of apnea and hypopnea events per hour of sleep (American Academy of Sleep Medicine, 2020). According to the International Classification of Sleep Disorders (2014), an AHI of at least 5, in addition to EDS, not explained by other factors, or an AHI ≥ 15 without daytime symptoms is required for OSA diagnosis. Depending on the AHI alone, OSA severity is further classified as mild (AHI 5-14.9 events/hr), moderate (25-29.9 events/hr), and severe OSA (≥30 events/hr) ("Sleep-Related Breathing Disorders in Adults," 1999).

From the outset, some researchers expressed skepticism about relying solely on AHI as a comprehensive indicator of OSA severity (Guilleminault, 1989). Over time, the conceptualization of OSA has evolved beyond the AHI to include various new respiratory events and revised working definitions, which are currently not included in the diagnostic criteria (Pevernagie et al., 2020). Despite its widespread use, concern has grown that AHI inadequately reflects the physiological abnormalities underlying OSA's neurocognitive, metabolic, and cardiovascular effects (Malhotra et al., 2021). One essential criticism is its simplicity, as it merely represents the average number of apnea, hypopnea, and desaturation events per hour of sleep without considering their duration, morphology, or downstream effects such as hypoxia and arousals, all of which significantly influence physiological stress (Kulkas, Tiihonen, Eskola, et al., 2013; Kulkas, Tiihonen, Julkunen, et al., 2013; Pevernagie et al., 2020). Consequently, patients with similar AHI values may experience vastly different levels of physiological stress, leading to variability in clinical outcomes (Kulkas, Tiihonen, Eskola, et al., 2013). Two individuals with different AHI values and breathing patterns illustrate this variability. One has an AHI of 16 events/h with longer breathing cessations and deeper oxygen desaturation, while the other has an AHI of 42 events/h with shorter cessations and shallower desaturations. Despite the lower AHI, the first patient may experience greater physiological stress and an elevated risk of health complications (Kulkas, Tiihonen, Julkunen, et al., 2013). This limitation has sparked ongoing discussion about the need for more nuanced, validated metrics that better capture the complexity of OSA and its multifaceted effects on health.

To overcome this issue, new methods have been developed, including the downstream effects on oxygen levels. The hypoxic parameters capture the respiratory episodes where SpO_2 levels fall below normal baseline, referred to as hypoxic burden or load (Kulkas, Tiihonen, Eskola, et al., 2013; Kulkas, Tiihonen, Julkunen, et al., 2013). Research has shown that patients with EDS tend to have longer average durations of apneic events and lower minimum and mean SpO_2 compared to patients with a similar AHI without EDS (Mediano et al., 2007). An Automatic Blood Oxygen Saturation Signal Analysis Software (ABOSA) has been developed, which automatically calculates hypoxic parameters from ODI 4% to capture the hypoxic load (Karhu et al., 2022). The hypoxic parameters desaturation severity (DesSev) and recovery severity (RecSev) enable the detection of the total desaturation area (Karhu et al., 2022). DesSev and RecSev are calculated as the sum of desaturation areas and recovery areas, respectively, normalized with TST. The sum of DesSev and RecSev (DesSev + RecSev) is calculated to detect the total area from baseline to nadir and back to baseline (Figure 1) (Karhu et al., 2022; Kulkas, Tiihonen, Eskola et al., 2013).

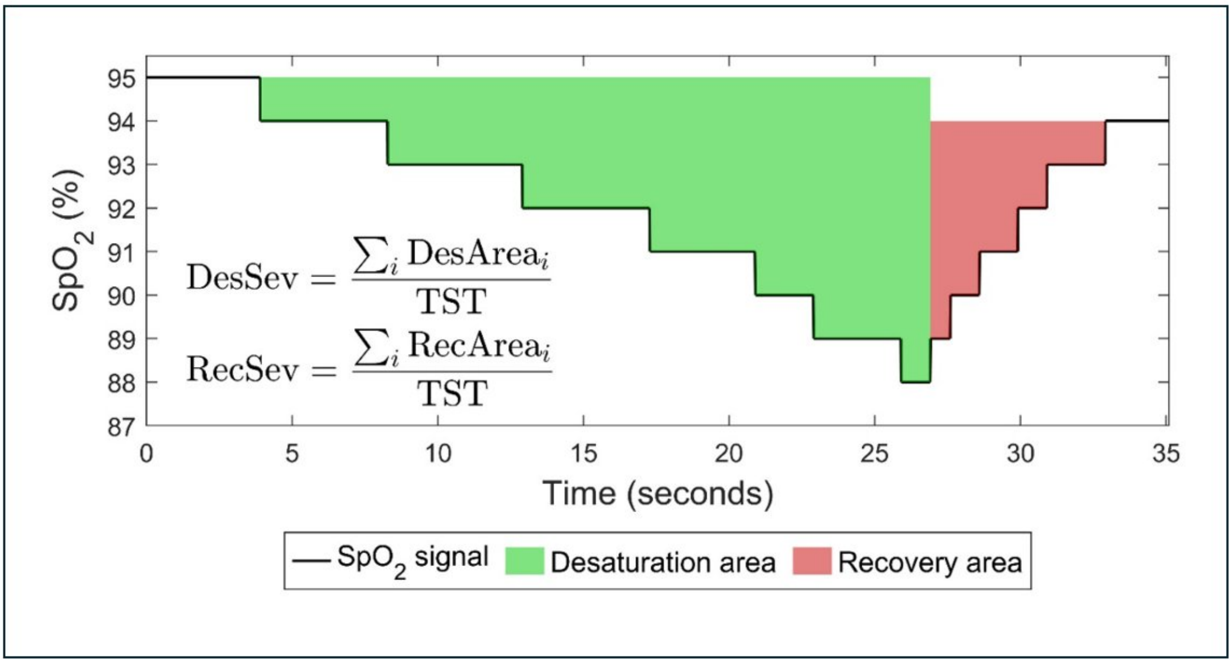

Figure 1. The calculation of desaturation severity (DesSev) and recovery severity (RecSev) from the oxygen saturation (SpO_2) signal. TST, total sleep time. Reproduced from Paper I.

Note. (Karhu et al., 2022)

The gold standard for diagnosing OSA is an in-laboratory PSG (Type I) (American Academy of Sleep Medicine, 2020; Kapur et al., 2017). This comprehensive overnight test records a range of physiological parameters, including EEG, to monitor brain activity, electrocardiography (ECG) for heart rate, electromyography (EMG) for muscle activity, and electrooculography (EOG) for eye movement, respiratory effort, nasal airflow, blood SpO_2, body position, body movement (American Academy of Sleep Medicine, 2020; Kapur et al., 2017; Punjabi, 2008). The setup and execution of PSG required the expertise of professional sleep technologists, who ensure proper equipment placement and monitoring through the night (Punjabi, 2008). Once the data is collected, sleep technologists manually review and score apnea and hypopnea events. However, this process is both time-intensive and costly (Fischer et al., 2012; Kapur et al., 2017). Consequently, in-laboratory PSG is expensive, and long waiting lists often delay access to testing due to the high demand placed on expert staff (Arnardottir et al., 2022). Another limitation of in-laboratory PSG is that it is typically performed over a single night (Le Bon et al., 2000; Newell et al., 2012). While this approach is standard, it may not accurately reflect OSA severity due to significant night-to-night variability, especially in milder cases (Le Bon et al., 2000; Newell et al., 2012; Stöberl et al., 2017). For example, OSA severity can fluctuate based on factors such as sleeping position and sleep stage, leading to potential underestimation or overestimation of the condition (Newell et al., 2012). Additionally, in-laboratory PSG can often introduce first-night effects, where the unfamiliar environment, equipment, and associated stress disrupt the individual's sleep (Newell et al., 2012; Punjabi, 2008). Therefore, less representative of a typical night's sleep (Arnardottir et al., 2022; Tamaki et al., 2005). Research indicates that the first-night effects are more pronounced in OSA patients compared to those with other sleep disorders (Byun et al., 2019). Although recording multiple consecutive nights could help mitigate the impact of first-night effects and improve diagnostic accuracy, the high cost and logistical challenges of in-laboratory PSG make this approach impractical (Deutsch et al., 2006). The AASM introduced the first classification of sleep studies (1994). The system classified sleep studies into four types based on the number and type of physiological variables recorded, as listed in Table 1.

Table 1. AAMS sleep study classification.

	Type I	Type II	Type III	Type IV
Number of channels	≥7	≥7	4-7	1-2
Description	Standard in-laboratory PSG	Comprehensive portable PSG	Portable testing, limited to OSA	Continuous recording of 1-2 signals
Personnel	Attended, usually in a sleep center	Unattended	Unattended	Unattended
Parameters	EEG, EOG, chin EMG, ECG, airflow, respiratory effort, and SpO_2	Same as type I	Airflow, respiratory effort, oximetry (at least two channels are respiratory or respiratory movement and airflow	SpO_2 and/or airflow

Abbreviation: ECG, electrocardiography; EEG, electroencephalography; EMG, electromyography; EOG, electrooculography; PSG, polysomnography; SpO_2, oxygen saturation.

Note. (Ferber et al., 1994).

Type II PSG is an unattended sleep study conducted in a home environment that provides the equivalent diagnostic capabilities as Type I PSG (Corral-Peñafiel et al., 2013). In this setup, electrodes are applied to the patient at a sleep laboratory by a sleep technologist, after which the patient sleeps at home (Corral-Peñafiel et al., 2013). Although the method reduces cost by approximately 30% compared to Type I PSG (Corral-Peñafiel et al., 2013), it still necessitates up to one hour of preparation by sleep technologists (Fischer et al., 2012). Despite its cost-effectiveness, the Type II PSG failure rate has been reported to be as high as 20%, presumably due to the absence of direct monitoring during the study (Campbell & Neill, 2011).

Type III sleep studies, on the other hand, utilize self-applied portable monitors approved by AASM for diagnosing OSA (Collop et al., 2007; Corral-Peñafiel et al., 2013). These devices primarily focus on respiratory parameters such as nasal airflow, SpO_2, respiratory effort, and body movement, making them suitable for OSA diagnosis (Lévy & Schiza, 2023). Type III sleep studies are substantially less expensive and more accessible than Type I PSG, offering a practical solution for screening and diagnosing OSA, particularly in individuals with a high pre-test probability of OSA (Corral-Peñafiel et al., 2013; Lévy & Schiza, 2023). However, these studies lack sleep stage information, limiting their ability to diagnose other sleep disorders that require EEG and OSA, which necessitate arousals for scoring. Additionally, higher failure rates may occur due to poor signal quality or sensor disconnection (Corral-Peñafiel et al., 2013; Lévy & Schiza, 2023).

Type IV sleep studies are further simplified, utilizing single-channel devices to measure one or two parameters, typically SpO_2 and/or airflow (Lévy & Schiza, 2023). These methods are highly cost-effective and offer significant advantages in terms of accessibility and patient comfort. They are particularly valuable for initial OSA screening in populations with a high pre-test probability of OSA or in resource-limited settings where PSG is not feasible (Abrahamyan et al., 2018). However, the limited diagnostic accuracy of Type IV sleep studies presents challenges, as their standalone use in clinical practice may result in false positives or negatives, necessitating cautious interpretation of the results (Abrahamyan et al., 2018). While Type II, III, and IV sleep studies provide more accessible and cost-effective alternatives to Type I PSG, their utility depends on the clinical context, diagnostic requirements, and patient population. Each type has unique advantages and disadvantages, as listed in Table 2.

Table 2. Advantages and disadvantages of the four types of sleep studies.

Type	**Advantages**	**Disadvantages**
I	Gold standard	Cost
	Technical support available	Time-consuming
	Many physiological variables measured	First night effect
	Provides important information	Long waiting lists
II	Home environment	Cost
		Time-consuming
		Long waiting lists
		Possible missing data
IV	Convenience	Potential missing data
	Patient acceptance	Potential poor-quality data
	Lower cost	Variability in sensor technology
	Easier to implement	Fewer physiological variables measured
	Home environment	Misinterpretation of the results
	Multi-night measurements	Variability in sensitivity and specificity
IV	Convenience	Potential missing data
	Lowest cost	Potential poor-quality data
	Simpler devices	Variability in sensor technology
	Easier to implement	Fewer physiological variables measured
	Home environment	Misinterpretation of the results
	Shorter waiting time	Variability in sensitivity and specificity
	Multi-night measurements	

Note. (Corral-Peñafiel et al., 2013; Lévy & Schiza, 2023)

The challenges and limitations of in-laboratory PSG, coupled with the high prevalence of underdiagnosed OSA (Costa et al., 2015), underscore the need for a more cost-effective, patient-centered diagnostic solution. OSA poses a significant epidemiological burden, with widespread health consequences and a substantial economic cost (Arnardottir et al., 2022; Benjafield et al., 2019; Lévy & Schiza, 2023). These factors have driven the development of innovative alternatives like the self-applied PSG system (Arnardottir et al., 2022). The self-applied PSG is a simplified EEG setup designed for self-application in non-hospital environments (Kainulainen et al., 2021; Rusanen et al., 2024), enabling individuals to conduct sleep studies at home. It features a fixed-position frontal montage with four EEG electrodes, four EOG electrodes, reference and ground electrodes, as well as four ECG electrodes and four EMG electrodes (two for each leg). Additional components include a nasal cannula for airflow, two respiratory inductance plethysmography belts to monitor thorax and abdomen respiratory movements, a finger pulse oximeter for SpO_2 and pulse rate, a three-dimensional accelerometer for activity and body position, and a microphone for snoring/audio recording (Rusanen et al., 2024). The use of self-applied PSG with forehead EEG and EOG electrodes has been shown to be technically feasible (Rusanen et al., 2024).

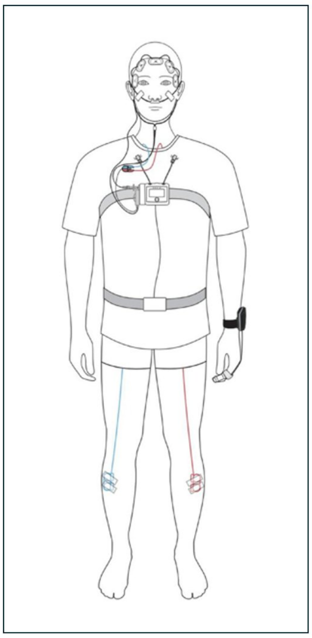

Figure 2. Illustration of the self-applied PSG sensor setup from Nox Medical (Reykjavik, Iceland) in full configuration.

Note. (Rusanen et al., 2024).

Research indicates that the EOG signals recorded using the self-applied PSG are comparable to those obtained through PSG. However, the self-applied EEG electrodes tend to produce lower signal amplitude and reduced power across the EEG frequency range compared to standard PSG setups (Kainulainen et al., 2021; Rusanen et al., 2024). This discrepancy may necessitate adjustments in amplitude thresholds to ensure accurate sleep staging, particularly for detecting N3 sleep (Kainulainen et al., 2021; Rusanen et al., 2024). Furthermore, the self-application process increases the likelihood of loose electrodes, potentially compromising signal quality. Studies show a technical failure rate of 14.9% to 15.9% in individuals with no prior experience in setting up the device (Ferretti et al., 2024; Punjabi et al., 2020), comparable to a failure rate of Type II PSG (Bruyneel & Ninane, 2014).

The self-applied PSG is a practical option for multi-night testing, which provides a more accurate assessment of OSA severity, especially in milder cases, while eliminating the first-night effect (Ferretti et al., 2024; Punjabi et al., 2020). The Sleep Revolution utilizes a three-consecutive-night diagnostic procedure using self-applied PSG. This approach effectively accounts for night-to-night variability in OSA severity and mitigates the impact of the first-night effect associated with sleeping while connected to monitoring equipment (Arnardottir et al., 2022; Ferretti et al., 2024). Research on this approach highlights that night-to-night variability is particularly pronounced among patients with mild to moderate OSA, with approximately 20% of cases potentially misclassified if only a single-night study had been conducted (Ferretti et al., 2024; Punjabi et al., 2020). Additionally, studies show that SE improves, and WASO decreases over the three consecutive nights of testing during weekdays, while the reverse pattern is observed during weekends (Ferretti et al., 2024). These results suggest that three consecutive nights of self-applied PSG sleep study testing are particularly valuable for milder OSA severity diagnosis.

1.4.3 Risk Factors

Age is a significant risk factor for OSA (Edwards et al., 2010), with the prevalence and severity of the condition increasing with higher age (Punjabi, 2008). Consequently, the risk of developing OSA increases progressively with age (Glasser et al., 2011; Peppard et al., 2013; Sands et al., 2023; Tufik et al., 2010) until the age of 65 years, when, for unclear reasons, the prevalence reaches a plateau (Young, Shahar, et al., 2002). Although the mechanism whereby aging increases the risk of OSA is not completely understood, it is likely due to age-related physiological changes (Pinilla et al., 2021), the prevalence of comorbidities (Mokhlesi et al., 2016), and changes in the upper airway and its muscle function (Glasser et al., 2011).

Men have a higher risk of developing OSA compared to women (Messineo et al., 2024). Studies report that OSA prevalence in males is two to four times higher than in premenopausal women (Kirkness et al., 2008; Peppard et al., 2013; Young et al., 2004). The reasons for this disparity are not entirely understood but are believed to arise from anatomical and physiological differences. One contributing factor is the weight-dependent compromise of the upper airway. Men are more likely to have visceral and neck adiposity, which increases upper airway collapsibility (Messineo et al., 2024). Additionally, the pharynx in men is often more elongated than in women (Malhotra et al., 2002), exposing a greater region to collapse (Sands et al., 2023). This elongation, combined with other structural differences, intensifies the severity of OSA in men (Malhotra et al., 2002; Sands et al., 2023). Postmenopausal women's prevalence levels approach those of men (Bixler et al., 2001). Hormonal changes during menopause, such as decreased levels of estrogen and progesterone, reduce airway stability (Bixler et al., 2001) and contribute to a redistribution of fat from subcutaneous to abdominal regions (Kodoth et al., 2022; Lizcano & Guzmán, 2014). These hormonal shifts also increase the likelihood of overweight and obesity, exacerbating OSA risk (Kodoth et al., 2022; Lizcano & Guzmán, 2014). Furthermore, postmenopausal women are naturally older than premenopausal women, and age itself is an independent risk factor for OSA (Punjabi, 2008).

High body mass index (BMI) is the primary risk factor for the development and progression of OSA, with at least 70% of OSA patients classified as obese ($BMI \geq 30kg/m^2$) (Malhotra & White, 2002; Tuomilehto et al., 2013; Vgontzas et al., 1994). Excess body weight is a public health concern (Islam et al., 2024), impacting nearly every aspect of life and posing a major challenge to healthcare systems (Withrow & Alter, 2011). BMI, the most frequently used metric to assess overweight and obesity, is calculated as an individual's weight divided by the square of their height in meters (kg/m^2) (Keys & Brozek, 1953). According to the World Health Organization (WHO) (2024c), adults with a BMI of 25-29.9 kg/m^2 are classified as overweight, while those with a BMI of 30 kg/m^2 or higher are considered obese. In 2022, approximately 2.5 billion adults (43%) worldwide were overweight, and 890 million (16%) were obese. Moreover, the global prevalence of obesity has more than doubled between 1990 and 2022 (World Health Organization, 2024c). Unsurprisingly, OSA prevalence rises in parallel with increasing BMI levels (Benjafield et al., 2019). The relationship between obesity and OSA is bidirectional, while obesity promotes the development of OSA, increasing evidence indicates that OSA itself may contribute to weight gain and obesity (Leinum et al., 2009). Studies have consistently shown a strong link between the two conditions (Kirkness et al., 2008; Peppard, Young, & Palta, 2000; Sands et al., 2023). For instance, a 10% weight gain predicts a 32% increase in AHI and six-fold odds of developing moderate-to-severe OSA, whereas a 10% weight loss predicts a 26% reduction in AHI (Peppard, Young, & Palta, 2000). Additionally, repeated episodes of OSA disrupt sleep and lead to EDS. This sleepiness can reduce physical activity (PA) and promote weight gain over time (Leinum et al., 2009).

Fat distribution also plays an essential role in the pathogenesis of OSA (Carter & Watenpaugh, 2008; Vgontzas et al., 2000). Visceral adiposity, or fat accumulation around internal organs in the abdominal cavity, has been shown to reduce lung volume and increase the risk of airway obstruction (Schwartz et al., 2010). Studies on obese males (Vgontzas et al., 2000) and females (Shinohara et al., 1997) with OSA have revealed that visceral adiposity is higher than in BMI-matched controls. Furthermore, in males, visceral adiposity shows a stronger association with OSA than other types of obesity (Kim et al., 2021; Kritikou et al., 2013), whereas in females, general adiposity appears to be a more significant predictor (Kritikou et al., 2013). Neck adiposity is another essential contributor to OSA development (Meurling et al., 2019). Even independent of BMI, neck circumference has been identified as the anthropometric variable most closely associated with OSA (Mortimore et al., 1998). Fat deposits in the neck area can directly obstruct the airway and increase the upper collapsibility (Schwartz et al., 2010). Larger neck circumference is linked to more severe OSA in both sexes (Meurling et al., 2019) and is considered an independent risk factor for severe OSA (Ahbab et al., 2013).

Physical inactivity is also a recognized risk factor for various chronic diseases (Booth et al., 2012), as well as for OSA, with inactive individuals more likely to develop OSA compared to their active counterparts (Simpson et al., 2015). PA is measured by metabolic equivalents of tasks (METs), a standard measure used to quantify the energy cost of PA and exercise. One MET represents the resting metabolic rate, equivalent to an oxygen uptake of 3.5 milliliters per kilogram of body weight per minute (ml O_2/kg/min) (Ainsworth et al., 1993). Physical inactivity is defined as an insufficient PA level to meet present recommendations (World Health Organization, 2020). In contrast, sedentary behavior refers to any waking activity that requires low energy expenditure (≤1.5 METs) and is performed while sitting, reclining, or lying down. Common sedentary behaviors include desk-based office work, driving, and watching television (World Health Organization, 2020). Physical inactivity and sedentary behavior are not mutually exclusive. An individual can meet the recommended PA levels for their age while still spending a significant proportion of their time engaged in sedentary behaviors. In other words, it is possible to be both physically active and sedentary (Thivel et al., 2018). Physical inactivity and sedentary behavior have emerged as major public health concerns. Approximately 1.8 billion adults, representing 31% of the global population, are physically inactive and fail to meet recommended PA levels, including 34% of women and 29% of men (World Health Organization, 2024a). Physical inactivity and sedentary behavior increase the risk of OSA by promoting obesity, systematic inflammation, and insulin resistance (Liu et al., 2022). Furthermore, it is associated with fluid retention in the legs, as the leg muscles play an important role in venous fluid dynamics. During sleep, the recumbent position facilitates fluid displacement, leading to its accumulation in the neck and thereby increasing the severity of OSA (Redolfi et al., 2011). Consequently, physical inactivity and sedentary behavior can increase both the risk and severity of OSA (Liu et al., 2022; Simpson et al., 2015).

Other lifestyle factors, such as smoking and alcohol consumption, are also closely linked to OSA (Franklin & Lindberg, 2015). Smoking, particularly heavy smoking, has been associated with an increased risk of developing moderate-to-severe OSA (Wetter et al., 1994). Studies have demonstrated a higher prevalence of smoking among individuals with OSA compared to those without the condition, suggesting an independent association between the two (Boussoffara et al., 2013; Kashyap et al., 2001). Smoking impacts OSA through several mechanisms, including enhanced upper airway inflammation, disruption in sleep architecture, instability in arousal mechanisms, and alteration of neuromuscular function (Krishnan et al., 2014). Nicotine in cigarettes has stimulating effects and prolonged action, which may increase the arousal threshold. This leads to longer and more severe respiratory events (Lin et al., 2012), resulting in a lower mean SpO_2 (Bielicki et al., 2019), higher arousal index, and longer time spent with SpO_2 below 90% (Conway et al., 2008). Similarly, alcohol consumption is associated with a higher risk of OSA (Ko et al., 2024). Alcohol exerts a paralyzing effect on the upper airway muscles, narrowing the airway and making it more prone to collapse, which increases the frequency of respiratory events (Issa & Sullivan, 1982). Additionally, alcohol raises the arousal threshold, prolonging respiratory events and leading to more severe episodes (Issa & Sullivan, 1982). Alcohol consumption may also negatively influence BMI, further increasing the risk and severity of OSA (Ko et al., 2024).

Lastly, sleeping position significantly influences the severity of OSA, with the supine position being linked to a higher AHI and more severe symptoms compared to non-supine positions (Joosten et al., 2015). This is largely due to gravity's effect on the tongue and soft palate, which increases airway collapse

(Bidarian-Moniri et al., 2015). The underlying mechanisms include inadequate upper airway geometry, heightened airway collapsibility, reduced lung volume, and insufficient compensation by airway dilator muscles (Joosten et al., 2014).

1.4.4 Symptoms

The hallmark symptom of OSA is the intermittent disruption of breathing during sleep. These interruptions (apneas and hypopneas) are often accompanied by loud and frequent snoring as well as witnessed breathing cessations. These observable signs are among the strongest indicators of OSA (Malhotra & White, 2002). However, many individuals with OSA may be unaware of these episodes, as they occur exclusively during sleep (Young, Peppard, et al., 2002). Consequently, a substantial number of people with OSA remain undiagnosed, particularly in the early stages of the condition (Motamedi et al., 2009).

Snoring is often one of the earliest signs of OSA (Keropian & Murphy, 2014; Stradling & Crosby, 1991). It occurs as a breathing noise during the inspiration phase and sometimes during expiration (Guilleminault et al., 1991). Snoring arises when airflow through the upper airway is restricted, causing air movement to become turbulent. This turbulence causes the surrounding tissues, such as the soft palate, to vibrate, producing the characteristic snoring sounds (Skatrud & Dempsey, 1985). A substantial proportion of the general population is habitual snorers, more common in men than women (Bhattacharyya, 2015; Chan et al., 2012). Snoring is the most common symptom of OSA, reported by over 90% of OSA patients (Keropian & Murphy, 2014; Stradling & Crosby, 1991). The intensity of snoring tends to increase as OSA becomes more severe (Maimon & Hanly, 2010). However, it is essential to note that snoring alone does not guarantee the presence of OSA (Young, Peppard, et al., 2002). Most previous studies have assessed the relationship between OSA and snoring using subjective methods, limited by biases such as self-perception and reliance on the presence or absence of a bed partner to report snoring (Hoffstein et al., 1994).

EDS is a well-recognized symptom of OSA (He & Kapur, 2017; Lal et al., 2021; Roure et al., 2008). It is defined as the inability to maintain wakefulness and alertness during primary waking periods (the longest period within a 24-hour cycle during which an individual is typically awake). EDS results in an overwhelming need for sleep or unintended lapses into drowsiness or sleep (American Academy of Sleep Medicine, 2014). The ESS (Johns, 1991) is a widely used self-reported questionnaire and the most common method for evaluating EDS in OSA (Gonçalves et al., 2023). EDS is often linked to repeated breathing disturbances characteristic of OSA, which lead to oxygen desaturation and arousal, disrupting the sleep cycle. This fragmentation results in non-restorative sleep (Eckert & Younes, 2014; Malhotra & White, 2002), ultimately contributing to EDS (Lal et al., 2021; Malhotra & White, 2002). However, the AHI does not reliably predict the presence or intensity of EDS (Slater & Steier, 2012; Ulander et al., 2022; Young, Peppard, et al., 2002). Interestingly, many patients with severe OSA do not report EDS, or their symptoms may go unrecognized (Bjorvatn et al., 2015; Kapur et al., 2005; Roure et al., 2008; Ulander et al., 2022; Young, Peppard, et al., 2002). The mechanisms underlying why some OSA patients complain of EDS, whereas others do not, remain unclear (He & Kapur, 2017; Roure et al., 2008). Some research suggests that other OSA risk factors, such as obesity and age, may have a more significant impact on EDS than OSA itself (Bixler et al., 2005; Pamidi et al., 2011). Additionally, the perception of sleepiness is highly subjective; individuals may report different levels of EDS based on their tolerance or sensitivity to fatigue, complicating comparisons across individuals (Roure et al., 2008). Furthermore, the gradual progression of OSA over time may lead patients to become accustomed to increasing sleepiness, causing them to overlook or fail to recognize their symptoms as EDS (Slater & Steier, 2012).

1.4.5 Comorbidities

OSA negatively affects nearly all organ systems, leading to chronic health conditions that significantly affect individuals' lives (Espiritu, 2021). One of the most severe consequences of OSA is its strong association with CVD (Mitra et al., 2021). CVD encompasses a wide range of conditions affecting the heart, arteries, veins, and capillaries (World Health Organization, 2011). CVD is the leading cause of death worldwide, accounting for approximately 17.9 million deaths annually, 32% of all global deaths (World Health Organization, 2011). The prevalence of CVD among OSA patients is notably high, ranging from 40-60% (Tietjens et al., 2019), with studies showing a link between OSA and elevated risk of CVD, coronary artery disease, heart attack, and stroke (Salari et al., 2022; Wang et al., 2013). Additionally, moderate-to-severe OSA is associated with an increased risk of CVD mortality (Xie et al., 2017). Although OSA and CVD share several common risk factors, such as age, sex, obesity, and physical inactivity (Mitra et al., 2021), research suggests that severe OSA is an independent risk factor for all-cause and cardiovascular mortality (Fu et al., 2017). Mechanistically, OSA promotes a chronic inflammatory state that leads to atherosclerosis and subsequent cardiovascular complications (Abbasi et al., 2021).

Hypertension is the leading risk factor for CVD and premature death (Mills et al., 2020) and is highly prevalent among OSA patients, affecting 35-80% of individuals (Battaglia et al., 2024; Khamsai et al., 2021; Peppard, Young, Palta, et al., 2000). OSA is not merely comorbid with hypertension but is also considered a causative factor (Peppard, Young, Palta, et al., 2000). Large population-based studies have demonstrated a strong independent relationship between OSA and hypertension (Bixler et al., 2000; Durán et al., 2012; Haas et al., 2005; Hla et al., 1994; Young et al., 1997). Particularly in young adults to middle-aged adults (<50 years) (Haas et al., 2005; O'Connor et al., 2009), with the risk increasing with OSA severity (Marin et al., 2012; Young et al., 1997). The mechanisms underlying hypertension in OSA patients include chronic sympathetic nervous system activation and impaired baroreflex sensitivity caused by intermittent hypoxemia and chemoreflex activation, leading to elevated blood pressure and heart rate (Parati et al., 2012).

OSA is also strongly associated with metabolic syndrome (MS), a cluster of metabolic abnormalities, including central obesity, insulin resistance, hypertension, and dyslipidemia (Swarup et al., 2024). The prevalence of MS among OSA patients is notably high, ranging from approximately 35% to 79%, and increases with OSA severity (Bonsignore et al., 2011; Parish et al., 2007; Peled et al., 2007). While obesity is a significant risk factor for both conditions, non-obese OSA patients show a 35% prevalence of MS (Chaudhary et al., 2022). Women with OSA tend to have a higher prevalence of MS than men, 88% and 68%, respectively (Chaudhary et al., 2021). Other common risk factors are age and BMI, which have been found to be significant risk factors for MS in men, while BMI is the primary risk factor for MS in women (Sasanabe et al., 2006). The mechanisms underlying MS in OSA patients include systemic inflammation, insulin resistance, intermittent hypoxia, oxidative stress, sympathetic activation (Lam & Ip, 2009), and circadian clock disruption (Malicki et al., 2022).

Mental health challenges are also prominent in OSA patients, particularly anxiety and depression, with prevalence rates of 32% and 35%, respectively (Garbarino et al., 2020). These conditions are closely related to elevated levels of perceived stress, which is common among this population (Wong et al., 2021), along with cognitive impairments such as reduced attention, memory deficits, diminished alertness, and impaired executive function (Vanek et al., 2020). Emotional health is significantly compromised, with studies revealing poor emotional well-being and social functioning scores in OSA patients (Akashiba et al., 2002; Scarpina et al., 2021). These mental health challenges collectively diminish the health-related quality of life (HRQoL) of OSA patients. Therefore, early diagnosis of OSA, followed by personalized treatment, is important for improving mental health conditions such as anxiety and depression (Garbarino et al., 2020).

OSA profoundly impairs individuals' HRQoL, with up to 87.7% of OSA patients reporting reduced HRQoL (Gassara et al., 2017). The SF-36 questionnaire is one of the most frequently used tools for assessing HRQoL in OSA patients (Pauletto et al., 2021). SF-36 evaluates 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 (Ware & Sherbourne, 1992). OSA patients generally show a lower HRQoL compared to healthy individuals (Smith & Shneerson, 1995). The most affected HRQoL domains in untreated OSA patients include general health, vitality, role limitations due to physical health, social functioning, role limitations due to emotional problems, emotional well-being, and physical functioning, while the least affected domain was pain (Pauletto et al., 2021). Interestingly, while OSA severity does not directly correlate with SF-36 scores, depressive symptoms, EDS (Akashiba et al., 2002; Lee et al., 2016), and physical inactivity (Lopes et al., 2008) are the strongest predictors of lower HRQoL in OSA patients.

1.4.6 Treatment

Positive airway pressure (PAP) therapy is widely recognized as the first-line treatment for moderate-to-severe OSA (Cao et al., 2017; Epstein et al., 2009; Randerath et al., 2022). By increasing the intraluminal pressure in the pharynx, PAP effectively prevents the collapse of the pharyngeal airway (Patel et al., 2003). It has been shown to reduce AHI and improve the oxygen desaturation index (ODI) (Cammaroto et al., 2017). Additionally, PAP enhances HRQoL, alleviates EDS, and reduces cardiovascular morbidity and mortality, even after a short-term consistent use (Cao et al., 2017; Patel et al., 2003; Spicuzza et al., 2015). However, despite its efficacy, adherence to PAP remains a persistent challenge, with low adherence, especially among patients with milder OSA (Eysteinsdottir et al., 2017; Qiao et al., 2023). A clinical benchmark for adherence is defined as using PAP for at least 4 hours per night on 70% of nights (Sawyer et al., 2011). However, adherence rates vary, with 46% to 83% of OSA patients reporting as nonadherent

(Weaver & Grunstein, 2008). Factors contributing to low adherence include psychological barriers such as anxiety and low motivation, physical discomfort from mask fit or nasal congestion, and lack of perceived benefits, especially in those with milder OSA symptoms. Additionally, insufficient education, inadequate support from healthcare providers or family, and early negative experiences with PAP further affect adherence (Aloia, 2011; Sawyer et al., 2011). Adherence to PAP treatment remains a significant challenge, and clearly, not everyone can tolerate PAP therapy, as reported compliance rates range between 50% and 80% in OSA patients (Jordan et al., 2014). Importantly, for those with milder OSA that are thought to be managed without PAP (Loube et al., 1999) and those unable to tolerate PAP, alternative treatments are essential to ensure effective management of OSA (Randerath et al., 2021).

The challenges posed by low PAP adherence in many patients highlight the need for effective alternatives. In this context, the European Research Society task force has recommended non-PAP treatment options, identifying mandibular advancement devices (MADs) as an equally viable option for patients with mild to moderate OSA (Randerath et al., 2021). MADs consist of two separate components that fit over the maxilla and mandible. This repositioning modifies the geometry of the upper airway, enlarges its size, and reduces the likelihood of airway collapse by displacing the tongue and surrounding tissues forward (Jayesh & Bhat, 2015). Research supports the effectiveness of MADs in reducing AHI, ODI, and lowest SpO_2 across different OSA severity (Liao et al., 2024). Additionally, MADs are considered to offer a reasonable alternative, especially for patients who cannot tolerate PAP (Iftikhar et al., 2017), as patients tend to prefer MADs over PAP (Phillips et al., 2013; Yamamoto et al., 2019). Adherence to MAD therapy is generally high, with an overall mean dropout rate of approximately 17%. However, the dropout rate tends to increase over time (Bortolotti et al., 2022). Further, MADs have been shown to be more cost-effective than PAP per AHI point improvement (de Vries et al., 2019). The disadvantages of MADs encompass dental and skeletal side effects that may manifest over time, including changes in overjet, overbite, and incisor inclination. These changes typically progress gradually, necessitating regular monitoring (Bartolucci et al., 2019).

Positional therapy involves encouraging patients to adopt a non-supine sleeping position to reduce OSA severity (Barnes et al., 2017). This approach is particularly effective for patients with positional-dependent OSA, wherein respiratory events occur with greater frequency in specific sleep positions, especially the supine position (Joosten et al., 2014). Given that the supine position predisposes individuals to a greater number of obstructive events, its avoidance can significantly decrease OSA severity. Various devices are employed to discourage supine position, including lumbar or abdominal binders, semi-rigid backpacks, full-length pillows, a tennis ball affixed to the back of nightwear, and vibratory devices that prompt supine position (Srijithesh et al., 2019). Studies have demonstrated that positional therapy effectively reduces AHI and EDS compared to controls (Omobomi & Quan, 2018; Srijithesh et al., 2019). Positional therapy utilizing vibratory devices or PAP has been recommended as a non-PAP therapy for patients with mild or moderate positional-dependent OSA (Randerath et al., 2021). Positional therapy may also provide benefits for OSA patients who experience difficulties with adherence to PAP. Although it is less effective than PAP in reducing AHI, it exhibits superior adherence rates (Barnes et al., 2017; Srijithesh et al., 2019). Nevertheless, long-term compliance with positional therapy remains a challenge, as the majority of studies on this intervention are of short duration, thus limiting the capacity to evaluate its long-term effectiveness. Consequently, the certainty of evidence supporting positional therapy is considered to be low to moderate, and the certainty of evidence is low to moderate (Srijithesh et al., 2019).

Myofunctional therapy involves exercises to strengthen the muscles of the upper airway. These exercises typically include both isotonic and isometric exercises, such as speaking, breathing, blowing, sucking, chewing, and swallowing (Rueda et al., 2020), with the aim of improving the function of the muscles in the mouth and throat to reduce OSA symptoms. Studies have shown that myofunctional therapy can reduce AHI and snoring and improve the lowest SpO_2 and EDS (Camacho et al., 2015; Meghpara et al., 2022). Myofunctional therapy may also be beneficial as an adjunct therapy to PAP (Diaféria et al., 2017). However, the variability in results between individuals is a concern, with some experiencing substantial improvement in AHI while others experience minimal changes (Camacho et al., 2015; de Felício et al., 2018; Rueda et al., 2020). While studies on myofunctional therapy have shown promising results, most studies focus on short-term outcomes. Further research is needed to further evaluate long-term effects (de Felício et al., 2018). Furthermore, successful outcomes with myofunctional therapy require consistency in the exercises, which can be challenging for patients to maintain, especially without continuous motivation and support (Huang et al., 2019).

Surgical modifications for OSA treatment are considered when the patient cannot tolerate or does not respond to other treatments (Aurora et al., 2010). The surgical operations focus on reducing the likelihood of airway obstruction by altering the airway structure (Thaler et al., 2016). These operations include tracheostomy, maxillo-mandibular advancement, laser-assisted uvulopalatoplasty, uvulopalatopharyngoplasty with or without tonsillectomy, radiofrequency ablation, and palatal implants (Aurora et al., 2010). Generally, maxilla-mandibular advancement is the most effective surgical modification; however, it carries a higher risk than the others (Aurora et al., 2010; Caples et al., 2010). While significant progress has been made in surgical techniques for OSA treatment, there is a lack of rigorous data evaluating surgical modifications of the upper airway (Aurora et al., 2010). Hypoglossal nerve stimulation is another surgical option for OSA patients involving the electrical stimulation of the hypoglossal nerve to activate upper airway muscles and prevent airway collapse. This type of treatment has been shown to reduce AHI and ODI and improve EDS in patients with moderate-to-severe OSA (Alrubasy et al., 2024). Another surgical option mentioned by the European Respiratory Society guidelines is gastric bypass surgery (Randerath et al., 2021). This type of surgery is recommended for patients with obesity-related OSA when their weight has not improved despite participating in a comprehensive weight reduction program (Randerath et al., 2021). Gastric bypass surgery leads to improvement in OSA symptoms, including reduced AHI and improved EDS (Rasheid et al., 2003; Sarkhosh et al., 2013). Greater weight loss post-surgery is associated with a higher likelihood of OSA remission. However, the severity of OSA cannot be reliably predicted by preoperative BMI alone (Rasheid et al., 2003). As surgery is naturally invasive and comes with a risk for complications, these types of treatment options are generally not used as the first treatment option for OSA patients.

Pharmacological treatments for OSA are emerging as a promising avenue, targeting upper airway collapsibility through different mechanisms (Taranto-Montemurro et al., 2019). However, robust evidence supporting the efficacy of pharmacotherapy for OSA management remains limited (Nobre et al., 2024). Weight-loss medications that can reduce fat deposition around the tongue base and neck have been shown to modify upper airway anatomy, contributing to a reduction in OSA severity (Nobre et al., 2024). One study found that after 52 weeks of Tirzepatide (10mg or 15mg), AHI decreased by 25.3 events/hr, accompanied by reductions in body weight and hypoxic load as well as improvements in self-reported sleep-related outcomes (Malhotra et al., 2024). Other medicines that enhance upper airway muscle responsiveness during sleep have shown promising results in mitigating OSA severity (Perger et al., 2023). A systematic review and meta-analysis showed that a combination of noradrenergic and antimuscarinic medications reduced AHI by 7.7 events/hr (Nobre et al., 2024). While these findings highlight the potential of pharmacological treatments in reducing OSA severity, further large-scale, well-controlled studies are needed to better understand the long-term efficacy, safety, and clinical applicability of these treatments.

1.5 Healthy Lifestyle

WHO (1999) defines a healthy lifestyle as a way of living that minimizes the risk of serious illness or premature death. The key aspects of a healthy lifestyle include a combination of regular PA, a nutritious diet, stress management, adequate sleep, positive social connections, and avoiding harmful substances such as tobacco, alcohol, and drugs. These components work together to improve physical, mental, and social health, ultimately enhancing HRQoL and reducing the risk of chronic diseases (World Health Organization, 1999).

PA and exercise have long been recognized as essential contributors to overall health and well-being (Hall et al., 2020; Lee et al., 2012). More recently, they have also gained recognition as potential effective non-PAP treatment options for OSA patients (Gottlieb & Punjabi, 2020; Iftikhar et al., 2017; Peng et al., 2022). Despite this, the European Research Society task force recommendations do not explicitly mention PA or exercise as non-PAP treatment options (Randerath et al., 2021), and in some guidelines, exercise is mainly emphasized in the context of weight reduction (Randerath et al., 2022). Evidence suggests their broader benefits, as systematic reviews and meta-analyses demonstrate that exercise can effectively reduce OSA severity, even without significant weight loss (Aiello et al., 2016; Bollens & Reychler, 2018; Iftikhar et al., 2014; Mendelson et al., 2018; Peng et al., 2022).

1.5.1 Physical Activity

PA is defined as any bodily movement produced by the skeletal muscles that results in energy expenditure (Caspersen et al., 1985). PA can be broadly classified into work-related, transportation, domestic, and leisure-time activities (Ainsworth et al., 2000). Work-related activities refer to the PA performed as a part of one's job, which may involve repetitive tasks or prolonged periods of standing or sitting (Howley, 2001). Transportation activities include PA, such as walking or cycling for transport. Domestic activities refer to the PA performed during household and gardening or yard work (Ainsworth et al., 2000), while leisure-time PA includes the PA undertaken during free time, such as sports, exercise, and recreational activities

(Howley, 2001). Together, these categories highlight the diverse context in which PA occurs, reflecting its integral role in work-related, self-powered transport, household and yard work as well as leisure-time settings (Craig et al., 2003). For adults aged 18-64 years, the WHO (2020) recommends engaging in 150-300 minutes of moderate PA or more than 75 minutes of vigorous PA per week to maintain health. These guidelines also emphasize the inclusion of muscle-strengthening activities at least twice weekly to derive additional health benefits. Meeting these recommendations has been shown to confer extensive health benefits (Bull et al., 2020), whereas engaging in regular PA reduces the risk of CVD (Kraus et al., 2019), hypertension (Pescatello et al., 2019), type II diabetes (Smith et al., 2016), and certain cancers (Mctiernan et al., 2019), thereby playing a critical role in preventing numerous chronic conditions. Additionally, PA has profound effects on mental health, helping to alleviate symptoms of anxiety and depression and enhancing overall emotional well-being. Furthermore, regular PA contributes to improved sleep and cognitive function and may reduce adiposity (Bull et al., 2020). As previously mentioned, PA is quantified using METs, with higher MET values corresponding to greater intensity. PA intensity is categorized into three levels: light (1.6–2.9 METs), moderate (3.0–5.9 METs), and vigorous (≥6.0 METs) (Ainsworth et al., 1993). Another common method of measuring PA is step count. A widely accepted recommendation for objectively assessed PA is achieving 10.000 steps per day (Tudor-Locke et al., 2008).

Being physically active is currently recognized as one of the most important health-promoting behaviors for OSA patients, as it favorably impacts chronic conditions often coexisting with OSA (Hargens et al., 2013). Research shows that physically active individuals are less likely to develop OSA (Hall et al., 2020; Liu et al., 2022; Mônico-Neto et al., 2018; Murillo et al., 2016), and OSA patients who maintain an active lifestyle are less likely to progress to moderate or severe forms of the condition (Simpson et al., 2015). Furthermore, physically active OSA patients have a lower risk of developing chronic conditions often associated with OSA (Mônico-Neto et al., 2018). Despite these benefits, individuals with OSA are generally less physically active compared to individuals without the condition (Hargens et al., 2019). One systematic review and meta-analysis gathered results from eight studies that objectively measured PA and showed that OSA patients achieved, on average, 5388 steps per day and did not meet the daily recommended step count of 10.000 steps (Mendelson et al., 2018). This physical inactivity in OSA patients can be influenced by factors such as the severity of the condition, obesity, EDS (Chasens et al., 2011), low energy, and fatigue, as well as the presence of comorbidities (Mendelson et al., 2018). Furthermore, one study showed that fear of movement in overweight OSA patients impacted PA among this population (Igelström et al., 2013b).

An individual’s PA can be assessed using either subjective or objective methods. Subjective methods, such as self-reported questionnaires, are commonly used to capture PA levels in OSA patients (da Silva et al., 2017; Hall et al., 2020; Mônico-Neto et al., 2018; Murillo et al., 2016; Quan et al., 2007; Simpson et al., 2015). One example is the International Physical Activity Questionnaire (IPAQ), which is frequently employed to assess PA over the past seven days (Ainsworth et al., 2000). It measures the total PA and moderate and vigorous PA through various domains, including work-related, transportation, domestic, and leisure-time activities. It also measures sedentary behavior and is considered a valid tool for this purpose (Craig et al., 2003). In contrast, objective tools, such as accelerometers, are generally recommended due to their ability to provide detailed data on the intensity and duration of PA and sedentary behavior, which is essential for accurate assessment (Igelström et al., 2013a; Mendelson et al., 2018). Despite the advantages of objective PA measures, the majority of studies evaluating PA levels among OSA patients rely solely on subjective PA measures, using IPAQ (da Silva et al., 2017; Hall et al., 2020; Mônico-Neto et al., 2018), Global Physical Activity Questionnaire (Murillo et al., 2016), Active Australia Survey (Simpson et al., 2015), or other indicators of PA (Quan et al., 2007). Subjective measures are often used due to their practicality, low cost, and low participant burden (Dishman et al., 2001). However, few studies have used objective methods to evaluate daily PA without intervention, but rather in connection to interventions such as PAP (Diamanti et al., 2013; Mendelson et al., 2014) or lifestyle intervention (Igelström et al., 2013b; Kline et al., 2011; Mendelson et al., 2016). Notably, one previous study utilized both subjective and objective PA measures in OSA patients, finding limited agreement between the two methods (Igelström et al., 2013a), highlighting the need for a comprehensive approach to accurately assess PA among OSA patients. Further research is needed to confirm this mismatch between subjective and objective PA measures among OSA patients to better understand the relationship between PA and OSA severity and whether daily PA levels predict OSA severity.

1.5.2 Exercise Definitions and Benefits

Exercise, a subset of PA, refers to planned, structured, and repetitive PA designed to improve physical fitness (Caspersen et al., 1985). It offers numerous health benefits, positively influencing both physical and mental well-being while serving as a powerful tool for preventing and managing chronic diseases (Ruegsegger & Booth, 2018).

Aerobic exercise is defined as PA in which the body and muscles move rhythmically over a sustained period (high volume) (World Health Organization, 2020). It is further characterized by the engagement of large muscle groups and the maintenance of an elevated heart rate (Howley, 2001). This type of exercise primarily relies on the oxidative energy system, which breaks down carbohydrates and fats in the presence of oxygen to generate adenosine triphosphate (ATP), the primary energy source for all biological processes (McArdle et al., 2016). Type I muscle fibers (slow-twitch fibers) have high aerobic endurance and are therefore recruited most often during low-to-moderate intensity, endurance-based activities, such as brisk walking, jogging, long-distance running, cycling, dancing, and swimming (Kenney et al., 2012).

Anaerobic exercise refers to short (low volume), intense bursts (high intensity) of exercise (World Health Organization, 2020). This type of exercise involves maximal or near-maximal exertion lasting from a few seconds to about two minutes (Chamari & Padulo, 2015). During anaerobic exercise, the body's energy demands exceed the available oxygen supply, requiring reliance on anaerobic metabolic pathways (Howley, 2001). The anaerobic alactic (ATP-PCr) system and the anaerobic lactic (glycolysis) system play key roles in rapidly generating ATP. The ATP-phosphocreatine (PCr) system utilizes phosphocreatine (PCr) for immediate energy, while the glycolytic system breaks down stored glucose to sustain high-intensity activities for a short duration (McArdle et al., 2016). These anaerobic processes primarily recruit type II (fast twitch) muscle fibers, which are well-suited for explosive, high-power movements due to their ability to produce force quickly. Type IIa fibers have both anaerobic and aerobic capacities, allowing for slightly longer bursts of activity, whereas Type IIx fibers (also referred to as Type IIb in some literature) rely almost exclusively on anaerobic metabolism, generating high force but fatiguing rapidly (Kenney et al., 2012). As a result, anaerobic exercises, such as sprinting, weightlifting, and high-intensity interval training (HIIT), heavily depend on Type II fibers to meet the rapid ATP demands.

Resistance training is a specialized form of physical conditioning that involves exercises designed to generate force against external resistance. It incorporates a variety of resistance loads, movement speeds, and training methods utilizing equipment such as weight machines, free weights (barbells and dumbbells), elastic bands, medicine balls, and plyometric exercises (Faigenbaum & Myer, 2010). The primary goal of resistance training is to progressively increase resistive loads to enhance muscular strength, endurance, power, and hypertrophy (muscle size) (Garber et al., 2011). According to the American College of Sports Medicine (2009), an effective resistance training program should emphasize dynamic exercises that incorporate both concentric (muscle shortening) and eccentric (muscle lengthening) movements, while engaging multiple muscle groups through multijoint exercises. It is further recommended that resistance training programs include exercises targeting all major muscle groups, including the chest, shoulders, back, hips, legs, trunk, and arms, to promote balanced strength development and overall functional fitness. Progression in resistance training should be an individualized process, tailored to the individual's specific goals, fitness levels, and needs. This requires careful selection of equipment, program design, and proper exercise techniques to ensure both safety and effectiveness throughout the training process (Garber et al., 2011).

Circuit training is a form of resistance training that utilizes progressive resistance loading exercises to enhance both muscular strength and cardiorespiratory fitness (Adamson, 1959). This form of exercise has been recommended as an effective type of training for individuals with little to no prior training or those with a lower basal level of fitness (Wilmore et al., 1978). Circuit training programs typically include a series of 10–15 resistance exercises targeting different muscle groups. Each exercise consists of 12–15 repetitions performed with moderate weights or bodyweight exercise and is completed within 30–60 seconds. Participants transition quickly between exercises, with 15–30 seconds of rest between stations. A minimum of two circuit training sessions per week is recommended and can be effectively combined with endurance training (Romero-Arenas et al., 2013). An important advantage of circuit training is its ability to accommodate a large number of participants in a single session. This inclusivity, combined with the diverse range of exercises, fosters greater interpersonal interaction during training. As a result, participants often experience higher levels of motivation and engagement (Romero-Arenas et al., 2013).

Concurrent training integrates both aerobic exercise and resistance training within a structured program, either within the same session or in separate sessions (Leveritt et al., 1999). In recent years, this training approach has gained popularity, with the WHO (2020) recommending a combination of aerobic and muscle-strengthening exercises on a weekly basis for the general population. While research suggests that concurrently performing strength and endurance training may compromise muscle hypertrophy and strength gains, a phenomenon known as the interference effect (Hickson, 1980), this effect appears to be less significant in untrained individuals (Petré et al., 2021). Importantly, concurrent training has been shown to enhance both cardiovascular fitness and muscular strength in middle-aged individuals (Canli & Aldhahi, 2024) and is recommended for novice individuals (Bompa & Haff, 2009). Beyond fitness improvements, concurrent training offers a range of health benefits and is considered more effective than aerobic exercise alone in reducing the risk of CVD (Schroeder et al., 2019), hypertension, MS (Pedersen & Saltin, 2015), type II diabetes, while also improving mental health (Al-Mhanna et al., 2024) than aerobic exercise alone. Additionally, this combination is recommended for obesity management (Lopez et al., 2022; Pedersen & Saltin, 2015). Notably, many of these chronic conditions can serve as both risk factors and consequences of OSA.

1.5.3 Exercise and OSA

In recent years, exercise interventions have gained attention as a cost-efficient and accessible treatment option for managing OSA (Peng et al., 2022). As a result, the number of randomized controlled trials (RCTs) examining the effects of exercise interventions on OSA severity has increased over the past 15 years. However, these studies vary in several aspects, including the OSA severity of participants, the type implemented, the intervention duration, the frequency of exercise sessions per week, and the length of each session. Table 3 lists the RCTs and provides information on the total sample randomized, intervention group sample size, drop-out rate, control group intervention, OSA severity group, type of exercise used, intervention duration, frequency of sessions per week, and duration of each session. As shown in Table 3, most studies focus on participants with moderate-to-severe OSA (AHI ≥15). The preferred exercise approach combines aerobic and resistance training, with 12-week interventions being the most common. Further, most studies follow the frequency of three sessions per week, each lasting 60 minutes. However, many of these studies are limited by the small sample size of the exercise intervention group (n<20) and the inclusion of an active control group.

Despite these variations and limitations, most of these studies indicate that exercise interventions can reduce AHI, a key measure of OSA severity (Table 4). Only one study failed to demonstrate a reduction in AHI, either within or between groups, following an unsupervised progressive walking intervention over a six-month period (Jurado-García et al., 2020). In contrast, other studies have observed a reduction in AHI following an exercise intervention. Systematic reviews and meta-analyses further support these findings, showing that exercise interventions can reduce OSA severity, with AHI decreasing by 6.7 events/hour (Peng et al., 2022), 8.1 events/hour (Lins-Filho et al., 2021), 8.9 events/hour (Mendelson et al., 2018), and 11.4 events/hour (Lins-Filho et al., 2020). Moreover, a combination of aerobic exercise and resistance training has been recommended for all OSA patients, regardless of severity (Lin et al., 2024), as this approach appears to produce greater reductions in AHI compared to aerobic exercise alone (Peng et al., 2022).

As shown in Table 3, research on individuals with mild-to-moderate OSA remains limited, with no studies including habitual snorers. Additionally, none of these studies have examined the changes in snoring following an exercise intervention. As discussed previously, loud and frequent snoring is a key symptom of SDB (Panossian & Daley, 2013) and an early indicator of OSA (Keropian & Murphy, 2014; Stradling & Crosby, 1991), with a strong correlation between snoring rates and OSA severity (Chiang et al., 2023). One older study found that a 16-week intervention combining a very low-energy diet with aerobic exercises and resistance training reduced snoring (Barnes et al., 2009). These gaps highlight the need for further research on whether exercise interventions could be effective in the early stages of OSA, potentially preventing its progression.

As previously mentioned, OSA often coexists with various chronic conditions, as they share the same risk factors, with obesity being the most significant (Malhotra & White, 2002; Tuomilehto et al., 2013; Vgontzas et al., 1994). While PA and exercise are well-known contributors to obesity reduction, evidence on whether exercise alone improves anthropometric measures such as weight, BMI, neck circumference, and waist-to-hip ratio in OSA patients remains conflicting (Table 4). Despite these uncertainties, several studies have demonstrated that exercise interventions can reduce OSA severity independently of changes in weight (Kline et al., 2011), BMI (Berger et al., 2019; Karlsen et al., 2017; Sengul et al., 2011), or both (Araújo et al., 2021; Lins-Filho et al., 2023). Systematic reviews and meta-analyses support these findings, reporting reductions in OSA severity with modest to no change in BMI (Iftikhar et al., 2014; Lins-Filho et al., 2021; Mendelson et al., 2018). While exercise resulted in an average weight reduction of 2.13kg (p=0.05) and a BMI reduction of approximately 0.55 kg/m^2 (p=0.008), these changes, though statistically significant, were clinically small (Lins-Filho et al., 2021), suggesting that improvements in OSA may be driven by mechanisms beyond weight loss alone.

Fat distribution plays an essential role in the pathogenesis of OSA (Carter & Watenpaugh, 2008; Vgontzas et al., 2000), with neck and visceral adiposity being significant contributors to its development and progression (Kim et al., 2021; Kritikou et al., 2013; Meurling et al., 2019). Notably, a 1 cm reduction in neck circumference has been associated with 2.9-3.4 fewer AHI events per hour (Kim et al., 2015). Although a systematic review and meta-analysis reported a 0.55 cm reduction in neck circumference (p=0.05) following an exercise intervention (Lins-Filho et al., 2021), only half of the studies listed in Table 4 assessed changes in neck circumference before and after the intervention, with just four reporting measurable reductions (Desplan et al., 2014; Jurado-García et al., 2020; Lins-Filho et al., 2023; Mendelson et al., 2016). Even fewer studies have examined changes in waist or hip circumference, or waist-to-hip ratio, following exercise interventions. A reduction in waist circumference was observed following an intense four-week aerobic and resistance training program combined with dietary management (Desplan et al., 2014). In contrast, no changes in waist or hip circumference were reported after a 12-week aerobic and resistance training program (Kline et al., 2011). The findings regarding waist-to-hip ratio also remain inconsistent, with studies showing no change (Jurado-García et al., 2020; Sengul et al., 2011; Yang et al., 2018) or a reduction (Guerra et al., 2019) following exercise interventions.

Table 3. Overview of randomized controlled trials.

Study	Total (N)	IG (n)	Drop-out (%)	AHI (e/h)	Type of exercise	Duration (weeks)	Frequency (days/week)	Session (min)
Araújo et al., (2021)	44	16	23	>15	Aerobic and strengthening exercises	40±3.9	3	60
Berger et al., (2019)	74	36	23	15-30	Aerobic and resistance training	36	3	60
Bughin et al., (2020)	54	27	16	15-45	Aerobic and resistance training Weekly OSA and health education	8	3	120
Desplan et al., (2014)	22	11	15	≥15	Aerobic and resistance training, health education and dietary management	4	6	120
Goya et al., (2021)	44	18	25	>15	Aerobic and resistance training	40±3.9	3	60
Gokmen et al., (2019)	50	23	10	5-30	Tai chi	12	3 supervised 2 home exercises	60
Guerra et al., (2019)	44	20	7	≥15	Aerobic and strengthening exercises	11.65±0.85 months	3	50-60
Jurado-García et al., (2020)	68	29	16	15-30	Aerobic	24	5	30-50
Karlsen et al., (2017)	30	13	10	≥15	HIIT	12	2	~40
Kline et al., (2011)	43	27	12	≥15	Aerobic and resistance	12	4 aerobic 2 resistance	45-60
Lins-Filho et al., (2023)	42	17	14	≥15	HIIT	12	3	35
Mendelson et al., (2016)	44	17	23	≥15	Aerobic	4	5	30
Sengul et al., (2011)	25	10	20	5 - 30	Aerobic and breathing exercises	12	3	60-90
Servantes et al., (2018)	65	17	7	>5 + symp. Or ≥15	Aerobic and resistance	12	3	AE: 30-45 RT: n/r
Yang et al., (2018)	70	32	4	15-30	Aerobic	12	3	30

Abbreviation: AE, aerobic exercises; AHI, apnea-hypopnea index; HIIT, high-intensity interval training; IG, intervention group; n/r, not reported; OSA, obstructive sleep apnea; RT, resistance training; Symp., symptoms.

Table 4. Changes in OSA severity, anthropometry, body composition, and physical fitness following an exercise intervention.

Exercise intervention	OSA Severity	Anthropometry				Body composition			Physical fitness	
Study	**AHI (e/h)**	**Weight (kg)**	**BMI (kg/m²)**	**NC (cm)**	**WHR**	**BF (%)**	**SMM (kg)**	**VA**	**HD**	**CRF**
Araújo et al., (2021)	†	n.s.	n.s.	n/r	n/r	n/r	n/r	n/r	n/r	* †
Berger et al., (2019)	** †	n/r	n.s.	n/r	n/r	n/r	n/r	n/r	n/r	**†
Bughin et al., (2020)	*	* ††	n/r	n/r	n/r	n/r	n/r	n/r	n/r	**†
Desplan et al., (2014)	** †	n/r	** †	* †	WC ∗	BFM ∗ †	n.s.	n/r	n/r	* †
Goya et al., (2021)	†	†	†	n/r	n/r	n/r	n/r	n/r	n/r	* †
Gokmen et al., (2019)	** ††	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r
Guerra et al., (2019)	* †	†	n.s.	n/r	†	n.s.	n/r	n/r	n.s.	* †
Jurado-García et al., (2020)	n.s.	n/r	*	**	n.s.	n/r	n/r	n/r	n/r	n/r
Karlsen et al., (2017)	*	n/r	n.s.	n/r	n/r	n/r	n/r	n/r	n/r	*
Kline et al., (2011)	* †	n.s.	n/r	n.s.	WC n.s. HC n.s.	†	n/r	TBF †	n/r	n/r
Lins-Filho et al., (2023)	†	n.s.	n.s.	** †	n/r	*	n/r	n/r	n/r	* ††
Mendelson et al., (2016)	* †	n/r	n/r	M-NC † OC-NC †	n/r	n/r	n/r	n/r	n/r	*
Sengul et al., (2011)	*	n/r	n.s.	n.s.	n.s.	n.s.	n/r	n/r	n/r	*
Schütz et al., (2013)	n.s.	n/r	n.s.	n.s.	n/r	n/r	n/r	n/r	n/r	n/r
Servantes et al., (2018)	*	n/r	n/r	n/r	n/r	n.s.	n/r	n/r	Other	* †
Yang et al., (2018)	* †	n/r	* †	n.s.	n.s.	n/r	n/r	n/r	n/r	n.s.

Abbreviation: HC, hip circumference; M-NC, morning neck circumference; n/r, not reported; n.s., no significant change; OC-NC, overnight change in neck circumference; TBF, trunk body fat; WC, waist circumference; ∗, Within exercise group difference p<0.05; **, Within exercise group difference p<0.001; †, Between-group difference p<0.05; ††, Between-group difference p<0.001.

Changes in body composition following exercise interventions in OSA patients have been explored in a limited number of studies (Table 4). While most of these studies have focused on reducing body fat percentage, with only one study assessing changes in skeletal muscle mass (Desplan et al., 2014), a critical factor for overall health, healthy aging, and prevention of chronic diseases (McLeod et al., 2016). Findings on body fat percentage remain inconsistent among these studies, with some reporting no change in body fat percentage (Guerra et al., 2019; Sengul et al., 2011; Servantes et al., 2018). In contrast, others report an intra-group reduction (Desplan et al., 2014; Lins-Filho et al., 2023) or a decrease when compared to controls (Kline et al., 2011) following an exercise intervention. Additionally, a systematic review and meta-analysis on the effects of exercise training on body composition in OSA patients revealed a 1.19% reduction in body fat percentage (p=0.0006) (Lins-Filho et al., 2021). However, research on skeletal muscle mass remains scarce, with only one study addressing its changes, which found no change following an aerobic and resistance training intervention (Desplan et al., 2014). This inconsistency in findings regarding body composition, coupled with the limited number of studies on body composition changes in OSA patients following exercise interventions, highlights the need for further investigation.

Physical fitness is defined as a set of attributes that are either health- or skill-related. These attributes can be measured with specific tests and include components such as muscle strength, muscular endurance, cardiovascular endurance, flexibility, and body composition (Caspersen et al., 1985). Being overweight or obese can negatively influence physical fitness, with long-term obesity particularly affecting hand grip strength (Stenholm et al., 2011). Additionally, high BMI, body weight, waist circumference, and body fat have been associated with reduced cardiorespiratory fitness (Zeiher et al., 2019). Hand dynamometry is a well-established measure of muscle strength and an important indicator of overall muscle function (Bohannon, 2015). Poor grip strength has been associated with an increased risk of chronic conditions commonly associated with OSA, including CVD, type II diabetes, and hypertension (Stenholm et al., 2012). Furthermore, low grip strength has been associated with a greater likelihood of premature mortality (Bohannon, 2008). Despite its clinical significance, only two RCTs have assessed muscular strength using hand dynamometry in OSA patients undergoing exercise interventions (da Silva et al., 2022; Guerra et al., 2019). Both studies (one with elderly OSA patients) reported no change in hand dynamometry following the intervention. Beyond muscle strength, cardiorespiratory fitness is strongly associated with overall health outcomes, with high levels linked to a lower risk of all-cause mortality and chronic conditions (Lang et al., 2024). Cardiorespiratory fitness refers to the ability of the circulatory and respiratory systems to efficiently deliver oxygen to skeletal muscle mitochondria, supporting energy production during PA (Ross et al., 2016). OSA is associated with impaired cardiorespiratory fitness (Beitler et al., 2015), with research suggesting that OSA patients exhibit altered physiological responses during exercise. These responses include exaggerated blood pressure and delayed heart rate recovery, which may affect their exercise tolerance (Mendelson et al., 2018). Despite these challenges, exercise has been shown to improve cardiorespiratory fitness in OSA patients. Studies incorporating HIIT (Karlsen et al., 2017; Lins-Filho et al., 2023), aerobic exercises (Mendelson et al., 2016; Sengul et al., 2011), and a combination of aerobic and resistance training or strength training (Araújo et al., 2021; Berger et al., 2019; Bughin et al., 2020; Desplan et al., 2014; Goya et al., 2021; Guerra et al., 2019; Servantes et al., 2018) have all demonstrated improvements in cardiorespiratory fitness. These findings are further reinforced by systematic reviews and meta-analyses, which have reported improvements in VO_2 peak following exercise interventions, with increases of 0.5 mL/kg/min (Peng et al., 2022), 3.4 mL/kg/min (Mendelson et al., 2018), and 3.9 mL/kg/min (Iftikhar et al., 2014).

As previously mentioned, OSA negatively impacts HRQoL (Gassara et al., 2017), with OSA patients generally reporting lower HRQoL than healthy individuals (Smith & Shneerson, 1995). However, research suggests that exercise interventions can improve HRQoL in OSA patients, as assessed using the SF-36 questionnaire (Desplan et al., 2014; Sengul et al., 2011; Servantes et al., 2018). Additionally, a systematic review and meta-analysis found that exercise enhances HRQL (Lins-Filho et al., 2020). Notably, a 4-week aerobic and resistance training intervention led to improvements in physical functioning, role limitations due to physical health, vitality, social functioning, pain, and general health (Desplan et al., 2014). In contrast, a 12-week intervention incorporating T'ai Chi and Qigong showed no changes in HRQoL (Gokmen et al., 2019). These inconsistencies, along with the limited number of studies and small sample sizes examining HRQoL in OSA patients following exercise interventions, underscore the need for further research.

Poor SQ, EDS, and altered sleep architecture are common symptoms of OSA, as frequent arousals fragment sleep and reduce time spent in the deeper, restorative sleep stages. These disruptions often result in persistent sleep disturbances, contributing to both poor SQ and increased EDS (Roure et al., 2008). Although the term "Sleep Health" has not been widely used in the context of exercise interventions for OSA patients, it provides a broader framework for evaluating sleep beyond isolated symptoms. Assessing sleep health can involve subjective, objective, or combined methods, with multidimensional tools recommended for more comprehensive evaluation (Chung et al., 2021, 2023; Meltzer et al., 2021). Exercise interventions have been shown to enhance both objective and subjective SQ in the general population, supporting the concept of improved sleep health (Zhou et al., 2025). Further, systematic reviews and meta-analyses have reported improvements in self-reported SQ and a reduction in perceived EDS among OSA patients (Lin et al., 2024; Lins-Filho et al., 2020; Peng et al., 2022). However, most studies evaluating the effects of exercise interventions in OSA patients have focused on changes in SQ, EDS, and sleep architecture (Table 5), either individually or as part of broader sleep-related assessments, rather than specifically addressing overall sleep health.

Studies examining self-reported SQ using the PSQI questionnaire following an exercise intervention in OSA patients have either reported the results as the overall score, termed "global score"(Desplan et al., 2014; Lins-Filho et al., 2023), or global score and most (Gokmen et al., 2019) or all subscales (Kline et al., 2011; Lins-Filho et al., 2024). These studies have shown an improvement in the PSQI global score, indicating a better overall perception of sleep health among OSA patients following an exercise intervention. The findings on specific subscales of the PSQI in OSA patients remain limited, with only three of the listed studies examining most or all subscales. All three studies reported improvements in the SQ subscale (Gokmen et al., 2019; Kline et al., 2011; Lins-Filho et al., 2024). Both studies assessing the sleep latency subscale reported improvement (Kline et al., 2011; Lins-Filho et al., 2024), suggesting that exercise may help individuals fall asleep faster. However, improvements in SE have only been noted in a single study (Gokmen et al., 2019), indicating that increased TST or reduced WASO may not be a consistent outcome of exercise interventions. Similarly, while Kline (2011) reported a decrease in sleep disturbances, these findings have not been replicated, raising questions about whether exercise effectively reduces nighttime awakenings or other disruptions in OSA patients. Additionally, improvements in daytime dysfunction have been observed in two studies (Gokmen et al., 2019; Lins-Filho et al., 2024), suggesting that exercise may enhance daytime alertness and reduce fatigue. However, the variability in findings across these studies suggests that other factors, such as exercise type, intensity, or individual differences in OSA severity, may influence these outcomes. These inconsistencies underscore the need for further research using standardized methodologies, larger sample sizes, and more comprehensive assessments to better understand the impact of exercise on specific aspects.

Several studies have evaluated changes in EDS using the ESS questionnaire following an exercise intervention in OSA patients, given that EDS is a hallmark symptom of the condition (He & Kapur, 2017; Lal et al., 2021; Roure et al., 2008). Most studies indicate a reduction in ESS score post-intervention, suggesting that exercise interventions can reduce EDS in OSA patients (Bughin et al., 2020; Desplan et al., 2014; Gokmen et al., 2019; Karlsen et al., 2017; Lins-Filho et al., 2024; Schütz et al., 2013; Servantes et al., 2018). The majority of these studies have focused on individuals with moderate-to-severe OSA. Few studies have examined EDS in individuals with milder conditions, and the limited evidence available presents contradictory findings (Gokmen et al., 2019; Sengul et al., 2011). One study reported an intragroup reduction in EDS (pre: 9.56 ± 5.68 vs. post: 5.76 ± 3.45, $p<0.001$) and a notable between-group difference ($p<0.001$) following a 12-week T'ai chi and Qigong training intervention (Gokmen et al., 2019). In contrast, another study found no changes in EDS after a 12-week aerobic and breathing exercise training (Sengul et al., 2011). These inconsistencies underscore the need for further research to determine the impact of various exercise modalities on EDS in patients with mild-to-moderate SDB.

Despite these findings, improvements in subjective sleep health do not always align with changes in objective sleep parameters in OSA patients, with only a few studies reporting concurrent improvements in both. One study found a reduction in EDS was observed alongside decreased light sleep (N1 and N2) and increased restorative N3 sleep, without changes in TST or SE (Bughin et al., 2020). Similarly, in an exercise intervention study, participants reported greater improvements in self-reported SQ as measured by the PSQI global score, compared to controls, accompanied by enhancements in TST, SE, SOL, and an increased proportion of sleep spent in N3 and REM sleep in the exercise group (Lins-Filho et al., 2023). However, other studies have found either minimal (Gokmen et al., 2019; Kline et al., 2011; Servantes et al., 2018) or no changes (Schütz et al., 2013) in objective sleep parameters despite improvements in subjective outcomes. A meta-analysis of RCTs showed that exercise programs lasting ≥12 weeks decreased N2 sleep and increased N3 sleep in OSA patients (Chen et al., 2024). Additionally, some studies reporting subjective improvements have not assessed objective sleep parameters (Jurado-García et al., 2020; Karlsen et al., 2017; Lins-Filho et al., 2024), limiting the ability to determine whether exercise directly influences sleep architecture or primarily alters sleep perception. This highlights the need for future research to incorporate both subjective and objective assessments to provide a more comprehensive understanding of the impact of exercise interventions on sleep health in OSA patients.

Table 5. Overview of studies assessing subjective and or objective sleep health parameters.

	Subjective sleep health									Objective sleep health								
Study	**ESS**	**PSQI Global score**	**PSQI SQ**	**PSQI SL**	**PSQI SD**	**PSQI SE**	**PSQI SDIS**	**PSQI SM**	**PSQI DD**	**TST**	**SE**	**SOL**	**WASO**	**Arousal Index**	**N1**	**N2**	**N3**	**REM**
Bughin et al., (2020)	* †	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n.s.	n.s.	n/r	n/r	n/r	N1+N2 *		*	n.s.
Desplan et al., (2014)	*	*	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n.s.	n/r	n/r	n/r	†		NREM n.s.		n/r
Gokmen et al., (2019)	** †	** †	*	n/r	n/r	†	n/r	n/r	**	n.s.	n.s.	n.s.	n/r	n.s.	n.s.	†	†	n.s.
Jurado-García et al., (2020)	*	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r
Karlsen et al., (2017)	†	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r
Kline et al., (2011)	n/r	* †	* †	†	n.s.	n.s.	†	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.
Lins-Filho et al., (2023)	n/r	†	n/r	n/r	n/r	n/r	n/r	n/r	n/r	†	* †	* †	n/r	n.s.	n.s.	n.s.	* †	* †
Lins-Filho et al., (2024)	* †	* †	* †	* †	n.s.	n.s.	n.s.	n.s.	* ††	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r
Sengul et al., (2011)	n.s.	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n.s.	n.s.	n/r	n/r	n/r	n/r	n/r	n/r	n/r
Schütz et al., (2013)	*	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Servantes et al., (2018)	* †	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n.s.	n.s.	n/r	n/r	* †	n.s.	n.s.	n.s.	n.s.

Abbreviation: DD, Daytime dysfunction; ESS, Epworth sleepiness scale; N1, non-rapid eye movement sleep stage 1; N2, non-rapid eye movement sleep stage 2; N3, non-rapid eye movement sleep stage 3; PSQI, Pittsburgh sleep quality index; REM, rapid eye movement sleep; SD, sleep duration; SDIS, sleep disturbances; SE, sleep efficiency; SL, sleep latency; SM, sleep medication; SQ, sleep quality; TST, total sleep time; SOL sleep onset latency, WASO, wake after sleep onset, Within exercise group difference p<0.05; **, Within exercise group difference p<0.001; †, Between-group difference p<0.05; ††, Between-group difference p<0.001.

1.6 Lifestyle Apps

The rapid advancement of smartphone technology has brought increased attention to lifestyle mobile applications delivered on a smartphone (hereinafter referred to as apps) designed to encourage healthy behaviors, such as improving diet, increasing PA, and reducing sedentary behavior (Schoeppe et al., 2016). These lifestyle apps are increasingly recognized as flexible and accessible tools to deliver behavioral interventions to large populations (Middelweerd et al., 2014). By leveraging apps, they provide personalized feedback, self-monitoring tools, and behavior-change techniques, empowering users to adopt and maintain a healthy lifestyle (Schoeppe et al., 2016). Traditional health and wellness apps primarily focus on tracking activities like diet, PA, exercise, and sleep (Lougheed, 2019). In contrast, digital exercise therapeutic apps, such as the Sidekick Health app, are evidence-based, clinically validated apps designed to prevent, manage, or treat medical conditions (Grannell et al., 2023). Many evidence-based apps are rooted in self-care principles or help to self-help frameworks, offering clinically proven benefits for managing, preventing or treating various health conditions (Oddsson et al., 2023). As a result, they hold the potential to improve healthcare by bridging treatment gaps, expanding access to care at lower cost, and enhancing clinical outcomes (Miao et al., 2022).

Evidence-based lifestyle apps have been demonstrated effective in managing chronic conditions such as obesity, type II diabetes, and MS (Björnsdottir et al., 2024; Hilmarsdóttir et al., 2021; Thorgeirsson et al., 2022). A four-month lifestyle app intervention focused on nutrition, PA, and stress management through the Sidekick Health app resulted in weight and BMI reductions (Thorgeirsson et al., 2022), supporting the role of digital therapeutic apps in structured lifestyle change programs for weight management. Similarly, a six-month lifestyle intervention using the Sidekick Health app resulted in intra-group improvements in glycemic control and anxiety symptoms among obese patients with type II diabetes, suggesting its potential to enhance outpatient treatment for both metabolic and psychological well-being (Hilmarsdóttir et al., 2021). Furthermore, a 12-week lifestyle app intervention led to reductions in weight and body fat mass, along with improvements in metabolic health parameters in patients with multiple chronic conditions, including MS, type II diabetes, and nonalcoholic fatty liver disease, with greater engagement correlating with better outcomes (Björnsdottir et al., 2024). While lifestyle apps show promising results, research indicates that multi-component approaches, including the provision of PA equipment and face-to-face counseling, are more effective than app-based interventions alone (Schoeppe et al., 2016).

1.6.1 Lifestyle Apps and OSA

The integration of apps has opened a new avenue for managing various health conditions, including OSA. These apps offer a user-friendly and cost-effective approach to both screening and management for OSA (Al-Mardini et al., 2014; Lin et al., 2024). For instance, apps have been utilized to screen and classify OSA, aiming to identify people at high risk who may require a diagnostic evaluation in a sleep laboratory or clinical setting (Al-Mardini et al., 2014). Some apps incorporate sleep diaries to collect longitudinal data on subjective SQ and habits over extended periods, such as three months (Schmitz et al., 2022), providing valuable insights into sleep patterns and potential disturbances. Other apps have been used to support PAP therapy in OSA patients, as they offer a feasible, patient-centered approach to improve adherence, reduce the need for in-person visits, and provide continuous support through remote monitoring and motivational strategies (Suarez-Giron et al., 2020). Furthermore, apps that provide home-based physical therapy exercises aimed at improving respiratory muscle strength and overall endurance have been designed and may benefit OSA patients (Bui-Diem et al., 2023).

Apps focused on lifestyle modification have been shown to support weight reduction (Thorgeirsson et al., 2022), a critical factor in OSA management. However, the effectiveness of lifestyle apps as a treatment option for OSA patients has only been assessed in a limited number of studies (Cho et al., 2018; Lin et al., 2024). In a study examining the effects of a short-term (4 weeks) lifestyle app modification incorporating diet and PA intervention for obese OSA patients, the app users experienced a reduction in BMI without changes in AHI. Nonetheless, a decreased proportion of snoring was reported (Cho et al., 2018). A more recent study evaluated the effects of a lifestyle app in managing OSA among overweight and obese high-tech employees (Lin et al., 2024). The study carried out two interventions for 6 months using the app 'MyFitnessPal' (diet and PA) for OSA patients (AHI>5). One group received additional in-person lectures on weight loss. While both intervention groups showed intra-group reductions in AHI ($p<0.05$), no differences were found compared to controls. However, BMI and waist circumference were reduced in both intervention groups compared to the control group (Lin et al., 2024). Despite these findings, the effectiveness of lifestyle apps in improving OSA-related outcomes remains uncertain and understudied. Existing studies have primarily focused on weight reduction and its connection to OSA, with little attention given to other important health outcomes. None of these interventions has examined their effects on body composition, physical fitness, HRQoL, or subjective and objective sleep health parameters. Given that improvements in BMI alone may not fully capture the impact of lifestyle modifications on OSA severity and overall well-being, research should adopt a more comprehensive approach. Assessing changes in HRQoL and subjective and objective sleep health could provide a clearer understanding of the true efficacy of app-based interventions for OSA management.

2 OBJECTIVES

Several key gaps remain in the literature. The role of daily PA levels in predicting OSA severity has predominantly been assessed using subjective methods, which often do not align with objective measurements. Assessing the relationship between subjective and objective PA assessments is essential to clarify their relationship and determine whether daily PA levels can reliably predict OSA severity. On the other hand, research on the effects of exercise interventions in mild-to-moderate SDB is limited (especially in RCTs) as most studies have focused on moderate-to-severe OSA without including habitual snorers. In addition, while lifestyle apps have shown promise in weight reduction, their effectiveness in improving SDB-related outcomes remains uncertain and underexplored. These gaps underscore the need to explore whether exercise and lifestyle app interventions can serve as an early-stage intervention to prevent SDB progression and improve other important risk factors and symptoms of SDB.

2.1 Overall Objectives

A key focus was to investigate whether PA could predict the severity of OSA and to assess how different methods of measuring PA, objective versus subjective, may influence this relationship. Understanding whether a mismatch exists between these assessment methods is crucial, as it could impact the interpretation of PA's role in OSA research. On the other hand, while PAP remains the first-line treatment for moderate-to-severe OSA, other treatment modalities, such as exercise interventions, show promise in reducing AHI and improving physical health, HRQoL, and subjective sleep health but require further evidence, especially among mild-to-moderate SDB. Similarly, understanding the effectiveness of evidence-based lifestyle apps in SDB-related outcomes through modified lifestyle habits could be an important step toward the development of individualized treatment strategies that extend beyond PAP therapy.

In this context, the overall objectives of this doctoral thesis were: (i) to explore the differences in the role of PA in individuals with OSA by examining both subjectively and objectively measured PA, and to study PA as a predictor of OSA severity; and (ii) to evaluate the effects of two distinct interventions: a structured exercise program and a lifestyle app, on various parameters including SDB severity, anthropometry, body composition, physical fitness, HRQoL, and sleep health in 18-50-year old individuals with mild to moderate SDB.

2.2 Objectives of Paper I

The objectives of the paper were twofold: (i) to assess the relationship between the OSA severity (both AHI and desaturation parameters) and both objectively (steps per day) and subjectively measured PA (IPAQ, sitting time from IPAQ, and exercise per day in minutes daily in an app) by considering the effects of anthropometry and body composition parameters; and (ii) to assess the relationship between the different objective and subjective PA parameters and the role of OSA severity on this relationship.

2.3 Objectives of Paper II

The objectives of the paper were to assess the effects of (i) a 12-week exercise program and (ii) a lifestyle app compared to controls on SDB severity (as indicated by AHI and snore percentage), physical health (anthropometry, body composition, physical fitness), and HRQoL in 18-50-year-old adults with mild-to-moderate SDB.

2.4 Objectives of Paper III

The objectives of the paper were to assess the effects of (i) a 12-week exercise program and (ii) a lifestyle app intervention compared to controls on subjective and objective sleep health in 18 to 50-year-olds with mild-to-moderate SDB.

3 MATERIALS AND METHODS

3.1 Participants

The three research papers described in this thesis are based on the results from two study cohorts. Paper I is based on the Pilot study cohort, and Papers II and III are based on the Lifestyle study cohort. In both studies, all participants were informed about the purpose of the study, and written consent was obtained as a prerequisite for participation. Both studies received approval from the National Bioethics Committee of Iceland and the Data Protection Authority of Iceland (Paper I: ref. no. 21-070, Papers II and III: ref. no. 22-082), adhering to the principles outlined in the Declaration of Helsinki.

3.1.1 Paper I - Pilot Study Cohort

The Pilot study cohort included 65 adult participants (49.2% males), recruited from the general population via media advertisement. The cohort included healthy participants, snorers, and individuals with suspected or confirmed sleep apnea, with a wide range of BMI and age. The inclusion criteria were: (i) participants had to complete at least a single night sleep study, with a minimum of four hours of SpO_2 and other sleep signals, out of three nights using self-applied PSG (Nox Medical, A1s, Reykjavík, Iceland), and (ii) to use a wrist-worn wearable (Withings Inc, ScanWatch, Paris, France) for at least 10 hours per day for 4 out of 7 days (Migueles et al., 2017). In total, 54 participants (83%) fulfilled the inclusion criteria and were included in the study, 25 male (46.3%) and 29 female (53.7%) participants. The participants were classified into three groups based on OSA severity using the AHI: no OSA (AHI <5), mild OSA (AHI 5-14.9), and moderate-to-severe OSA (AHI ≥15) ("Sleep-Related Breathing Disorders in Adults," 1999).

3.1.2 Papers II and III - Lifestyle Study Cohort

A total of 1299 people responded to the study advertisement. The inclusion criteria were: (i) subjects had to be between 18 and 50 years old, (ii) overweight or obese (BMI between 25 and 42 kg/m^2), (iii) physically inactive (not enrolled in an exercise intervention), and (iv) diagnosed with mild-to-moderate SDB based on specific criteria. Certain factors led to exclusion from the study, such as current OSA treatment, pregnancy, shift work, or an inability to exercise. All participants who met the first three criteria were invited to a preliminary study of a single-night type III sleep study and anthropometric measurements. In total, 422 participants accepted participation in the preliminary study, of whom 357 completed the preliminary sleep study, and 222 were found eligible for the study. Finally, 192 participants, 101 (52.6% males), with a mean age of 37.4 years and an average BMI of 33.3 kg/m², met all criteria and agreed to participate in the study. These participants were randomly assigned to either the exercise, app, or control group, with 64 participants assigned to each group. Since the group assignment was randomized, participants in the exercise group may not have had a prior interest in exercise. Given that all participants were inactive and either overweight or obese, the program set a realistic adherence target of approximately two sessions per week. Participants were required to attend at least 60% of the scheduled sessions to be included in the analysis. The study was registered in ISRCTN: 16974764.

In Paper II, participants who completed both pre- and post-intervention anthropometric, body composition, and physical fitness measurements were included in the analysis. In the exercise group, 11 participants failed to complete the post-intervention measurements and were excluded from the study. Six participants who did not meet the criteria of 60% attendance in the exercise intervention were excluded. In the lifestyle app group, 16 participants withdrew from the study, and nine were in the control group. Additionally, two control group participants with abnormal differences in AHI pre- and post-intervention were considered outliers and excluded from all analyses. Out of the 192 randomized participants, 111 (58.7%) participants, 48.6% males, fulfilled all criteria of the study and were analyzed. The flowchart is shown in Figure 3.

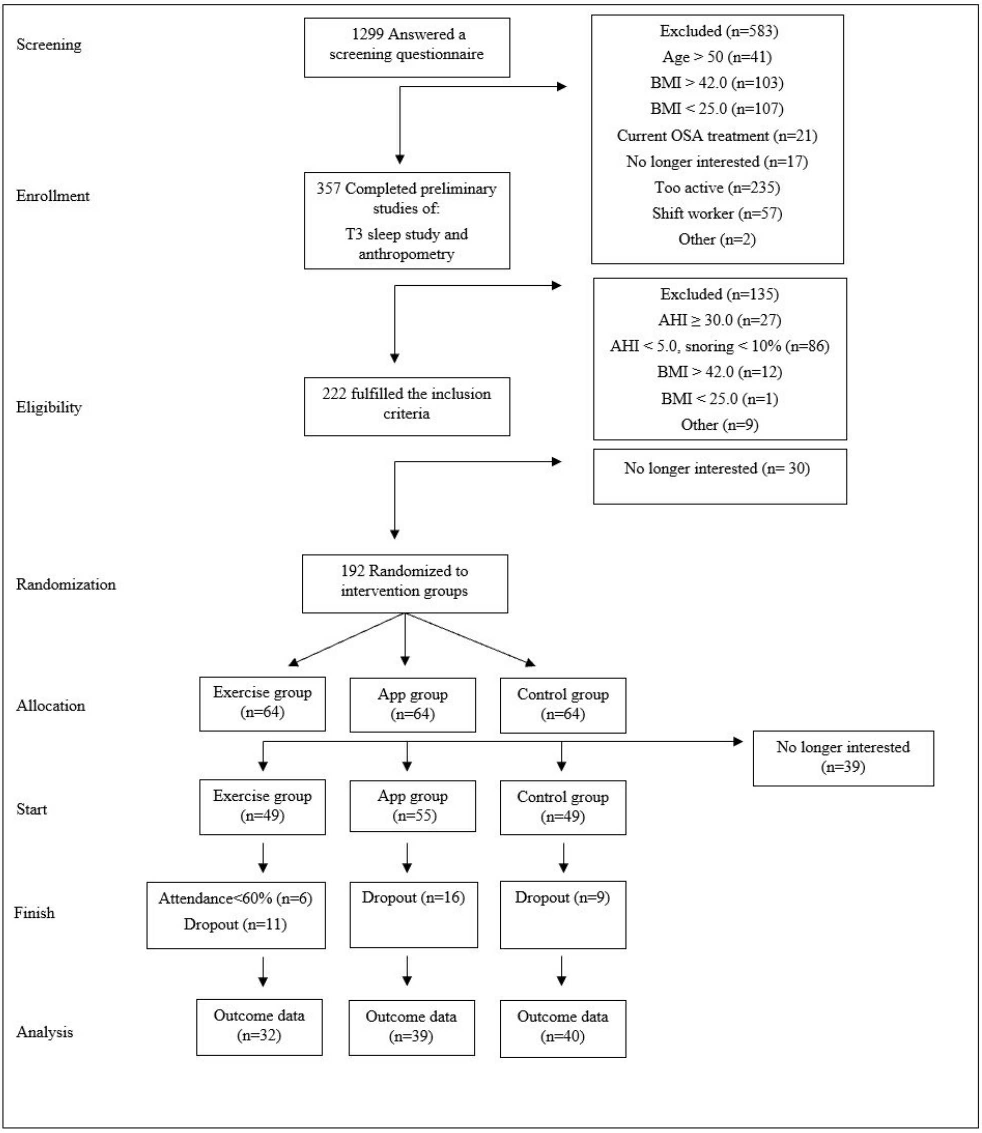

Figure 3. Summary of participants' flow through Paper II.

In Paper III, participants who completed pre- and post-intervention sleep studies were included in the analysis. In total, 103 participants completed pre- and post-sleep studies. Two control group participants with abnormal differences in AHI pre- and post-intervention were considered outliers and excluded from all analyses. In total, 101 participants, 46.5% males, were analyzed.

3.2 Measurements

3.2.1 Sleep Measurements

3.2.1.1 Self-Applied Polysomnography

In the Paper I (Pilot study cohort) and the Lifestyle cohort (Papers II and III), all participants underwent a three-night sleep study using a self-applied PSG device (Nox Medical, A1s, Reykjavík, Iceland). The setup included a frontal EEG and EOG (Kainulainen et al., 2021). Nasal airflow was measured using a cannula, while SpO_2 was tracked through oximetry. Heart rate was monitored using ECG and oximetry, and respiratory movements were recorded through respiratory inductance plethysmography with thorax and abdominal belts. Body position and movement were tracked using an accelerometer, while leg movements were measured via EMG on the left and right anterior tibialis muscles. An audio recording was also used to detect snoring. All sleep studies that fulfilled the criteria of a minimum of four hours of wearable O_2 measures and other sleep study signals (Kapur et al., 2017) were manually scored by expert sleep technologists according to the AASM manual, version 2.6 (American Academy of Sleep Medicine, 2020).

In Paper I, the average AHI from valid nights was used to determine OSA severity. The ODI was calculated based on a manually scored ≥ 3% blood oxygen desaturation. Other parameters included the percentage of sleep time spent with SpO_2 below 90% (T90%) and the average SpO_2 value during sleep.

In Paper II, the average AHI from valid nights was used to assess OSA severity, calculated as the total number of apnea and hypopnea events per hour of sleep. A snoring threshold of ≥10% was used to confirm habitual snoring without OSA, although no official cutoff exists. Snoring was automatically detected and then manually validated by listening. Events were recorded as snoring if they exceeded 65 dB and occurred in a series of at least three. The snoring rate was determined by calculating the percentage of TST spent snoring.

In Paper III, objective sleep health was assessed using several key parameters, including TST, SE, SOL, WASO, arousal index, and sleep stages (NREM, N1, N2, N3, and REM), with sleep stages expressed as a percentage of TST.

The reported values represent the average measurements from completed sleep studies.

3.2.1.2 Type III Sleep Study

In Papers II and III (Lifestyle study cohort), all subjects who fulfilled the criteria for the preliminary study were invited to a type III single-night sleep study to confirm mild to moderate SDB. The type III sleep study was conducted using a sleep monitoring device (Nox Medical, A1, Reykjavík, Iceland). The setup included nasal airflow measured using a cannula, SpO_2 tracked through oximetry, respiratory movements recorded through respiratory inductance plethysmography with thorax and abdominal belts, body position and movement tracked using an accelerometer, and an audio recording detected snoring. The diagnostic criteria used for mild to moderate SDB were an AHI between 5 and 30 events per hour ("Sleep-Related Breathing Disorders in Adults," 1999) and/or more than 10% of TST spent snoring, although no official snore cutoff exists.

3.2.2 Hypoxic Load

In Paper I, the hypoxic load was assessed using the ABOSA software, which automatically calculates nocturnal hypoxic parameters from ODI 4%, capturing the hypoxic load (Karhu et al., 2022). The DesSev metric was calculated by summing desaturation areas and normalizing them with TST. Similarly, RecSev measured the return of oxygen levels to baseline. The total hypoxic load was determined by summing DesSev and RecSev (DesSev+RecSev) (Karhu et al., 2022; Kulkas, Tiihonen, Eskola, et al., 2013).

3.2.3 Physical Health Parameters

3.2.3.1 Physical Activity

In Paper I, PA was assessed using both subjective and objective methods. For the subjective PA assessment, participants completed the long version of the IPAQ (Ainsworth et al., 2000) and kept a daily exercise diary (Sleep Revolution, App, Reykjavík University, Iceland) (Schmitz et al., 2022). The IPAQ tracks health-enhancing activities (walking, moderate, and vigorous intensity PA) over the past seven days across five domains: job-related PA, transportation, household activities, leisure-time PA, and total sitting time (a measure of physical inactivity). The total of walking and moderate or vigorous activities was reported as weekly PA, measured in MET-minutes per week. The IPAQ is a well-established tool for self-reported PA (Ainsworth et al., 2000; Dyrstad et al., 2014). A sedentary score was also calculated based on the total sitting time per day over the past week, using questions like "How much time did you spend sitting on a weekday?" and "How much time did you spend sitting on a weekend day?" (Ainsworth et al., 2000). Exercise duration per day (in minutes) was recorded subjectively using a daily question in the Sleep Revolution app sleep diary, which participants filled out for seven days (Schmitz et al., 2022). The question asked, "*How much did you exercise?*".

For the objective PA measurement, participants wore a ScanWatch to track their daily PA by counting steps. The device was worn on the non-dominant hand around the clock for one week. Daily PA was measured as the average number of daily steps over seven days. A valid day was defined as having at least 10 hours of heart rate recordings (Migueles et al., 2017).

3.2.3.2 Anthropometric Measurements

In Papers I and II, anthropometric measurements, including height, weight, BMI, and neck circumference, were taken following the guidelines of the International Society for the Advancement of Kinanthropometry (2011). Body mass was measured to the nearest 0.1 kg using a digital scale (TANITA MC-780, Tokyo, Japan), with participants wearing light everyday clothing, such as trousers and a t-shirt. Standing height was measured without shoes to the nearest 0.1 cm using a wall-mounted stadiometer (Soehnle Professional 5002.01, Backnang, Germany). BMI was calculated by dividing body mass (kg) by height squared (m^2) (Keys & Brozek, 1953). Neck circumference was assessed using a flexible, non-stretchable tape measure with an accuracy of 0.1 cm. Also for Paper II, waist and hip circumference were additionally measured with a flexible but non-stretchable tape measure with an accuracy of 0.1cm, following the guidelines of the International Society for the Advancement of Kinanthropometry (2011).

3.2.3.3 Body Composition

In Papers I and II, body composition was assessed using a bioelectrical impedance device (Multifrequency Segmental Body Composition Analyzer TANITA MC-780MA, Tokyo, Japan). Participants stood barefoot on the device’s built-in digital scale in standard mode. After entering their sex, age, and height, they held the handgrips at their sides while the impedance measurement was conducted. The assessment provided data on total fat mass, muscle mass, body water, and visceral adiposity index (ranging from 1 to 59).

3.2.3.4 Physical Fitness

In Paper II, physical fitness was assessed through muscle strength and cardiorespiratory fitness. Muscle strength was measured using hand dynamometry of the dominant hand using a Vernier hand dynamometer (Vernier, Orlando, FL, USA) (Fess, 1992). Hand dynamometry is a widely used method to measure muscular strength and is considered an effective way to track changes in physical function (Roberts et al., 2011). Participants were given three attempts, with a 20-second rest between each. The average force in Newtons from the three attempts was recorded.

Cardiorespiratory fitness was evaluated through a 6-minute walking test (Butland et al., 1982). This submaximal, self-paced test assessed an individual's ability to perform activities by walking as quickly as possible for 6 minutes on a flat, hard surface. The total distance covered (in meters) was recorded.

3.2.3.5 Health-Related Quality of Life and Subjective Sleep Health

For all three papers, the data from questionnaires were collected and managed using the Research Electronic Data Capture data management platform (REDCap), a secure, web-based software platform for research data capture hosted at Reykjavík University in Iceland (Harris et al., 2019). In Papers II and III, the questionnaires were answered pre- and post-intervention.

In Paper II, HRQoL was assessed using the MOS 36-item short-form health survey (SF-36). The questionnaire measures HRQoL across eight 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

(Ware & Sherbourne, 1992). Each domain is scored from 0 to 100, with higher scores indicating better HRQoL.

In Paper III, subjective sleep health was assessed using PSQI and ESS questionnaires. The PSQI is a self-reported questionnaire that covers seven areas: SQ, sleep duration, SE, sleep disturbance, use of sleep medication, and daytime dysfunction (Buysse et al., 1989). Scores range from 0 to 21, with scores ≤5 indicating good SQ and scores above 5 indicating poor SQ.

The ESS assesses the likelihood of falling asleep in eight everyday situations: sitting and reading, watching TV, sitting inactive in a public space, as a passenger in a car for an hour without a break, lying down to rest in the afternoon when circumstances permit, sitting and talking to someone, sitting quietly after a lunch without alcohol, and in a car while stopping for a few minutes in traffic (Johns, 1991). The total score ranges from 0 to 24, with scores above 10 indicating EDS.

3.3 Procedure

3.3.1 Paper I

After being included in the study, participants visited the Reykjavik University Sleep Institute for their initial assessments. After completing anthropometric and body composition measurements, they downloaded the Withings Health Mate app (Withings Inc, App, Paris, France). Each participant received a Withings ScanWatch to use for one week and a self-applied PSG for a three-night home sleep study. At home, they also completed the IPAQ and other questionnaires through the REDCap platform (Harris et al., 2019).

3.3.2 Papers II and III

Participants were recruited from the general population through media advertisements and completed a screening questionnaire covering basic information such as sex, height, weight, shift work, previous OSA diagnosis, current OSA treatment, and PA levels. Those meeting the initial inclusion criteria were invited for a preliminary assessment, which included a type III sleep study and anthropometric measurements to further evaluate eligibility. Participants who fulfilled all the study's criteria were then randomly assigned to one of three groups. Those placed in the exercise group were consulted about their preferred workout times to adapt the program schedule to their needs. Participants in the app group were instructed to install the lifestyle app (Sidekick Health, Reykjavik, Iceland) on their smartphones. The exercise intervention took place at the Sports Science Laboratory at Reykjavik University. The program was designed by one of the supervisors (JMS). It was supervised by the PhD student (KYF) and delivered by MSc and third-year BSc students in Sports Science. The Principal Investigator of the Sleep Revolution project was one of the thesis supervisors (ESA).

3.4 Randomization

In Papers II and III (the lifestyle cohort), participants who met the inclusion criteria and accepted participation in the study were randomly assigned to one of the three groups: exercise, lifestyle app, and control groups. The randomization was stratified by age, sex, BMI, and AHI based on preliminary findings, as these factors could potentially influence the study outcomes. To ensure balanced group assignment, we used Python (version 3.10.6) and the A* Pathfinding algorithm—an artificial intelligence-based method designed to group individuals with similar characteristics as evenly as possible. Given the small study population in Iceland, traditional randomization methods posed a higher risk of bias in group selection. The AI-driven approach provided a more robust solution by prioritizing balance. The algorithm first ensured an even distribution of males and females across the three groups (exercise, app, and control). It then calculated a “score” for each group, reflecting how closely its key variables (e.g., age, BMI, and AHI) aligned with the overall sample averages. While gender balance was not a limiting factor, the algorithm used this score to further refine group assignments, maintaining consistency across the total sample, as well as within the male and female subgroups.

3.5 Interventions

In Papers II and III (the lifestyle cohort), participants were randomized into exercise, lifestyle app, and control groups, with two interventions carried out: exercise and lifestyle app interventions.

3.5.1 Exercise Intervention

A supervised exercise intervention was conducted three times a week for 60 minutes over a 12-week period, a common duration in similar studies (da Silva et al., 2022; Gokmen et al., 2019; Kline et al., 2011; Lins-Filho et al., 2023; Sengul et al., 2011; Servantes et al., 2018). The program was designed based on previous research and recommendations (Agner et al., 2018; Saavedra et al., 2021; Timmons et al., 2018), following a structured progression, to ensure participants adapted safely while minimizing the risk of injury. Trained supervisors closely monitored each session to provide guidance and ensure proper technique, further enhancing the program's safety.

Each session included a warm-up lasting five to ten minutes, focusing on mobility and activation, followed by 15 to 22 minutes of circuit training, eight to fourteen minutes of brisk walking, and a five to ten-minute cool-down with stretching and relaxation. The intensity and volume of the circuit training gradually increased throughout the intervention. During the first two weeks, participants completed ten exercises, each lasting 60 seconds with a 30-second rest in between, followed by an eight-minute brisk walk. By weeks three and four, the number of exercises increased to twelve, with the same work-to-rest ratio and a ten-minute brisk walk. From weeks five to eight, participants performed fourteen exercises, still maintaining 60-second work intervals and 30-second rest periods, followed by 12 minutes of brisk walking. In the final phase, from weeks nine to twelve, the number of exercises increased to sixteen, with the rest period reduced to 20 seconds and a brisk walk lasting 14 minutes. An overview of the exercise intervention is shown in Table 6.

Table 6. An overview of the exercise intervention.

Weeks	Stations	Work:Rest (s)	Exercises	Brisk walking (min)
1st to 2nd	10	60:30	1 × push, 2 × pull, 1 × knee dominant, 1 × hip dominant, 1 × specific core, 1 × medicine ball throw, 3 × specific aerobic	8
3rd to 4th	12	60:30	1 × push, 2 × pull, 1 × knee dominant, 1 × hip dominant, 2 × specific core, 1 × medicine ball throw, 4 × specific aerobic	10
5th to 8th	14	60:30	1 × push, 2 × pull, 2 × knee dominant, 1 × hip dominant, 2 × specific core, 1 × medicine ball throw, 1 × arms, 4 × specific aerobic	12
9th to 12th	16	60:20	1 × push, 2 × pull, 2 × knee dominant, 1 × hip dominant, 2 × specific core, 1 × medicine ball throw, 1 × arms, 6 × specific aerobic	14

The circuit training incorporated a variety of movements targeting different muscle groups and fitness components. Upper body push exercises included the bench press and shoulder press, while upper body pull movements involved resistance band face pulls and bicep curls. Lower body exercises were divided into knee-dominant movements, such as squats and forward lunges, and hip-dominant exercises, including deadlifts and glute bridges. Core-specific movements included a modified plank and alternating superman exercise. Medicine ball-specific exercises included wall throws and slam balls, and aerobic-specific exercises included jump rope and box toe taps.

The exercise intensity was monitored using the Borg Rating of Perceived Exertion scale (BORG scale) (Borg, 1962). The warm-up was rated as very light (8-9), while circuit training ranged from somewhat hard to very hard (14-17). Brisk walking was perceived as moderate to somewhat hard (12-13), and the cool-down was extremely light (7).

3.5.2 Lifestyle App Program

Participants assigned to the app group were asked to complete daily tasks within the

Sidekick Health app (Reykjavik, Iceland) throughout the 12-week intervention period. These tasks were designed to promote healthy behaviors through goal setting, self-monitoring, and engagement in four key areas: diet, PA, sleep, and stress management. To enhance motivation, the app incorporated gamification elements, which have been shown to encourage users to adopt and maintain healthier habits (Willermark & Islind, 2022). Figure 4 shows examples of daily missions with the Sidekick Health app.

The PA component was divided into three categories: walking, home exercises, and stress management exercises. Walking was structured as a daily challenge, where participants aimed to reach a specific step count, tracked using their phone's pedometer. Home exercises focused on bodyweight movements such as squats, push-ups, and sit-ups, with instructional videos for guidance. Stress management exercises, centered on breathing techniques, meditation, and mindfulness practices. To boost engagement, participants earned points for completing tasks, which were translated into virtual and altruistic rewards such as achievement badges and charitable water donations. Additionally, participants received personalized support and feedback from a live coach through in-app text messages.

The Sidekick Health app has been shown to be effective in various health interventions, including weight loss for overweight and obese individuals (Thorgeirsson et al., 2022), glycemic control, and improved psychological well-being in obese patients with type II diabetes (Hilmarsdóttir et al., 2021), and improvements in metabolic health for patients with multiple conditions, including MS, type II diabetes, and non-alcoholic fatty liver disease (Björnsdottir et al., 2024).

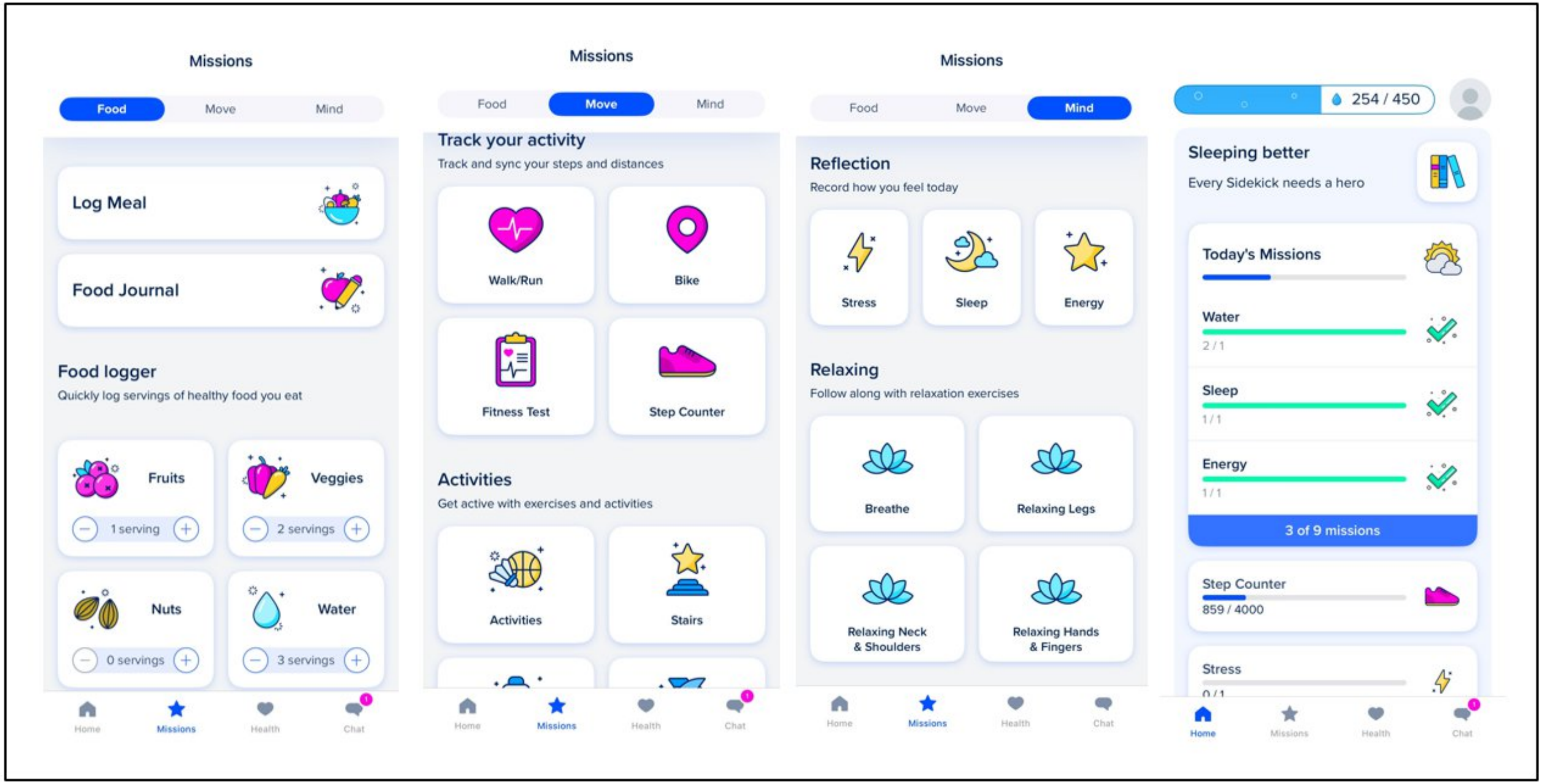

Figure 4. Examples of daily missions within the Sidekick Health app.

3.6 Statistical Analysis

In all three papers, variables were tested for homoscedasticity using Levene's variance homogeneity test and normality of their distribution using the Kolmogorov-Smirnov test. If a variable did not follow a normal distribution, a logarithmic transformation was applied to ensure normality. For baseline analysis in all papers, one-way ANOVA was used for descriptive statistics, including means and standard deviation. All missing data were excluded from the analysis. The statistical significance was set at $p<0.05$, and statistical analyses were performed using IBM SPSS Statistics 28.

3.6.1 Paper I

In the Paper, I, AHI, and DesSev+RecSev did not follow a normal distribution. Therefore, a logarithmic transformation was applied for these variables to ensure a normal distribution. A one-way ANOVA was used to compare differences between the three OSA severity groups, followed by a Bonferroni post hoc test. Effect sizes (η^2) were also calculated, categorized as small ($\eta^2 < 0.01$), medium ($0.01 \leq \eta^2 < 0.06$), or large ($\eta^2 \geq 0.06$) (Richardson, 2011). A stepwise multiple linear regression was conducted for all participants and separately for men and women, to identify factors predicting AHI and DesSev+RecSev. To avoid spurious relationships, the number of predictor variables was limited, using a more conservative approach than recommended (Norman & Streiner, 2000). Seven key variables were selected based on their relevance to anthropometric, body composition, and PA measures: age, BMI, neck circumference, visceral adiposity, IPAQ score, daily steps, and daily sitting time. Spearman correlation coefficients were calculated to explore the relationships between objective and subjective PA measures within each OSA severity group.

3.6.2 Paper II

In Paper II, for the SDB and physical health parameters, AHI, weight, BMI, skeletal muscle mass, visceral adiposity, and hand dynamometry did not follow a normal distribution. Therefore, a logarithmic transformation was applied for these variables to meet the normal distribution. In the case of the HRQoL parameters (SF-36 questionnaire), non-parametric tests were used as the variables did not achieve normal distribution after logarithmic transformation. Repeated measures ANOVA with a Bonferroni post hoc test was used to examine changes in the dependent variables (SDB parameters and physical health) based on the independent variable (intervention groups: exercise program, lifestyle app program, and no intervention). The main effects of time, group, and the interaction between time and group were also assessed. A Wilcoxon signed-rank test was used to analyze the difference in pre- and post-intervention HRQoL scores within each group. A Kruskal-Wallis H test was applied to compare post-intervention HRQoL scores across the three groups.

3.6.3 Paper III

In Paper III, for subjective health parameters, PSQI and ESS did not achieve normal distribution after logarithmic transformation. Therefore, non-parametric tests were used. For the objective sleep health variables, including SE, SOL, WASO, arousal index, and N1(%), a logarithmic transformation was applied. The Wilcoxon signed-rank test was used to assess changes in subjective sleep health parameters (PSQI and ESS) before and after the intervention. A Kruskal-Wallis H test was used to compare post-intervention PSQI and ESS scores across the three groups. A Chi-square test was used to evaluate the changes in the prevalence of poor sleep (PSQI >5) and EDS (ESS >10) within each group. Repeated measures ANOVA, with the Bonferroni post hoc test, was used to examine changes in objective sleep health variables. Additionally, the main effects for group, time, and group × time interactions were analyzed.

4 RESULTS

This chapter presents the results of the three papers on which this thesis is based. First, findings from Paper I (Pilot study) are described. This study focused on whether subjectively or objectively measured PA could predict OSA severity, as reflected in two key parameters: AHI and DesSev+RecSev. Additionally, it examined the agreement between subjective and objective PA measures. Next, results from Papers II and III (Lifestyle study) are presented. This study evaluated the effects of two distinct 12-week interventions: exercise and lifestyle app interventions. Paper II focused on whether these interventions led to improvements in SDB severity, physical health, and HRQoL parameters, while Paper III specifically examined whether they contributed to improvements in subjective and objective sleep health parameters.

4.1 Paper I

4.1.1 Baseline Characteristics

In Paper I (Pilot study cohort), 65 subjects were recruited from the general population. Of these 65 participants, 33 (50.8%) were female, and 32 (49.2%) were male, with a mean age of 46.9 years and an average BMI of 28.8kg/m^2. Of these, one participant had less than four hours of scorable SpO_2 and other sleep study signals, seven did not fulfill the wearable criteria, and three failed to meet either criterion. As a result, the final cohort comprised 54 participants with a mean age of 47.7 years, an average BMI of 28.5kg/m^2, and 46.3% males. The participants were categorized into three severity groups: no OSA, mild OSA, and moderate-to-severe OSA. Seventeen participants had AHI < 5 and were classified into the no OSA group, 19 participants had AHI between 5-14.9 and were classified into the mild OSA group, and 18 had AHI ≥ 15 and were classified into the moderate-to-severe OSA group. Within the moderate-to-severe OSA group, 12 participants had an AHI between 15 and 29.9 events/hr, and 6 participants had an AHI ≥ 30 events/hr.

The baseline characteristics of each group showed some expected patterns, where participants with moderate-to-severe OSA were older, more obese, with greater BMI, neck circumference, and visceral adiposity, and had poorer SQ, reflected in lower SE than those without OSA. Other expected patterns also emerged, including variables like arousal index, ODI (3% and 4%), DesSev, RecSev, DesSev+RecSev, T90%, and SpO_2 parameters, all worsening with increased OSA severity. Interestingly, despite these factors, they also reported spending less time sitting than participants in the other groups ($p<0.004$; $\eta^2=0.204$). They also tended to have lower levels of PA both objectively (step count) and subjectively measured (IPAQ scores and exercise minutes), but these differences were not significant. Table 7 displays the demographics of participants for different OSA severity groups.

Table 7. Demographics of participants, presented as mean and standard deviation (SD) for different OSA severity groups. Also, one-way ANOVA (analysis of variance), F, η², and differences between groups using the Bonferroni post hoc test are provided.

	(A) No OSA n = 17	(B) Mild OSA n = 19	(C) Moderate-to-Severe OSA n = 18				
	mean ± SD	mean ± SD	mean ± SD	F	*p*	η²	Diff.
General							
Age (years)	37.3 ± 14.6	47.9 ± 14.4	57.3 ± 8.8	10.524	**<0.001**	0.292	**A<C**
Males (%)	11.8	68.4	55.6				
Sleep parameters							
TST (min)	383.5 ± 62.7	375.2 ± 41.4	383.1 ± 51.7	0.148	0.863	0.006	n.s.
Sleep efficiency (%)	92.2 ± 3.1	89.0 ± 5.4	86.8 ± 7.5	3.967	**0.025**	0.135	**A>C**
Arousal index (events/hr)	10.6 ± 4.0	12.6 ± 3.5	19.5 ± 8.9	10.684	**<0.001**	0.295	**A,B<C**
AHI (events/hr)	2.3 ± 1.4	9.3 ± 2.5	30.6 ± 12.5	70.357	**<0.001**	0.734	**A,B<C**
Nocturnal hypoxic parameters							
$ODI_{3\%}$ (events/hr)	2.3 ± 1.5	8.5 ± 3.6	26.6 ± 12.6	48.756	**<0.001**	0.657	**A,B<C**
$ODI_{4\%}$ (events/hr)	1.0 ± 0.8	4.66 ± 2.4	17.7 ± 11.7	28.622	**<0.001**	0.529	**A,B<C**
DesSev (%-point)	0.0 ± 0.0	0.1 ± 0.1	0.6 ± 0.5	16.619	**<0.001**	0.538	**A,B<C**
RecSev (%-point)	0.0 ± 0.0	0.1 ± 0.0	0.3 ± 0.2	18.400	**<0.001**	0.558	**A,B<C**
DesSev+RecSev (%-point)	0.03 ± 0.0	0.17 ± 0.1	0.84 ± 0.8	17.256	**<0.001**	0.545	**A,B<C**
T90% (%)	1.11 ± 1.5	6.16 ± 9.3	21.42 ± 25.0	8.254	**<0.001**	0.405	**A,B<C**
SpO_2 avg. (%)	94.60 ± 1.2	93.34 ± 1.6	91.81 ± 1.9	13.386	**<0.001**	0.495	**A,B>C**
Anthropometry							
BMI (kg/m²)	25.7 ± 4.8	28.4 ± 5.4	31.3 ± 4.4	5.782	**0.005**	0.185	**A<C**

Neck circumference (cm)	35.7 ± 3.3	38.7 ± 3.6	39.9 ± 4.9	5.113	**0.009**	0.167	**A<C**
Body composition							
Fat mass (%)	30.4 ± 7.2	28.6 ± 7.8	33.1 ± 6.7	1.751	0.184	0.064	n.s.
Visceral adiposity	6.4 ± 3.8	9.3 ± 3.9	11.5 ± 4.2	7.336	**0.002**	0.223	**A<C**
Physical activity							
IPAQ (MET min/week)	3254.8 ± 2795.4	3258.7 ± 4400.6	2400.5 ± 2304.2	0.506	0.671	0.021	n.s.
Steps/day (n)	5365.6 ± 1755.9	5710.1 ± 1894.9	5062.8 ± 2934.6	0.380	0.686	0.015	n.s.
Exercise min/day (min)	21.8 ± 20.3	24.4 ± 27.9	12.4 ± 13.1	1.583	0.215	0.058	n.s.
Physical inactivity							
Sitting time (min)	340.6 ± 94.1	349.4 ± 118.6	240.0 ± 91.3	6.286	**0.004**	0.204	**A,B>C**

Note. Significant values are denoted in bold, n.s, no statistically significant difference.
Abbreviations: AHI, apnea-hypopnea index; BMI, body mass index; DesSev, desaturation severity; DesSev+RecSev, total desaturation and recovery severity; IPAQ, International Physical Activity Questionnaire; MET min/week, metabolic equivalents minutes per week; $ODI_{3\%}$, oxygen desaturation index for ≥ 3% desaturation, manually scored; $ODI_{4\%}$, oxygen desaturation index for ≥ 4% desaturation automatically calculated with ABOSA; RecSev, recovery severity; SpO_2 avg, average oxygen saturation during sleep; TST, total sleep time; T90%, percentage of sleep time with oxygen saturation <90%.

4.1.2 Predictors of OSA Severity

The sex-stratified results from the stepwise multiple linear regression for AHI and DesSev+RecSev showed some clear trends (Table 8). Overall, the model explained 63.3% of the variance in AHI, with age, BMI, and neck circumference being key factors. When assessing males and females separately, the models explained 61.2% and 61.7% of the variance in AHI, respectively, with age and BMI being the strongest predictors. For DesSev+RecSev, the model accounted for 67.8% of the variance among all participants, mainly driven by age, BMI, and visceral adiposity. When split by sex, the models explained 62.6% of the variance in males and 63.3% in females, again with age and BMI as the primary predictors. Interestingly, PA parameters did not have a significant impact on the model's performance once age and obesity-related variables were taken into account.

4.1.3 Agreement Between Different PA Measures

The correlations between objective and subjective PA assessments were analyzed across the three groups (Table 9). In the mild OSA group, a correlation was found between objective and subjective measures of steps per day and exercise minutes per day recorded in the app (r=0.522, p=0.022). Additionally, a correlation was observed between the two subjective PA measures: IPAQ and exercise minutes per day in the app (r=0.469, p=0.043). For the other groups, no correlations were found between objective and subjective PA measures. However, while not statistically significant, the correlation strength tended to be higher for exercise minutes per day in the app compared to IPAQ when matched with objective PA measurements.

Table 8. A stepwise multiple linear regression analysis of predicting factors for AHI and DesSev+RecSev for all participants and by sex.

	Sex	R	R^2	ΔR^2	SEE	B	SE	β	t	*p*	Selected variables
AHI	Total	0.710	0.656	**0.633**	0.350	0.037	0.013	0.271	2.892	<0.001	Age, BMI, neck circumference
	Male	0.806	0.649	**0.612**	0.227	0.041	0.013	0.462	3.258	<0.001	Age, BMI
	Female	0.804	0.647	**0.617**	0.380	0.053	0.013	0.517	4.173	<0.001	Age, BMI
DesSev+RecSev	Total	0.836	0.699	**0.678**	0.376	0.041	0.011	0.325	3.603	<0.001	Age, BMI, visceral adiposity
	Male	0.813	0.661	**0.626**	0.348	0.019	0.005	0.501	3.693	<0.001	Age, BMI
	Female	0.813	0.661	**0.633**	0.374	0.023	0.005	0.513	4.277	<0.001	Age, BMI

Note. The models' explanatory variables included age, BMI, neck circumference, visceral adiposity, IPAQ, steps/day, and sitting time/day. Abbreviation: AHI, apnea-hypopnea index; DesSev+RecSev, total desaturation and recovery severity; BMI, body mass index; IPAQ, International Physical Activity Questionnaire; R, the correlation between the predicted values and the observed values; R^2, the percentage of variation explained; ΔR^2, a corrected goodness-of-fit; SEE, standard error of estimation; B, unstandardized coefficient; SE, standard error; β, standardized coefficient; t, Coefficients/Standard Error; p, significance.

Table 9. Spearman correlation coefficients calculated between objective and subjective measures of physical activity.

	No OSA				Mild OSA				Moderate-to-Severe OSA			
	Steps	IPAQ	Exerc.	Sitting	Steps	IPAQ	Exerc.	Sitting	Steps	IPAQ	Exerc.	Sitting
Steps/day (n)	-				-				-			
IPAQ (MET min/week)	0.066	-			0.363	-			-0.220	-		
Exercise/day (min)	0.423	0.120	-		**0.522***	**0.469***	-		0.450	-0.034	-	
Sitting time (min/week)	-0.106	-0.452	-0.007	-	-0.381	-0.461	-0.361	-	-0.14	-0.226	-0.091	-

Note: Statistically significant values are denoted in bold, * correlation is significant at the level of $p<0.05$.
Abbreviation: Exerc., Exercise minutes/day; IPAQ, International Physical Activity Questionnaire; MET min/week, metabolic equivalent of task minutes per week; OSA, obstructive sleep apnea.

4.2 Paper II

4.2.1 Baseline Characteristics

The Lifestyle study cohort initially included 192 participants who were randomly assigned to exercise, lifestyle app, and control groups. However, 39 participants withdrew from the study before attending the baseline measurements. As a result, a total of 153 participants completed the baseline physical assessments, with 49 in the exercise group, 55 in the lifestyle app group, and 49 in the control group (Figure 3). There was no difference in any of the SDB severity, physical health, and HRQoL parameters studied at baseline.

4.2.2 The Effects of Exercise and Lifestyle App Interventions on OSA Severity and Physical Health

The effects of the two interventions carried out, the exercise program and lifestyle app interventions, were compared to a control group. For the primary outcome, AHI showed a time effect (F=6.290, p=0.014), indicating a change over the study period (Figure 5). Among the secondary outcomes, several physical health measures also showed a time effect, including neck circumference (F=5.253, p=0.024) (Figure 6b), hand dynamometry (F=7.102, p=0.009), and the 6-minute walking test (F=8.340, p=0.005) (Figures 7a and b). Additionally, time × group interactions were found for weight (F=9.318, p<0.001), BMI (F=9.302, p<0.001), body fat percentage (F=4.756, p=0.010), body fat mass (F=5.916, p=0.004), and skeletal muscle mass (F=9.360, p<0.001) (Figures 6a, c, d, and e) suggesting that these variables responded differently depending on the intervention group. Table 10 shows the basic descriptive statistics, repeated measures ANOVA values, intra-group comparison, and SBD severity and physical health variables´ studied time, group, and time x group interaction effects.

Table 10. Mean ± standard deviation and repeated measures ANOVA results for sleep-disordered breathing severity and physical health parameters corresponding to the exercise program (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 x Group effect	
		Pre-intervention	Post-intervention	Δ%	F	p	F	p	F	p
Sleep parameters										
AHI¶ (events/h)	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/m²)	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¶	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 WT (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						

AG, app group; AHI, apnea-hypopnea index; BMI, body mass index; BF%, body fat percentage; BFM, body fat mass; CG, control group; EG, exercise group; NC, neck circumference; SM%, skeletal muscle percentage; SMM, skeletal muscle mass; WHR, waist to hip ratio; WT, walking test; Δ%, percentages change from pre to post-intervention,¶, a logarithmic transformation; * p<0.05; ** p<0.001.

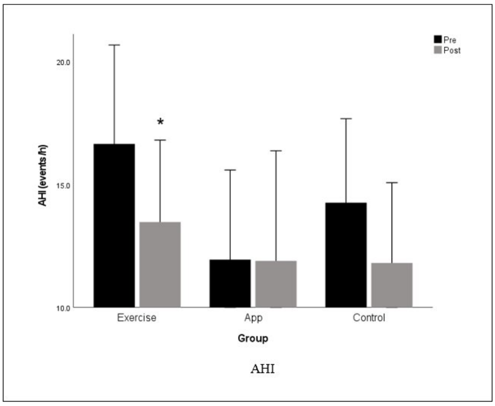

Figure 5. Intra-group changes in the apnea-hypopnea index (AHI) across exercise, app, and control groups.

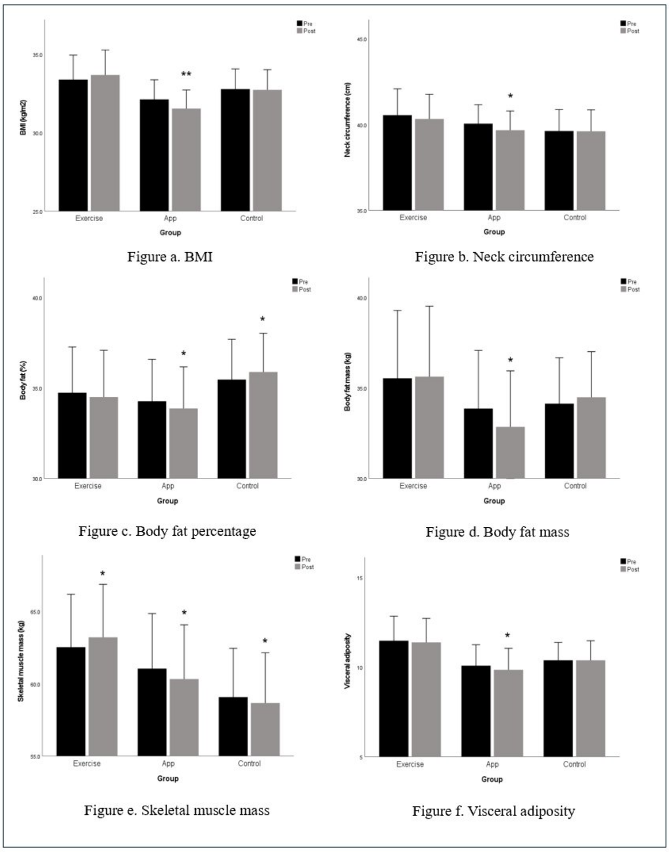

Figure 6. Intra-group changes in anthropometry and body composition parameters across exercise, app, and control groups.

Abbreviation: BMI, body mass index

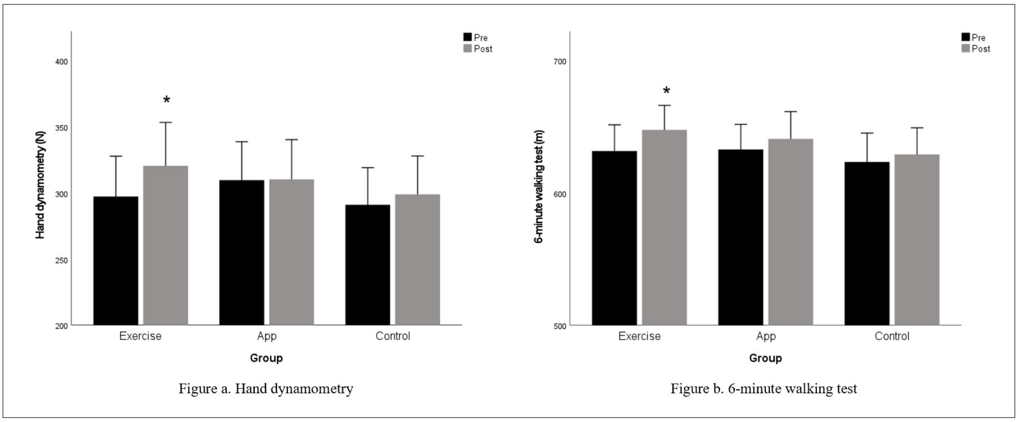

Figure 7. Intra-group changes in physical fitness parameters across exercise, app, and control groups.

4.2.3 The Effects of Exercise and Lifestyle App Interventions on HRQoL

The results from nonparametric tests for HRQoL parameters (secondary outcomes) showed that the exercise program led to improvements in 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 lifestyle app program also improved physical functioning (p<0.001), vitality (p=0.002), and general health (p=0.010). However, there were no differences in HRQoL parameters between the groups after the interventions (p>0.073). Figure 8 shows the intragroup changes in HRQoL parameters across the three groups.

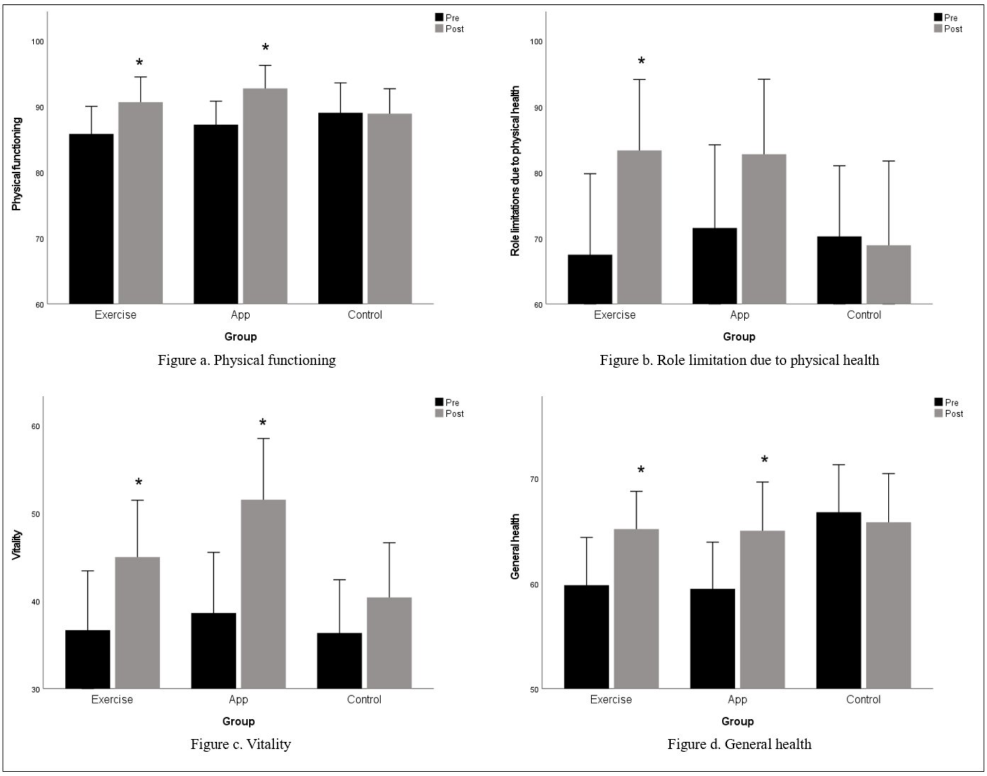

Figure a. Physical functioning

Figure b. Role limitation due to physical health

Figure c. Vitality

Figure d. General health

Figure 8. Intra-group changes in HRQoL parameters across exercise, app, and control groups.

4.3 Paper III

4.3.1 Baseline Characteristics

The lifestyle cohort initially included 192 participants; in Paper III, the baseline characteristics were the same as in Paper II. No difference was found in subjective or objective sleep health parameters at baseline.

4.3.2 The Effects of Exercise and Lifestyle App Interventions on Subjective Sleep Health

Results from nonparametric tests for subjective sleep health parameters (PSQI and ESS) showed that the exercise program led to improvements in the PSQI global score (p=0.021) (Figure 9), as well as SQ (p=0.025), sleep latency (p=0.040), and sleep disturbance (p=0.033) (Figures 10a, b, and c). Interestingly, the control group also showed improvements in the global score (p=0.001), SQ (p=0.034), and sleep latency (*p*=0.001). Meanwhile, the lifestyle app program improved daytime dysfunction (*p*=0.005) (Figure 10d). However, there were no differences in PSQI parameters between the groups after the interventions (*p*>0.079).

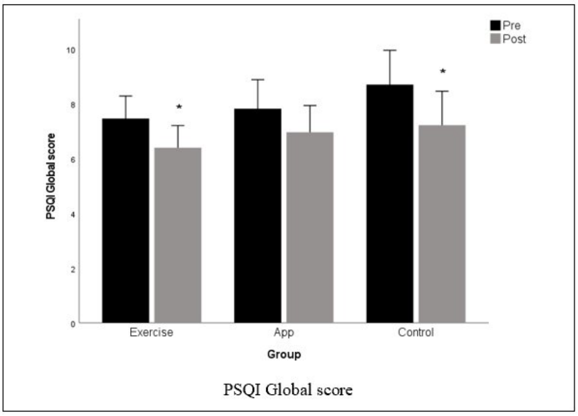

Figure 9. Intra-group changes in the subjective sleep health parameter Pittsburgh sleep quality index (PSQI) global score across exercise, app, and control groups.

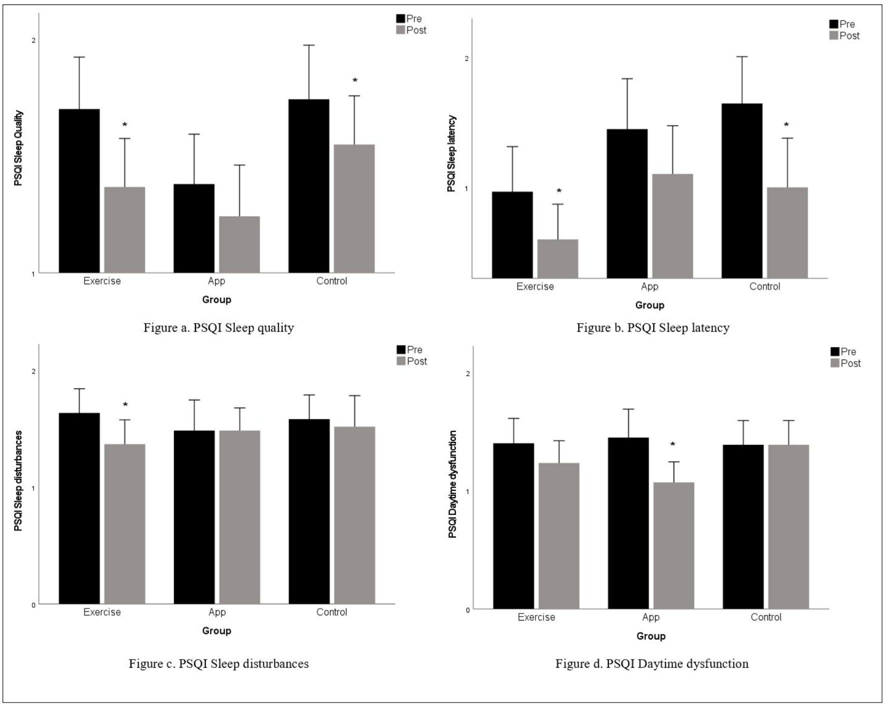

Figure 10. Intra-group changes in the Pittsburgh sleep quality index (PSQI) subscales across exercise, app, and control groups.

Further analysis of subjective sleep health focused on the prevalence of poor sleepers (PSQI>5) and EDS (ESS>10) across the three groups (Figure 11). In the exercise group, the prevalence of poor sleepers decreased (p=0.015), with 23.3% of participants transitioning from poor to good sleep (Figure 11a). Similarly, the control group also saw a reduction (p=0.007), with 19.4% reporting improved sleep. In contrast, the lifestyle app group showed an increase in the prevalence of poor sleepers (p=0.667), with 6.9% improving but 10.3% experiencing worsening sleep (Figure 11a). Regarding EDS (ESS score), no changes were observed in any of the groups. Despite no difference, in the exercise group, there was a trend towards a lower prevalence of EDS (p=0.252), with 13.8% of participants showing improvement (Figure 11b). The control group also showed a small decline (p=0.696), with 9.4% of participants experiencing improvement. In contrast, the app group showed a trend towards an increase in EDS (p=0.663), with 13.3% improving but 10% experiencing worsening symptoms (Figure 11b).

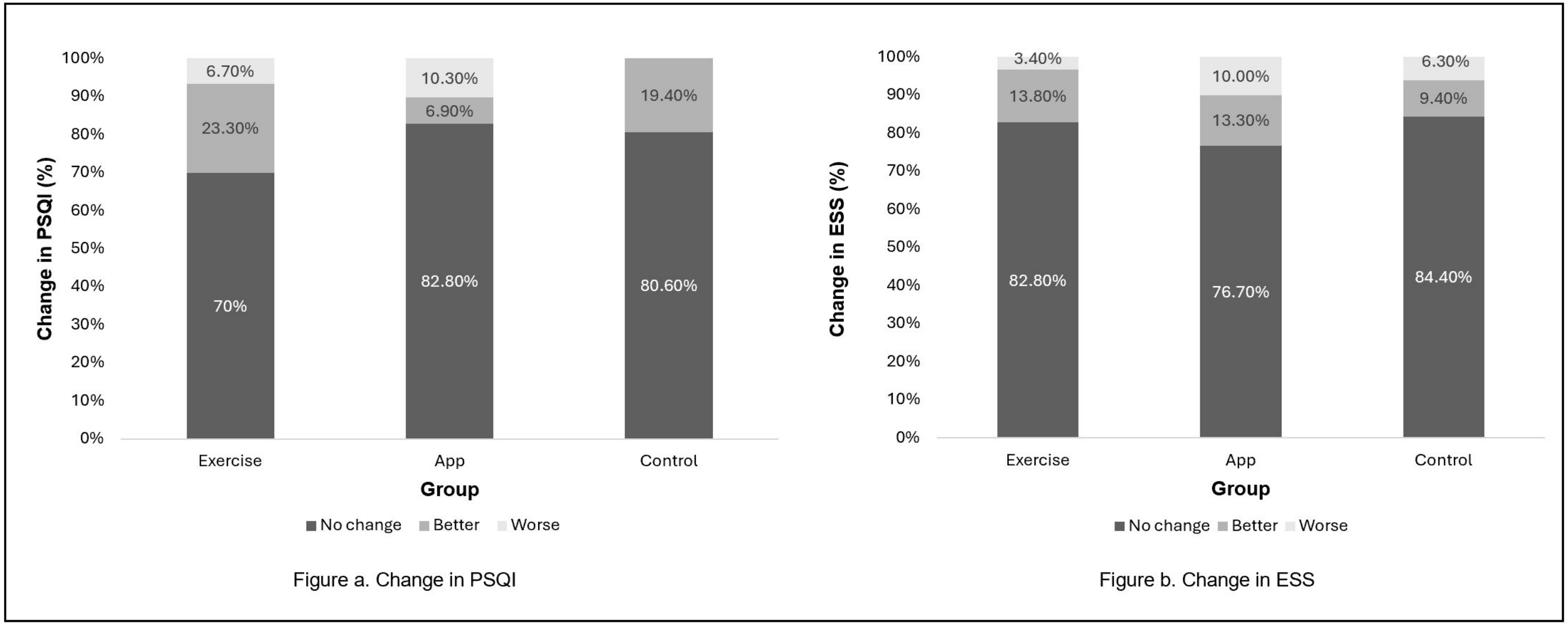

Figure 11. Changes in prevalence of poor sleep (Pittsburgh sleep quality index global score>5) and excessive daytime sleepiness (Epworth sleepiness scale>10) across exercise, app, and control groups.

4.3.3 The Effects of Exercise and Lifestyle App Interventions on Objective Sleep Health

The results from the repeated measures ANOVA, which included time, group, and time × group interaction effects, as well as intra-group comparisons for objective sleep health variables (Table 11), revealed several notable findings. First, in the exercise group, no change was observed in any of the objective sleep health parameters studied. The lifestyle app intervention resulted in a decrease in WASO, an increase in N2 sleep, and a reduction in N3 sleep both post-intervention and compared to the control group (p=0.038). In the control group, a reduction in WASO and a decrease in N1 sleep were observed. A time effect was found for WASO (F=19.334, p<0.001), arousal index (F=9.240, p=0.003), and N2% (F=5.064, p=0.027). Additionally, time × group interactions were observed in N1% (F=4.414, p=0.015) and N3% (F=3.644, p=0.030), suggesting that these variables responded differently across the intervention groups. Figure 12. Illustrates the changes in objective sleep health parameters across exercise, app, and control groups.

Table 11. Mean ± standard deviation and repeated measures ANOVA results for objective sleep health parameters corresponding to the exercise program (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 x Group effect	
		Pre-intervention	Post-intervention	Δ%	F	p	F	p	F	p
Objective Sleep Health										
TST (min)	EG	394 ± 47	380 ± 41	-3.55	3.296	0.073	0.393	0.676	0.109	0.897
	AG	398 ± 50	389 ± 62	-2.26						
	CG	401 ± 53	392 ± 52	-2.24						
SE¶ (%)	EG	92.8 ± 3.7	93.3 ± 3.4	0.57	0.260	0.611	0.324	0.724	1.154	0.320
	AG	91.6 ± 4.8	93.4 ± 3.2	1.90						
	CG	92.2 ± 4.8	92.9 ± 4.6	0.74						
SOL¶ (min)	EG	8.2 ± 7.1	7.5 ± 5.6	-8.57	1.795	0.184	0.448	0.641	0.903	0.409
	AG	7.6 ± 5.4	7.1 ± 7.4	-5.96						
	CG	7.6 ± 5.6	6.8 ± 5.5	-10.27						
WASO¶ (min)	EG	29.1 ± 16.5	23.3 ± 13.5	-19.87	19.334	**<0.001**	0.386	0.681	0.694	0.502
	AG	32.2 ± 21.7	22.9 ± 12.3	**-29.11***						
	CG	30.2 ± 22.6	23.5 ± 17.5	**-22.42***						
Arousal index¶	EG	15.6 ± 5.8	14.5 ± 6.0	-7.09	9.240	**0.003**	2.446	0.092	0.014	0.987
	AG	13.0 ± 4.2	12.5 ± 6.0	-4.09						
	CG	13.3 ± 4.5	12.1 ± 4.6	-8.98						

	EG	296.3 ± 35.2	293.2 ± 33.2	-1.05						
NREM (min)	AG	306.9 ± 38.0	296.2 ± 49.4	-3.50	2.373	0.127	0.382	0.683	0.260	0.771
	CG	303.2 ± 36.0	297.1 ± 39.8	-2.01						
	EG	75.4 ± 4.3	77.3 ± 5.0	2.54						
NREM (%)	AG	77.1 ± 4.9	76.1 ± 4.1	-1.31	0.003	0.957	0.517	0.598	2.522	0.086
	CG	76.0 ± 5.2	75.2 ± 6.3	-1.07						
	EG	10.7 ± 5.4	12.3 ± 6.1	14.36						
N1¶ (%)	AG	10.9 ± 4.8	10.6 ± 5.3	-2.79	0.263	0.609	0.488	0.615	4.414	**0.015**
	CG	10.8 ± 5.0	9.6 ± 4.7	**-11.03***						
	EG	43.8 ± 8.3	45.2 ± 7.4	3.19						
N2 (%)	AG	46.1 ± 6.0	49.0 ± 5.9	**6.40***	5.064	**0.027**	1.915	0.153	1.172	0.314
	CG	44.9 ± 7.9	45.3 ± 9.0	0.84						
	EG	20.8 ± 8.1	19.9 ± 7.1	-4.50						
N3 (%)	AG	20.2 ± 7.2	16.5 ± 6.6	**-18.13*[a]**	3.434	0.067	1.212	0.302	3.644	**0.030**
	CG	20.3 ± 7.3	21.1 ± 8.4	3.84						
	EG	24.5 ± 4.2	22.7 ± 5.0	-7.31						
REM (%)	AG	22.9 ± 4.8	23.8 ± 4.1	3.97	0.484	0.488	0.377	0.687	1.930	0.151
	CG	24.3 ± 5.2	24.0 ± 5.2	-1.11						

AG, app group; CG, control group; EG, exercise group; NREM, non-rapid eye movement sleep, REM, rapid eye movement sleep; SE, sleep efficiency; SOL, sleep onset latency; TST, total sleep time; WASO, wake after sleep onset; Δ%, percentages change from pre- to post-intervention, * $p<0.05$; [a], significantly different from control group post-intervention $p<0.05$.

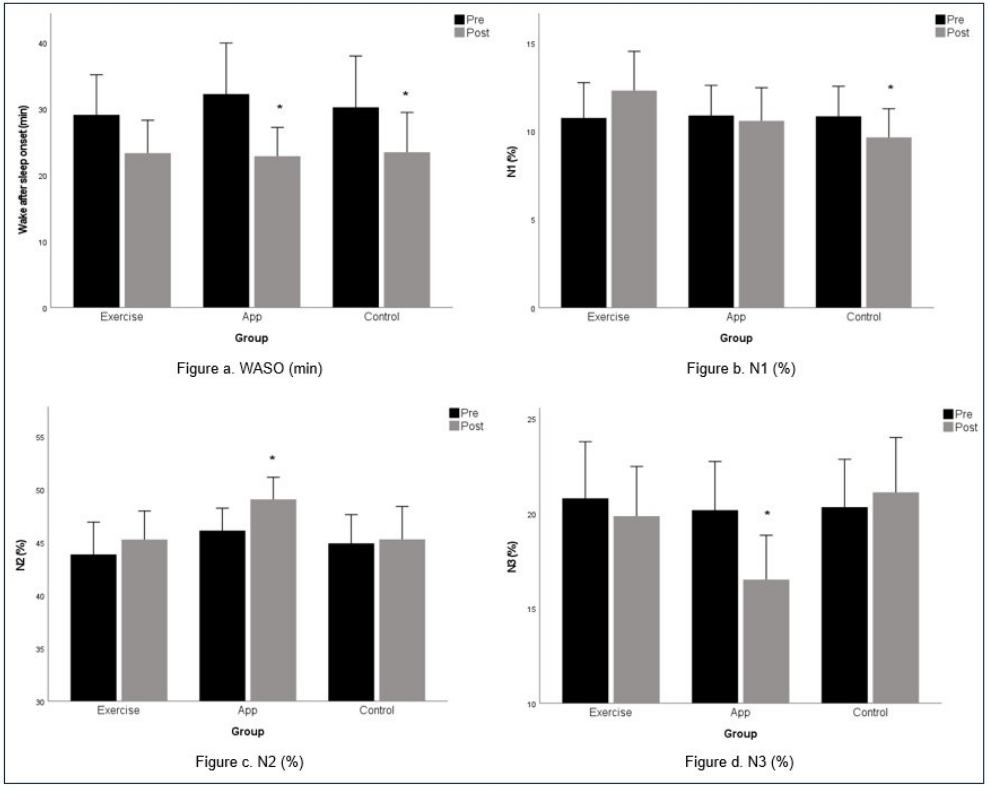

Figure 12. Intra-group changes in objective sleep health parameters across exercise, app, and control groups.

Abbreviations: N1, non-rapid eye movement sleep stage 1; N2, non-rapid eye movement sleep stage 2; N3, non-rapid eye movement sleep stage 3; WASO, Wake after sleep onset.

5 DISCUSSION

The overall objectives of this doctoral thesis were: (i) to explore the differences in the role of PA in individuals with OSA by examining both subjectively and objectively measured PA, and to study PA as a predictor of OSA severity; and (ii) to evaluate the effects of two distinct interventions, a structured exercise program and a lifestyle app, on various parameters including SDB severity, anthropometry, body composition, physical fitness, HRQoL, and sleep health in 18-50-year old individuals with mild to moderate SDB.

The main findings of the three papers presented in this thesis suggest that PA, whether measured objectively or subjectively, does not provide additional predictive value for OSA severity after accounting for age, BMI, and body composition parameters. With a weak correlation between objective and subjective PA assessments. In the RCT, the 12-week exercise intervention reduced AHI and improved physical health and HRQoL, without changes in snoring rates. Whereas the lifestyle app program improved anthropometric and body composition parameters and HRQoL, but did not impact AHI or snoring. Additionally, the exercise program led to improvements in subjective sleep health, although there were no changes in objective sleep health parameters. In contrast, the lifestyle app resulted in more modest improvements in subjective sleep health, as well as in certain objective sleep metrics.

5.1 The Role of PA in Predicting OSA Severity

Our study (Paper I) evaluated the role of PA in OSA severity after adjustment for body composition and other confounders. To the best of our knowledge, this was the first study that evaluated both objective and subjective PA levels in participants with and without OSA with extensive body composition assessments.

The current study used stepwise multiple linear regression to develop a multivariate model explaining OSA severity (i.e., AHI and DesSev+RecSev) for all participants, as well as for men and women separately (Table 8). Across all models, age, anthropometric measures, and body composition parameters, specifically BMI and neck circumference, accounted for most of the variance in AHI, aligning with previous research (Edwards et al., 2014; Hargens et al., 2013; Kim et al., 2021; Kritikou et al., 2013; Malhotra & White, 2002; Meurling et al., 2019). A similar pattern emerged for the OSA severity parameter DesSev+RecSev, where age, BMI, and visceral adiposity were the primary contributors. These findings suggest that baseline PA measures have minimal direct association with OSA severity after adjustment for confounders. However, this is likely due to the strong relationship between PA levels and body composition, which in turn plays a key role in OSA severity.

5.2 The Agreement Between Different PA Measures

The present study (Paper I) showed that participants with moderate-to-severe OSA reported spending less time sitting compared to those with mild or no OSA, despite no differences in objective PA measurements. Paradoxically, there was a nonsignificant trend suggesting that those with moderate-to-severe OSA had the lowest average PA levels across all assessments. Since this group was also older than the other groups, these findings align with previous research showing that older adults tend to underestimate their sitting time when self-reporting (Harvey et al., 2015).

Previous studies have suggested an inverse relationship between PA and OSA (da Silva et al., 2017; Hall et al., 2020; Mônico-Neto et al., 2018; Murillo et al., 2016; Quan et al., 2007). However, these studies have either used subjective or objective PA assessments, rarely both, without accounting for body composition parameters. The present study revealed a low correlation between subjective and objective PA measures (Table 9), consistent with previous studies showing that subjective assessments often overestimate PA compared to objective measurements, leading to weak correlations (Igelström et al., 2013a; Steene-Johannessen et al., 2016). Notably, the strength of these correlations remained similar across all OSA severity groups, suggesting that OSA status does not influence the agreement between subjective and objective PA assessments. However, in the mild OSA group, a correlation was observed between exercise/day and step count, as well as exercise/day and IPAQ. Interestingly, the daily exercise question in the Sleep Revolution app showed a stronger relationship with objective PA than the IPAQ (Schmitz et al., 2022), aligning with research indicating that digital logging reduces memory bias compared to retrospective recall (Vallo Hult et al., 2022). Similarly, another study found that a daily logbook correlated more strongly with objective PA than the IPAQ (Igelström et al., 2013a).

5.3 The Effects of Exercise and Lifestyle App Interventions on SDB Severity

The current RCT (Paper II) evaluated the effects of a 12-week exercise program and a lifestyle app program on the primary outcome variable SDB severity in adults aged 18-50 with mild-to-moderate SDB. To the best of our knowledge, this is the largest RCT on exercise effects in SDB to date and the first to compare the impact of two interventions, an exercise program and a lifestyle app program, in this population.

The study demonstrated 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 5), with a time effect. Similar reductions in AHI have been reported in studies using comparable aerobic exercise (on a bicycle) and resistance training for individuals with moderate-to-severe OSA, with reductions of 19% (Goya et al., 2021) and even higher values ranging from 29% to 45% (Bughin et al., 2020; Desplan et al., 2014; Kline et al., 2011). However, these studies had smaller sample sizes (n=11 and 18, respectively) (Desplan et al., 2014; Goya et al., 2021), and their control groups either engaged in active interventions (Kline et al., 2011) or received dietary education (Bughin et al., 2020; Desplan et al., 2014). To further understand these differences, AHI reductions were achieved in programs with varying weekly session frequencies, ranging from three to six sessions per week (Desplan et al., 2014; Goya et al., 2021) and longer sessions lasting up to 120 minutes (Bughin et al., 2020; Desplan et al., 2014). In contrast, this study utilized a 12-week program consisting of three 60-minute sessions per week, which included 15–22 minutes of circuit training and 8–14 minutes of brisk walking. Previous studies allocated more time to aerobic exercise, ranging from 37.5 minutes to 45 minutes (Bughin et al., 2020; Desplan et al., 2014; Kline et al., 2011) and resistance training for 30 minutes (Bughin et al., 2020; Desplan et al., 2014). These findings suggest that for individuals with mild-to-moderate OSA, it is unnecessary to commit to lengthy sessions (over 60 minutes) or frequent weekly sessions (more than three) to achieve meaningful reductions in AHI. Conversely, no reduction in AHI was observed in the lifestyle app group despite weight loss, in agreement with a previous study (Cho et al., 2018). This highlights the importance of structured exercise programs, preferably those combining aerobic and resistance training, to effectively reduce OSA severity, consistent with findings from a recent systematic review and meta-analysis (Peng et al., 2022).

5.4 The Effects of Exercise and Lifestyle App Interventions on Physical Health

In the same RCT (Paper II), we examined the effects of a 12-week exercise program and a lifestyle app program on secondary outcome parameters of physical health, including changes in anthropometry, body composition, and physical fitness.

The results showed changes in anthropometry in the app group, including reductions in weight ($p<0.001$), BMI ($p<0.001$) (Figure 6a), and neck circumference ($p=0.013$) (Figure 6b), without a change in AHI. These findings partly align with a previous study that reported reduced weight and BMI despite no change in AHI, following a 4-week lifestyle app intervention for OSA patients (Cho et al., 2018). However, that study had a smaller sample size (n=24) and did not measure neck circumference or waist-to-hip ratio, focusing solely on PA and diet. In contrast, the current study also addressed sleep and stress management. The findings of the current study are particularly noteworthy given the well-established relationship between high BMI and OSA severity. Previous research indicates that a high BMI is one of the most important risk factors for the development and progression of OSA (Malhotra & White, 2002). Weight loss is considered important in reducing OSA severity, where a 10% weight reduction can lead to a 26% reduction in AHI (Peppard, Young, & Palta, 2000). However, in the current study, the app group achieved a weight loss of 1.8 kg (-1.8%) and a BMI reduction of 0.6 (-1.8%). While clinically meaningful, these changes may have been insufficient to produce measurable improvements in AHI within the intervention period, as the mean post-intervention

BMI of 31.5 in the app group remains within the classification of obesity (World Health Organization, 2024b).

Interestingly, in the exercise group, no changes were observed in weight (p=0.066), BMI (p=0.065), neck circumference (p=0.190), or waist-to-hip ratio (p=0.844), despite a 19% reduction in AHI. These results indicate that the structured exercise program may improve OSA through effects beyond changes in anthropometry, consistent with previous research showing exercise to reduce overnight fluid shift to the neck, improve upper airway muscle tone, and respiratory stability (Mendelson et al., 2016, 2018). The results of the current study align with a previous study that found no changes in anthropometry following a 12-week exercise program, despite achieving reductions in AHI (Kline et al., 2011). Another study using HIIT also reported no changes in BMI but found reduced neck circumference (Lins-Filho et al., 2023). Conversely, other studies have shown changes in weight, BMI, neck circumference, and waist-to-hip ratio with exercise interventions (Bughin et al., 2020; Desplan et al., 2014), likely due to the inclusion of dietary management as part of the intervention. Notably, in the current study, a time x group effect was observed for weight (F=9.318, p<0.001) and BMI (F=9.302, p<0.001) (reductions in the app group) and a time effect for neck circumference (F=5.253, p=0.024). These findings highlight the app's effectiveness in reducing weight and BMI, an important risk factor for SDB severity (Malhotra & White, 2002; Tuomilehto et al., 2013; Vgontzas et al., 1994), which suggests promise for using digital therapeutics for weight management in SDB, albeit not associated with reduced OSA severity over a period of 12 weeks. The exercise group showed a significant increase in skeletal muscle mass (p = 0.008; Figure 6e), without a corresponding reduction in body fat mass (+0.1 kg, p = 0.776). Although neither weight (+0.8 kg) nor BMI (+0.3 kg/m^2) reflected clinically meaningful changes, these findings highlight a limitation of using BMI alone to assess health outcomes in exercise interventions. The increase in muscle mass likely offset any reductions in fat mass, resulting in stable BMI and weight values. Therefore, body composition measurements, particularly skeletal muscle mass and fat mass, offer a more sensitive and informative assessment of physiological changes than BMI in this context (Rothman, 2008). Future studies should consider prioritizing these measures when evaluating the effects of exercise in populations with sleep-disordered breathing. The results of the current study contrast with a previous study that reported reduced fat mass but no changes in fat-free or skeletal muscle mass following a 4-week individualized exercise program (Desplan et al., 2014). The differences might stem from the shorter duration and higher intensity of that program, as well as the inclusion of dietary management, which could explain the contrasting results. The app group demonstrated reductions in body fat percentage (p=0.048), and fat mass (p<0.001), as well as a loss of skeletal muscle mass (p=0.002) (Figures 6c, d, and e), with a notable decrease in visceral adiposity (p=0.029) (Figure 6f). While weight loss should ideally stem from reductions in fat mass (Liao et al., 2019), the skeletal muscle loss observed in the app group might partly explain the drop in BMI. This highlights the importance of resistance training to preserve muscle mass, as supported by previous studies (Liao et al., 2019). A time x group effect was observed for 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 the app group). These results suggest that while the app effectively reduced body fat, the exercise program was more effective in increasing skeletal muscle mass.

In terms of physical fitness, only the exercise group showed improvements in hand dynamometry (muscular strength) and the 6-minute walking test (cardiorespiratory fitness) (Figures 7a and b), with a time effect. The hand dynamometry results differ from a previous study that reported no changes in isometric hand strength after a 6-month aerobic and resistance training program (Guerra et al., 2019). However, that study had a smaller sample size (n=20) and spread its sessions over 11.7±0.9 months, with only 10 minutes per session dedicated to resistance training compared to the 15–22 minutes of circuit training in this study. The shorter weekly frequency and extended duration may explain the discrepancies. The improvements observed in cardiorespiratory fitness in the current study align with a study that reported improved cardiorespiratory fitness after a 9-month aerobic and resistance training program (Berger et al., 2019). Similarly, studies using HIIT (Lins-Filho et al., 2023) and aerobic exercise (Sengul et al., 2011) in moderate-to-severe OSA patients also showed improvements in cardiorespiratory fitness. It is worth noting that low hand dynamometry and poor cardiorespiratory fitness are associated with several comorbidities commonly coexisting with SDB, including obesity, type II diabetes, CVD, and impaired HRQoL (Ross et al., 2016; Stenholm et al., 2011).

5.5 The Effects of Exercise and Lifestyle App Interventions on HRQoL

In the same RCT (Paper II), we examined the effects of a 12-week exercise program and a lifestyle app program on the secondary outcome variable HRQoL. The current study found improvements in four domains of the SF-36 questionnaire in the exercise group. These improvements were reflected in physical functioning, role limitations due to physical health, vitality, and general health (Figures 8a, b, c, and d). Similarly, the app group showed improvements in three domains, physical functioning, vitality, and general health (Figures 8a, c, and d). These findings are broadly consistent with a previous study by Desplan et al. (2014), which reported improvements across multiple domains, including physical functioning, role limitations due to physical health, vitality, social functioning, pain, and general health, following a 4-week aerobic and resistance training program. However, the current study did not observe changes in pain or social functioning. Additionally, another study demonstrated that improvements in HRQoL were most pronounced in an exercise group compared to PAP, exercise + PAP, and control groups (Servantes et al., 2018). Further supporting the role of exercise in enhancing HRQoL in OSA patients. These findings align with a recent systematic review and meta-analysis, which confirms the effectiveness of exercise in improving HRQoL in this population (Lins-Filho et al., 2020). However, the results of the current study contradict those of Gokmen et al. (2019), who found no improvements in HRQoL following a 12-week T'ai Chi and Qigong intervention. This discrepancy may be due to differences in the types of exercise interventions used, as well as the inclusion of an active control group (home exercises) in the previous study. Both interventions resulted in improved HRQoL, despite the app group not showing changes in AHI. Previous studies have indicated that OSA severity does not directly correlate with SF-36 scores, but physical inactivity is one of the strongest predictors of lower HRQoL in OSA patients (Lopes et al., 2008). Increasing PA through daily tasks within the app or participating in an exercise program increases physical activity, which could improve HRQoL in SDB patients in the study.

The findings of this study should not be interpreted as diminishing the role of PA or exercise in the management of SDB. On the contrary, the two interventions carried out were different, resulting in different outcomes in the variables studied. Importantly, PA and exercise are not only well-established strategies for weight loss, an important risk factor of OSA (Malhotra & White, 2002), but also play a critical role in preventing and managing numerous chronic diseases, improving sleep and overall well-being (Bull et al., 2020). This is particularly relevant for individuals with SDB, who frequently present with a range of comorbidities (Hargens et al., 2013), along with EDS, which can reduce engagement in PA and contribute to weight gain over time (Leinum et al., 2009). Moreover, physical inactivity and sedentary behavior are known to increase both the risk and severity of OSA (Liu et al., 2022; Simpson et al., 2015) and lower HRQoL (Lopes et al., 2008). Therefore, promoting PA and exercise may substantially benefit individuals with SDB. However, the current findings also underscore the complex and potentially individualized physiological responses to different types of interventions in this population, highlighting the need for a personalized approach to SDB management.

5.6 The Effects of Exercise and Lifestyle App Interventions on Subjective Sleep Health

In the same RCT (Paper III), we explored the effects of a 12-week exercise program and a lifestyle app on sleep health parameters in adults aged 18 to 50 with mild-to-moderate SDB. To our knowledge, this is the largest RCT to date focusing on a comprehensive evaluation of both subjective and objective sleep health parameters in an SDB population.

Regarding subjective sleep health, the exercise group demonstrated a 1.1-point reduction (improvement) in the PSQI global score (pre: 7.5, post: 6.4, p=0.02) (Figure 9). This improvement is comparable to the 1.5-point reduction reported in a smaller 12-week aerobic and resistance training program for participants with moderate-to-severe OSA (Kline et al., 2011). Other studies using HIIT (Lins-Filho et al., 2024), T'ai Chi and Qigong (Gokmen et al., 2019), and an intense 4-week intervention combining health education, diet, and exercise (Desplan et al., 2014) have reported greater reductions of 2.6 points (Gokmen et al., 2019), 2.7 (Desplan et al., 2014), and 3.5 points (Lins-Filho et al., 2024). However, the baseline PSQI global scores in these studies were higher (8.4 to 8.9) than in the current study (7.5), which may account for the differences. Additionally, the exercise group showed improvements in PSQI subscales for SQ, sleep latency, and sleep disturbances (Figures 10a, b, and c), partially aligning with findings from previous research (Lins-Filho et al., 2024; Lins-Filho et al., 2020).

A reduction in the prevalence of poor sleepers (PSQI >5) was also observed in the exercise group, decreasing from 83% to 67% (p=0.015). Notably, 23% of participants improved from poor to good sleep after the intervention (Figure 11a). The app group, on the other hand, showed improvement in the daytime dysfunction subscale (Figure 10d) but no change in the PSQI global score. Interestingly, the prevalence of poor sleepers in the app group increased slightly from 72% to 76% (p=0.667), with 7% showing improvement and 10% worsening after the intervention (Figure 11a). While no prior studies have specifically examined PSQI in app-based interventions for SDB patients, subjective metrics like PSQI are often recommended for sleep self-management apps (Choi et al., 2018).

Unexpectedly, the control group also showed improvements in the PSQI global score (Figure 9) and the subscales for SQ and sleep latency (Figures 10a and b). Recruitment from the general population and the non-blinded study design may have heightened participants' health awareness, potentially leading to self-initiated lifestyle changes through the Hawthorne effect (French, 1953), which is known to enhance behaviors such as PA even in control groups (Waters et al., 2012). The prevalence of poor sleepers in the control group decreased from 80.6% to 61.3% (p=0.007), with 19.4% transitioning from poor to good sleep (Figure 11a). These results, which occurred despite the absence of an intervention, have not been previously reported (Desplan et al., 2014; Kline et al., 2011; Lins-Filho et al., 2024). While the reduction in AHI was not significant in the control group, OSA severity is known to influence PSQI subscales such as sleep latency and sleep disturbances (Lusic Kalcina et al., 2017), which could explain the observed improvements.

Regarding EDS assessed using the ESS questionnaire, no changes were found in any group, consistent with findings from a study on mild-to-moderate OSA (Sengul et al., 2011). However, this contrasts with systematic reviews (Lin et al., 2024; Lins-Filho et al., 2020; Peng et al., 2022) and RCTs (Bughin et al., 2020; Desplan et al., 2014; Lins-Filho et al., 2024) on moderate-to-severe OSA, which have reported reductions in EDS following exercise interventions. Notably, participants in the current study had lower baseline ESS scores compared to those in previous studies, as they were recruited from the general population (Bughin et al., 2020; Desplan et al., 2014; Lins-Filho et al., 2024). Among the groups, the exercise group showed the largest reduction in the prevalence of EDS (ESS >10), decreasing from 38% to 28%, with 13% of participants experienced improvement following the intervention (Figure 11b).

5.7 The Effects of Exercise and Lifestyle App Interventions on Objective Sleep Health

Regarding objective sleep health, WASO decreased across all three groups (Figure 12a), with a time effect observed. However, the reduction in the exercise group was not statistically significant (p=0.109). These findings partially align with a previous study, which reported no change in WASO in either the exercise group or the stretching control group following a 12-week exercise program (Kline et al., 2011). Notably, while that study used a single-night in-laboratory PSG, the current study utilized a three-night self-applied home PSG, which may account for the observed WASO reductions. A similar reduction in WASO over three consecutive nights using self-applied home PSG has been reported (Ferretti et al., 2024), further supporting these results.

In terms of sleep stages, no changes were observed in the exercise group, despite the previously reported 19% reduction in AHI (Paper II). These findings are consistent with earlier studies that reported no changes (Desplan et al., 2014; Schütz et al., 2013; Servantes et al., 2018) or limited changes (Kline et al., 2011) in sleep stages following exercise interventions, even with reductions in AHI. However, some research has shown different effects, such as decreased light sleep (N1 and N2) and increased N3 sleep (Bughin et al., 2020) or increases in both N3 and REM sleep (Lins-Filho et al., 2023). These discrepancies highlight the variability in how exercise interventions affect sleep stages, likely depending on factors such as intervention design, exercise type, and participant characteristics. In the app group, the proportion of N2 sleep increased while N3 sleep decreased (Figures 12c and d), resulting in a reduction in N3 sleep compared to the control group (time x group interaction). Although the effects of lifestyle apps on sleep stages have not been specifically studied, the reduction in N3 sleep observed in the app group may partially explain the slight increase in the prevalence of poor sleepers (PSQI >5) and EDS (ESS >10), which rose from 72% to 76% and 23% to 27%, respectively. Interestingly, the control group showed a reduction in N1 sleep (p=0.012, Figure 12b), a finding not previously reported in exercise intervention studies (Gokmen et al., 2019; Kline et al., 2011; Lins-Filho et al., 2023).

5.8 Strengths, Limitations, and Future Research

The **strengths of Paper I** (Pilot study) were: First, the use of state-of-the-art three-night self-applied PSG for OSA diagnosis, which allowed for the detection of night-to-night variability in OSA severity (Newell et al., 2012) and minimized the first-night effect on SQ. Second, it was the first study to assess predicting factors of two OSA severity parameters, the AHI and DesSev+RecSev, calculated as averages over successful PSG recordings, enhancing the reliability of the findings. Thirdly, this study assessed both objective and subjective PA, which, as stated earlier, had only been done in one previous study in OSA patients. The **limitations of Paper I** were. First, this study was a Pilot study and was limited by its small sample size and the inclusion of only three AHI severity groups. Second, no formal priori power analysis was performed, as the study was exploratory. The sample size was therefore based on practical constraints such as time, funding, and recruitment capacity. Lastly, the study was conducted during a period when government-imposed COVID-19 restrictions were still in place, potentially affecting participants' sleep, PA, and exercise levels.

The **strengths of Papers II and III** (Lifestyle study) include: First, the largest RCT to date assessing the effects of exercise in individuals with mild-to-moderate SDB. Second, it is also the first study to compare the impact of a structured exercise program and a lifestyle app on individuals with SDB, utilizing extensive measurements of SDB severity, physical health, and HRQoL, along with subjective and objective sleep health parameters. Third, the exercise program was specifically designed for sedentary individuals and included structured aerobic and resistance training, with perceived exertion monitored during every session to ensure appropriate intensity. Finally, the use of state-of-the-art three-night PSG at baseline and follow-up allowed for the assessment of night-to-night variability, which is known to be greater in individuals with mild-to-moderate OSA compared to those with severe OSA or healthy individuals (Punjabi et al., 2020). **The limitations of Papers II and III were**. First (Paper II), while the three-night PSG was performed at home to maintain a natural sleep environment, no specific recommendations were given regarding sleeping with or without a partner. This could have influenced the data if participants shared a bed with a snoring partner, potentially inflating the number of recorded snoring events. Second (Papers II and III), one participant in the control group, with a pre-test AHI of 51.8 and a post-test AHI of 15.9, was identified as an outlier and excluded from the analysis for this variable, which may slightly limit the generalizability of findings related to the control group. Third (Papers II and III), the study was conducted on adults aged 18-50 years (mean age: 37.4 years), meaning the results cannot be directly generalized to older populations with SDB. These findings should, therefore, be interpreted cautiously when applied to older adults. Fourth (Paper II), the study had a high dropout rate (44%), which, while comparable to the upper range reported in similar studies (e.g., 7% in Servantes et al., 2018 to 44% in Schutz et al., 2013; average: 16%). In Paper III, the dropout rate was higher (47%), with 10 participants failing to complete the post-intervention sleep study. The dropout rate falls within the range reported in similar studies, which show dropout rates between 4% (da Silva et al., 2022) and 44% (Schutz et al., 2013), with an average of 17%. This suggests that while the interventions were effective, they were demanding and required substantial participant commitment to complete. Fifth

(Paper II) it would have been beneficial to include a group combining both the exercise program and the app intervention. However, as the app already included physical exercise as part of its program, it was decided not to include such a group in this study to avoid redundancy. Sixth, the initial study (Papers II and III) design included only the exercise group and the control group, and a sample size calculation was performed to achieve an effect size of 0.5 and a statistical power of 80%, resulting in 128 subjects in total. This was later increased to 200 to account for a possible dropout rate. Subsequently, the study was expanded to include a third group, the app group, but a new a priori calculation was not performed, and the target of 200 participants was maintained, as it was considered a sufficiently ambitious goal. Seventh, the participants did not undergo a familiarization trial for either the hand dynamometry or the 6-minute walking test. Learning effect during these measurements may have influenced the post-test results. Finally (Papers II and III), self-organized PA was not systematically assessed. This limits the ability to assess the potential contribution of unsupervised PA to the observed outcomes.

Future research should focus on integrating objective PA measurements with daily activity logs to improve the reliability of PA assessments and clarify its predictive role in SDB severity. A promising direction for future research is to explore how different intensities of PA and exercise—light, moderate, and vigorous—affect SDB, rather than focusing solely on overall PA or exercise. Emerging evidence suggests that these varying intensities affect sleep health parameters in distinct ways (Zhao et al., 2023), which may, in turn, be linked to SDB. Additionally, studies investigating exercise and lifestyle app interventions should assess a broader range of SDB parameters beyond AHI, as its use as the sole measure of intervention effectiveness has been criticized for oversimplifying the condition. A more comprehensive assessment could provide deeper insights into the physiological and subjective changes induced by lifestyle interventions and help identify individual differences in response. This approach is a crucial step toward developing personalized treatment strategies, which are urgently needed to address the diverse needs of SDB patients.

6 CONCLUSIONS

The **overall conclusions** of this doctoral thesis were: (i) Individuals with moderate-to-severe OSA tended to underestimate their sedentary time, with subjective PA assessments misaligning with objective measurements. PA was not a significant predictor of OSA severity after accounting for age, BMI, and body composition. (ii) Both structured exercise and lifestyle app interventions benefited 18-50-year-old individuals with mild-to-moderate SDB but had distinct effects. The 12-week exercise program reduced AHI, increased skeletal muscle mass, and improved physical fitness, HRQoL, and subjective sleep health, without changes in anthropometry. In contrast, the lifestyle app intervention promoted improvements in anthropometry, body composition, and HRQoL and influenced both subjective and objective sleep health parameters but did not lower AHI and led to muscle mass reduction

The conclusions of **Paper I** were (i) participants with moderate-to-severe OSA tended to underestimate their sitting time compared to objectively measured PA, a discrepancy not observed in participants with no or mild OSA. Moreover, PA was not a predictive factor for OSA severity after adjusting for age, BMI, and body composition, suggesting that PA levels may either be influenced by these factors or that baseline PA is too variable to have a consistent impact on OSA severity. (ii) There was little to no correlation between objective and subjective PA measurements, regardless of OSA severity, indicating that subjective PA assessments often either overestimate or underestimate actual activity levels. These findings emphasize the complex role of PA as a predictor for OSA severity and the importance of how PA is measured. Therefore, healthcare professionals should encourage OSA patients to increase their PA levels while also engaging in conversations to better understand whether patients are subjectively overestimating or underestimating their activity which could skew interpretations of PA's role in OSA. As a result, combining objective measurements with daily activity logs is essential for more accurate evaluations and future research on the role of PA as a predictor for OSA severity.

The conclusions of **Paper II** were (i) the 12-week exercise intervention resulted in a reduction in AHI, an increase in skeletal muscle mass and physical fitness (grip strength and aerobic endurance), and enhancements in four domains of HRQoL; (ii) the 12-week lifestyle app intervention led to reductions in weight, BMI, neck circumference, body fat, and visceral adiposity, alongside improvements in three HRQoL domains. However, the app intervention negatively impacted skeletal muscle mass and did not reduce AHI, indicating that while it addressed some aspects of health and sleep, its effects were less comprehensive compared to the exercise program. These findings underscore that while both interventions provided health benefits for individuals with mild-to-moderate SDB, the exercise program had a greater impact on SDB severity, skeletal muscle mass, and HRQoL. The lifestyle app intervention, while effective in supporting weight loss and improving certain sleep health parameters, lacked the ability to reduce AHI, a core metric of SDB.

The conclusions of **Paper III** were (i) the 12-week exercise training intervention improved subjective sleep health, as evidenced by better PSQI global scores and improvements in three PSQI subscales, despite no changes in objective sleep health parameters in participants with mild-to-moderate SDB. (ii) The lifestyle app intervention also improved subjective sleep health, specifically reducing the daytime dysfunction subscale of the PSQI. The lifestyle app intervention produced objective sleep health changes including reduced WASO, increased N2 sleep, and decreased N3 deep sleep. These findings underscore the benefits of incorporating 60 minutes of aerobic exercise and resistance training three times per week to enhance perceived sleep health in individuals with mild-to-moderate SDB, as assessed by the PSQI. In contrast, the lifestyle app yielded more modest improvements in subjective sleep health and certain objective sleep health metrics, suggesting its role as a complementary tool rather than a standalone intervention.

The studies included in this thesis suggest that the relationship between daily PA levels and OSA is complex, highlighting the need for more precise assessment methods to accurately evaluate PA's role in OSA severity, as used in this study. A 12-week exercise program, performed three times per week for 60 minutes, was shown to effectively reduce SDB severity while improving skeletal muscle mass, physical fitness, HRQoL, and perceived sleep health. In contrast, the lifestyle app provided more modest benefits, reinforcing the importance of individualized, evidence-based strategies for SDB management. While PAP therapy remains the gold standard for moderate-to-severe cases, structured exercise programs offer a viable, non-invasive treatment option for individuals with mild-to-moderate SDB. More studies are needed to explore the potential of exercise interventions and lifestyle apps as complementary approaches to treating mild-to-moderate SDB.

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RESEARCH ARTICLE

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The role of physical activity on obstructive sleep apnea severity and hypoxic load, and the mismatch between subjective and objective physical activity assessments

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Summary

Obesity is the primary risk factor for the development of obstructive sleep apnea, and physical inactivity plays an important role. However, most studies have either only evaluated physical activity subjectively or objectively in obstructive sleep apnea. The objectives of this study were: (i) to assess the relationship between obstructive sleep apnea severity (both apnea–hypopnea index and desaturation parameters) and both objectively and subjectively measured physical activity after adjustment for anthropometry and body composition parameters; and (ii) to assess the relationship between objective and subjective physical activity parameters and whether obstructive sleep apnea severity has a modulatory effect on this relationship. Fifty-four subjects (age 47.7 ± 15.0 years, 46% males) were categorized into groups according to obstructive sleep apnea severity: no obstructive sleep apnea; mild obstructive sleep apnea; and moderate-to-severe obstructive sleep apnea. All subjects were evaluated with subjective and objective physical activity, anthropometric and body composition measurements, and 3-night self-applied polysomnography. A one-way ANOVA was used to evaluate the differences between the three obstructive sleep apnea severity groups and multiple linear regression to predict obstructive sleep apnea severity. Differences in subjectively reported sitting time ($p \leq 0.004$) were found between participants with moderate-to-severe obstructive sleep apnea, and those with either mild or no obstructive sleep apnea ($p = 0.004$). Age, body mass index and neck circumference explained 63.3% of the variance in the apnea–hypopnea index, and age, body mass index and visceral adiposity explained 67.8% of the variance in desaturation parameters. The results showed that the person's physical activity does not affect obstructive sleep apnea severity. A weak correlation was found between objective and subjective physical activity measures, which could be relevant for healthcare staff encouraging patients with obstructive sleep apnea to increase their physical activity.

KEYWORDS
apnea–hypopnea index, body mass index, neck circumference, nocturnal hypoxic parameters, sleep-disordered breathing, visceral adiposity

1 | INTRODUCTION

Sleep disorders and short sleep duration, in parallel with obesity and physical inactivity, are some of the main health challenges in modern society (Ding et al., 2018). Obstructive sleep apnea (OSA) is one of the most prevalent sleep disorders, affecting about one billion adults worldwide (Benjafield et al., 2019). OSA characteristics are repeated episodes of partial (hypopnea) or complete (apnea) airway collapse during sleep, resulting in oxygen desaturations and arousal (Lee et al., 2008). OSA is associated with chronic conditions, such as hypertension, cardiovascular diseases (Mitra et al., 2021), metabolic syndrome, depression (Simpson et al., 2015) and weight gain (Ong et al., 2013). The apnea–hypopnea index (AHI) is the traditional parameter used to define OSA severity, referring to the average number of apnea and hypopnea events per hour of sleep. However, the AHI developed in 1970 has been criticized for simplicity and needs to be updated (Pevernagie et al., 2020). For example, the AHI does not consider important factors such as the duration of respiratory events or depth and characteristics of related oxygen desaturations (Pevernagie et al., 2020), and thus, new methods to estimate the severity of OSA have been developed during the past decade. These nocturnal hypoxic parameters, describing the conditions where the oxygen saturation levels (SpO_2) are reduced below normal baseline, are bringing new insight into OSA severity estimation (Kulkas, Tiihonen, Eskola et al., 2013; Kulkas, Tiihonen, Julkunen et al., 2013). For example, desaturation severity (DesSev) and recovery severity (RecSev) parameters allow the detection of the total desaturation area from baseline to nadir and back to baseline (Karhu et al., 2022).

Obesity is the primary risk factor for the development of OSA (Hargens et al., 2013), with over 70% of patients with OSA having a body mass index (BMI) over 30 kg m^{-2} (Malhotra & White, 2002). Obesity contributes to OSA through increased body weight, but fat distribution also plays a major role (Carter & Watenpaugh, 2008). Visceral adiposity (accumulation of fat around the internal organs in the abdominal cavity) has a stronger association with OSA than other types of obesity in males (Kim et al., 2021; Kritikou et al., 2013), while general adiposity predicts OSA in females (Kritikou et al., 2013). Furthermore, greater neck circumference indicates more severe OSA in both sexes (Meurling et al., 2019). Other risk factors include male sex, age (40 years or older; Young et al., 2002) and physical inactivity (Simpson et al., 2015).

A physically active lifestyle is one of the most important health-promoting behaviours that favourably impact chronic diseases often coexisting with OSA (Hargens et al., 2013). Physical activity (PA) and exercise are also known key factors in obesity reduction. PA is defined as any bodily movement the skeletal muscles produce that results in energy expenditure (Caspersen et al., 1985). Global recommendations on health-related PA advise at least 150 min of moderate PA, or more than 75 min of vigorous PA a week for adults aged 18–64 years (World Health Organization, 2020). Exercise training is defined as a planned, structured and repetitive PA aimed to improve physical fitness (Caspersen et al., 1985), and is a potential non-pharmacological treatment option for patients with OSA (Iftikhar et al., 2017).

Previous studies have generally shown an inverse association between PA and OSA, but these studies have only assessed PA either subjectively or objectively, not both, and most studies do not assess body composition parameters (Da Silva et al., 2008; Hall et al., 2020; Mônico-Neto et al., 2018; Murillo et al., 2016; Quan et al., 2007; Simpson et al., 2015). To the best of our knowledge, only one study has assessed PA both subjectively and objectively in patients with OSA (Igelström et al., 2013). This study found an overestimation of PA in a group of 39 obese patients with moderate-to-severe OSA recruited from a sleep clinic. Whether this overestimation is different from controls and affected by OSA severity, obesity levels or other confounders remains to be studied.

In this context, the objectives of this study were: (i) to assess the relationship between the OSA severity (both AHI and desaturation parameters) and both objectively (steps per day) and subjectively measured PA (International Physical Activity Questionnaire [IPAQ], sitting time from IPAQ, and exercise per day in minutes daily in an app) by considering the effects of anthropometry and body composition parameters; and (ii) to assess the relationship between the different objective and subjective PA parameters and the role of OSA severity on this relationship.

2 | METHODS

2.1 | Participants

In total, 65 participants were recruited. Fifty-four participants (83%; age = 47.7 ± 15.0 years, BMI = 28.5 ± 5.3 kg m^{-2}, 46.3% males) fulfilled the inclusion criteria and were included in the analysis. The studied cohort included healthy participants, snorers, and individuals with suspected or confirmed sleep apnea, with a wide range of BMI, age and sex. A minimum of 4 hr of good quality oxygen saturation and other sleep study signals from at least 1 night out of the 3-night self-applied polysomnography (PSG) were required. Also, included participants had to use a wrist-worn wearable for at least 10 hr per day for 4 out of 7 days. One participant had less than 4 hr of scorable SpO_2 and sleep signals, seven did not fulfil the wearable criteria, and three did not fulfil either criterion. Participants were categorized into three groups, according to OSA severity using the AHI: no OSA (AHI < 5, $n = 17$); mild OSA (AHI 5–14.9, $n = 19$); moderate-to-severe OSA (AHI ≥ 15, $n = 18$; "Sleep-Related Breathing Disorders in Adults", 1999). All participants were informed about the purpose of this study, and signed written consent was a prerequisite for participation. The study was approved by National Bioethics Committee of Iceland, ref. no. 21-070 and respected the Declaration of Helsinki.

2.2 | Measurements

All participants underwent a comprehensive battery of tests, including: (a) 3-night self-applied PSG; (b) basic anthropometry and body composition; and (c) PA measurements.

(a) Three-night self-applied PSG. All participants had a 3-night sleep study using self-applied PSG (Nox Medical, A1s, Reykjavík, Iceland). A 3-night sleep study was performed to detect the night-to-night variability in OSA severity (Newell et al., 2012). The setup included frontal electroencephalogram (AF4, AF3, AF8 and AF7) and electrooculography (E1, E2, E3 and E4) recordings (Kainulainen et al., 2021). Nasal airflow was determined based on a cannula measurement, oxygen saturation based on oximetry, heart rate based on electrocardiography and oximetry, respiratory movements based on respiratory inductance plethysmography, thorax and abdominal belts, activity and body position based on 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 American Academy of Sleep Medicine (AASM) manual, version 2.6 (American Academy of Sleep Medicine., 2020). The average AHI from valid nights was used to determine OSA severity. The oxygen desaturation index (ODI) was calculated based on manually scored ≥ 3% blood oxygen desaturation (American Academy of Sleep Medicine, 2020). ODI 4% was calculated automatically through Automatic Blood Oxygen Saturation signal analysis software (ABOSA), which was also used to automatically calculate nocturnal hypoxic parameters, capturing the hypoxic load (Karhu et al., 2022). The nocturnal hypoxic parameter, DesSev, was calculated as the sum of desaturation areas normalized with total sleep time. The corresponding recovery variable, RecSev, was calculated the same way (Karhu et al., 2022; Kulkas, Tiihonen, Eskola et al., 2013). The sum of DesSev and RecSev (DesSev + RecSev; Figure 1) was also calculated to detect the total area from baseline to nadir and back to baseline. Other parameters calculated were sleep time spent with SpO_2 below 90% (T90%) and the average value of SpO_2 during sleep (SpO_2 avg.; American Academy of Sleep Medicine, 2020).

(b) Basic anthropometry and body composition measurements. Anthropometric measurements, including height, weight (to calculate BMI; Keys & Brozek, 1953) and neck circumference, were measured and calculated following International Society for the Advancement of Kinanthropometry (ISAK) recommendations (2011). A digital scale (TANITA MC-780, Tokyo, Japan) measured the weight to the nearest 0.1 kg. Body composition was measured with a bioelectrical impedance device (Multifrequency Segmental Body Composition Analyser TANITA MC-780MA, Tokyo, Japan). The device has high accuracy and test–retest reliability (Verney et al., 2015). Total fat mass, muscle mass, body water and visceral adiposity index (from 1 to 59) were reported for further statistical analysis.

(c) PA measurements. PA was evaluated subjectively using the IPAQ – long version (Ainsworth et al., 2000) and an exercise diary (Schmitz et al., 2022), and an objective wearable measurement (ScanWatch, Withings, Paris, France; Lechat et al., 2021). The IPAQ subjectively assesses the health-enhancing PA (walking, moderate and vigorous intensity activities) of the last 7 days through five domains: job-related PA; transportation PA; household-related PA; leisure-time PA; and total sitting time (an indicator of inactivity). The sum of walking and moderate or vigorous intensity activities was reported as the weekly PA, recorded as the metabolic equivalent of task minutes per week (MET-min per week). IPAQ is a validated and frequently used self-reported measure of PA (Ainsworth et al., 2000; Dyrstad et al., 2014). The IPAQ sedentary score was also calculated as the total sitting time per day (minutes) of the last 7 days: "*During the last 7 days, how much time did you spend sitting on a weekday?*", and "*During the last 7 days, how much time did you spend sitting on a weekend day?*" answered in time units (Ainsworth et al., 2000). Exercise duration per day (minutes) was evaluated subjectively with a daily exercise question within the Sleep Revolution mobile application sleep diary for 7 days: "How much did you exercise?" answered in minutes (Schmitz et al., 2022). A wearable device objectively measured the daily PA, using the total step count (steps per day; Lechat et al., 2021). Participants were asked to use the wearable device on their non-dominant hand around the clock for 1 week. The PA was quantified as the average number of steps covered per day for 7 days. A valid day was defined as a minimum of 10 hr of daily heart rate recordings.

2.3 | Procedure

Once included in the study, the participants visited the laboratory at Reykjavik University Sleep Institute (RUSI), Reykjavik, Iceland. After all anthropometric and body composition measurements, the participants downloaded a mobile application (Withings Health Mate, Withings, Paris, France). All participants received the wearable device to use for 1 week, and a self-applied PSG for the 3-night home sleep study. At home, participants answered the IPAQ, and other questionnaires using the Research Electronic Data Capture (REDCap) platform (Harris et al., 2009).

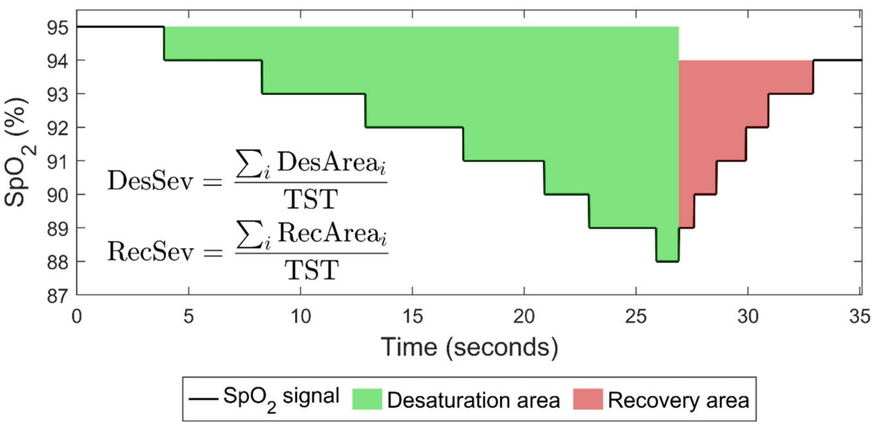

FIGURE 1 The calculation of desaturation severity (DesSev) and recovery severity (RecSev) from the oxygen saturation (SpO_2) signal. TST, total sleep time (Karhu et al., 2022).

2.4 | Statistical analysis

All the variables satisfied the tests of homoscedasticity (Levene's variance homogeneity test) and normality (the Kolmogorov–Smirnov test) of the distribution. AHI and DesSev + RecSev were log-transformed to satisfy the normality of the distribution. Basic descriptive statistics (mean and standard deviations) were calculated. A one-way ANOVA established the differences between the three OSA severity groups using the Bonferroni post hoc test. The eta-squared (η^2) effect size was calculated. The effect size η^2 was considered small ($\eta^2 < 0.01$), medium ($0.01 \le \eta^2 < 0.06$) or large ($\eta^2 \ge 0.06$; Richardson, 2011). Sex-stratified multiple linear regression (stepwise) identified the predicting factors of the AHI and DesSev + RecSev for all participants. The number of predicting variables was limited in the model to prevent spurious relations among variables (Norman & Streiner, 2000). However, we used more strict criteria, and only seven variables were used (age, BMI, neck circumference, visceral adiposity, IPAQ, steps per day, and sitting time per day). These variables were selected as they cover anthropometric, body composition and PA fields. Spearman correlation coefficients between different objective and subjective PA measures were calculated for each OSA severity group. All results were presented as mean ± standard deviation. The limit for statistical significance was set to $p < 0.05$, and IBM SPSS statistics 28 was used for all statistical analysis.

3 | RESULTS

As expected, participants with moderate-to-severe OSA were older and had higher obesity levels and worse sleep quality than participants without OSA (Table 1). However, the participants in the moderate-to-severe OSA group reported less sitting time than the participants in other groups ($p < 0.004$; $\eta^2 = 0.204$). In addition, participants with moderate-to-severe OSA had a tendency to have lower values of objectively measured PA and calculated IPAQ; however, these differences were not statistically significant.

Table 2 shows the sex-stratified results of the multiple linear regression (stepwise) for the AHI and DesSev + RecSev. Among all participants, the model explained 63.3% of the variance in the AHI with age, BMI and neck circumference. For males and females, the models explained 61.2% and 61.7%, respectively, of the variance in the AHI with age and BMI. Among all participants, the model explained 67.8% of the variance in DesSev + RecSev with visceral adiposity, age and BMI. For males and females, the models predicted 62.6% and 63.3%, respectively, of the variance in DesSev + RecSev with age and BMI. Therefore, the PA parameters did not have a significant effect on the model performance after the stepwise inclusion of age and relevant obesity variables.

Table 3 shows the correlations between objective and subjective assessments of PA in each of the three groups. A correlation was found between objective and subjective measures of steps per day and exercise minutes per day in the app ($r = 0.522$, $p = 0.022$), and between two subjective PA measures: IPAQ and exercise minutes per day in the app ($r = 0.469$, $p = 0.043$) in the mild OSA group only. No significant correlations were found between the other PA measures in the other groups. However, the strength of the correlation, albeit non-significant, was higher for the exercise minutes per day in the app than for the IPAQ with objective PA measurements.

4 | DISCUSSION

This study evaluated the role of PA in OSA severity after adjustment for body composition and other confounders. To the best of our knowledge, this is the first study that has evaluated both objective and subjective PA levels in participants with and without OSA with extensive body composition assessment. The main findings of this study were that based on the objective PA measures, participants with moderate-to-severe OSA underestimated their subjectively measured sitting time compared with those with mild and no OSA due to no significant differences in other PA parameters. However, no marked differences were found in the relationships between different subjective and objective PA measures for the three OSA severity groups. Also, the daily exercise question in an app had a stronger correlation with objective PA assessment than the IPAQ, albeit non-significant, likely because of limited number of participants. Importantly, PA had no effects on OSA severity after adjustment for body composition, a likely mediator for any PA effects found in earlier studies.

TABLE 1 Demographics of participants presented as mean and standard deviation (SD) for different OSA severity groups.

	(A) No OSA $n = 17$ Mean ± SD	(B) Mild OSA $n = 19$ Mean ± SD	(C) Moderate-to-severe OSA $n = 18$ Mean ± SD	F	p	η^2	Diff.
General							
Age (years)	37.3 ± 14.6	47.9 ± 14.4	57.3 ± 8.8	10.524	**< 0.001**	0.292	**A < C**
Males (%)	11.8	68.4	55.6				
Sleep parameters							
TST (min)	383.5 ± 62.7	375.2 ± 41.4	383.1 ± 51.7	0.148	0.863	0.006	n.s.
Sleep efficiency (%)	92.2 ± 3.1	89.0 ± 5.4	86.8 ± 7.5	3.967	**0.025**	0.135	**A > C**
Arousal index (events per hr)	10.6 ± 4.0	12.6 ± 3.5	19.5 ± 8.9	10.684	**< 0.001**	0.295	**A, B < C**
AHI (events per hr)	2.3 ± 1.4	9.3 ± 2.5	30.6 ± 12.5	70.357	**< 0.001**	0.734	**A, B < C**
Nocturnal hypoxic parameters							
$ODI_{3\%}$ (events per hr)	2.3 ± 1.5	8.5 ± 3.6	26.6 ± 12.6	48.756	**< 0.001**	0.657	**A, B < C**
$ODI_{4\%}$ (events per hr)	1.0 ± 0.8	4.66 ± 2.4	17.7 ± 11.7	28.622	**< 0.001**	0.529	**A, B < C**
DesSev (%-point)	0.0 ± 0.0	0.1 ± 0.1	0.6 ± 0.5	16.619	**< 0.001**	0.538	**A, B < C**
RecSev (%-point)	0.0 ± 0.0	0.1 ± 0.0	0.3 ± 0.2	18.400	**< 0.001**	0.558	**A, B < C**
DesSev + RecSev (%-point)	0.03 ± 0.0	0.17 ± 0.1	0.84 ± 0.8	17.256	**< 0.001**	0.545	**A, B < C**
T90% (%)	1.11 ± 1.5	6.16 ± 9.3	21.42 ± 25.0	8.254	**< 0.001**	0.405	**A, B < C**
SpO_2 avg. (%)	94.60 ± 1.2	93.34 ± 1.6	91.81 ± 1.9	13.386	**< 0.001**	0.495	**A, B > C**
Anthropometry							
BMI ($kg\ m^{-2}$)	25.7 ± 4.8	28.4 ± 5.4	31.3 ± 4.4	5.782	**0.005**	0.185	**A < C**
Neck circumference (cm)	35.7 ± 3.3	38.7 ± 3.6	39.9 ± 4.9	5.113	**0.009**	0.167	**A < C**
Body composition							
Fat mass (%)	30.4 ± 7.2	28.6 ± 7.8	33.1 ± 6.7	1.751	0.184	0.064	n.s.
Visceral adiposity	6.4 ± 3.8	9.3 ± 3.9	11.5 ± 4.2	7.336	**0.002**	0.223	**A < C**
PA							
IPAQ (MET min per week)	3254.8 ± 2795.4	3258.7 ± 4400.6	2400.5 ± 2304.2	0.506	0.671	0.021	n.s.
Steps per day (n)	5365.6 ± 1755.9	5710.1 ± 1894.9	5062.8 ± 2934.6	0.380	0.686	0.015	n.s.
Exercise min per day (min)	21.8 ± 20.3	24.4 ± 27.9	12.4 ± 13.1	1.583	0.215	0.058	n.s.
Physical inactivity							
Sitting time (min)	340.6 ± 94.1	349.4 ± 118.6	240.0 ± 91.3	6.286	**0.004**	0.204	**A, B > C**

Note: Significant values denoted in bold, n.s., no statistically significant difference.
Also, one-way ANOVA (analysis of variance), F, η^2, and differences between groups using the Bonferroni post hoc test are provided.
Abbreviations: AHI, apnea–hypopnea index; BMI, body mass index; DesSev, desaturation severity; DesSev + RecSev, total desaturation and recovery severity; IPAQ, International Physical Activity Questionnaire; MET min per week, metabolic equivalents minutes per week; $ODI_{3\%}$, oxygen desaturation index for ≥ 3% desaturation, manually scored; $ODI_{4\%}$, oxygen desaturation index for ≥ 4% desaturation automatically calculated with ABOSA; OSA, obstructive sleep apnea; PA, physical activity; RecSev, recovery severity; SpO_2 avg., average oxygen saturation during sleep; TST, total sleep time; T90%, percentage of sleep time with oxygen saturation < 90%.

Interestingly, participants with moderate-to-severe OSA reported spending less time sitting compared with participants with mild and no OSA despite no such differences being found for objective PA variables. Controversially there was a trend, albeit non-significant, for moderate-to-severe OSA participants to have the lowest average PA values in all other PA assessments. As participants with moderate-to-severe OSA were significantly older than participants in other OSA severity groups, these results are in line with a previous study showing that older adults tend to underestimate their sitting time when subjectively measured (Harvey et al., 2015).

A stepwise multiple linear regression was performed to obtain a multivariate model explaining OSA severity (i.e. the AHI and DesSev + RecSev) in all participants as well as sex-stratified (Table 2). All models showed that age, anthropometric and body composition parameters (BMI and neck circumference) explained the majority of the variance in AHI, which is in line with the literature (Edwards

TABLE 2 A stepwise multiple linear regression analysis of predicting factors for AHI and DesSev + RecSev for all participants and by sex.

	Sex	*R*	R^2	ΔR^2	SEE	B	SE	β	*t*	*p*	Selected variables
AHI	Total	0.710	0.656	**0.633**	0.350	0.037	0.013	0.271	2.892	< 0.001	Age, BMI, neck circumference
	Male	0.806	0.649	**0.612**	0.227	0.041	0.013	0.462	3.258	< 0.001	Age, BMI
	Female	0.804	0.647	**0.617**	0.380	0.053	0.013	0.517	4.173	<0.001	Age, BMI
DesSev + RecSev	Total	0.836	0.699	**0.678**	0.376	0.041	0.011	0.325	3.603	< 0.001	Age, BMI, visceral adiposity,
	Male	0.813	0.661	**0.626**	0.348	0.019	0.005	0.501	3.693	< 0.001	Age, BMI
	Female	0.813	0.661	**0.633**	0.374	0.023	0.005	0.513	4.277	< 0.001	Age, BMI

Note: The models' explanatory variables included age, BMI, neck circumference, visceral adiposity, IPAQ, steps per day, and sitting time per day.
Abbreviations: AHI, apnea–hypopnea index; B, unstandardized coefficient; BMI, body mass index; DesSev + RecSev, total desaturation and recovery severity; IPAQ, International Physical Activity Questionnaire; *p*, significance; *R*, the correlation between the predicted values and the observed values; R^2, the percentage of variation explained; ΔR^2, a corrected goodness-of-fit; SE, standard error; SEE, standard error of estimation; *t*, coefficients/standard error; β, standardized coefficient.

TABLE 3 Spearman correlation coefficients calculated between objective and subjective measures of PA.

	No OSA				Mild OSA				Moderate-to-severe OSA			
	Steps	IPAQ	Exerc.	Sitting	Steps	IPAQ	Exerc.	Sitting	Steps	IPAQ	Exerc.	Sitting
Steps per day (*n*)	–				–				–			
IPAQ (MET min per week)	0.066	–			0.363	–			−0.220	–		
Exercise per day (min)	0.423	0.120	–		**0.522***	**0.469***	–		0.450	−0.034	–	
Sitting time (min per week)	−0.106	−0.452	−0.007	–	−0.381	−0.461	−0.361	–	−0.14	−0.226	−0.091	–

Note: Statistically significant values denoted in bold.
Abbreviations: Exerc., exercise minutes per day; IPAQ, International Physical Activity Questionnaire; MET min per week, metabolic equivalent of task minutes per week; OSA, obstructive sleep apnea.
*Correlation is significant at the level of $p < 0.05$.

et al., 2014; Hargens et al., 2013; Kim et al., 2021; Kritikou et al., 2013; Malhotra & White, 2002; Meurling et al., 2019). In addition, we found a similar phenomenon in case of DesSev + RecSev: age, anthropometric and body composition parameters (BMI and visceral adiposity) explained the majority of the variance in DesSev + RecSev. These results highlight the fact that baseline PA measures are minimally associated with OSA severity; however, we consider that this is due to the strong association between PA measures and anthropometric and body composition parameters.

Low correlations were found between different subjective and objective PA measures (Table 3). These results align with previous studies indicating that subjective measures tend to overestimate PA compared with objectively measured PA, resulting in poor correlation (Igelström et al., 2013; Steene-Johannessen et al., 2016). In addition, correlations were of similar strength and non-significant for participants in the three OSA severity groups, despite the mild OSA group having significant correlations between exercise per day and step count, and between exercise per day and IPAQ. This indicates that OSA status does not affect the correlation between subjective and objective PA assessment. Importantly, the daily exercise question in our Sleep Revolution app had a stronger relationship with objective PA than the IPAQ (Schmitz et al., 2022). This is in line with earlier studies showing reduced memory bias with digital logging of events closer to their occurrence, even though the IPAQ only asks about the last 7 days (Vallo Hult et al., 2022). Similarly, Igelström et al. (2013) found a stronger relationship between a daily logbook and objective PA than the IPAQ (Igelström et al., 2013).

The novelty of our findings is the lack of additive effects of PA, measured either objectively or subjectively, for OSA severity after adjustment for BMI and body composition parameters. This indicates that the role of PA is either mediated by these factors or that overall PA may be too variable to affect OSA severity systematically. However, our results contradict with findings of Mendelson et al.'s (2016) randomized controlled trial on PA and OSA severity, reporting improvement in OSA severity with increased PA (Mendelson et al., 2016). However, in our study, we only looked at general PA without instructions about increased PA, which could explain the different results. A tailored exercise program, to increase PA and exercise levels, and using objective measures of PA should be recommended for patients with OSA (Igelström et al., 2013; Kline et al., 2011; Mendelson et al., 2016; Sengul et al., 2011). In the present study, 7.4% of the participants had less than10 min of continuous PA per week, 11.1% PA was low, 40.7% were moderately active, and 37.1% were highly active according to the criteria of the long version of the IPAQ (Ainsworth et al., 2000). Also, 3.7% did not complete the IPAQ.

This study has some limitations. First, the study was a pilot study and therefore limited by a small sample size and three AHI severity groups. However, the 3-night self-applied PSG for OSA diagnosis enabled the detection of the night-to-night variation in OSA severity (Newell et al., 2012) and limited the first-night effect on sleep quality, i.e. the AHI and DesSev + RecSev were calculated as averages over the successful PSG recordings. Second, the effects of Covid-19 could have affected participant's sleep, PA and exercise levels as some restrictions were still obligatory by the government during the time of this study.

5 | CONCLUSIONS

The main finding of the present study was that participants with moderate-to-severe OSA underestimated their sitting time compared with objectively measured PA, which was not observed in participants with no-to-mild OSA. In addition, no significant effects of PA were found on OSA severity after adjustment for age, BMI and body composition. This indicates that PA measures are either mediated by these variables or baseline PA activity is too variable to have a systematic effect on OSA severity. Furthermore, there was little or no correlation between objective and subjective PA measures regardless of OSA severity, indicating that subjective PA measures either over- or underestimate general PA. The present results highlight the fact that healthcare professionals should encourage patients with OSA to increase their PA levels and communicate with them to understand whether they are subjectively over- or underestimating their PA levels. A combination of objective PA measures and a daily logbook provides healthcare professionals more accurate information about the general PA of OSA patients than subjective measures alone.

AUTHOR CONTRIBUTIONS

Katrin Y. Fridgeirsdottir: Conceptualization; data curation; formal analysis; methodology; writing – original draft; writing – review and editing. **Kristín A. Ólafsdóttir:** Data curation; funding acquisition; project administration; writing – review and editing. **Anna Sigridur Islind:** Data curation; funding acquisition; writing – review and editing. **Timo Leppänen:** Funding acquisition; data curation; writing – review and editing. **Erna S. Arnardottir:** Conceptualization; methodology; funding acquisition; project administration; supervision; writing – original draft; writing – review and editing. **Jose M. Saavedra:** Conceptualization; methodology; funding acquisition; supervision; writing – original draft; writing – review and editing; formal analysis.

CONFLICT OF INTEREST STATEMENT

ESA reports honoraria from Nox Medical, ResMed, Jazz Pharmaceuticals, Linde Healthcare, Wink Sleep, Apnimed and Vistor as well as being a member of the Philips Sleep Medicine and Innovation Medical Advisory Board. None for other authors.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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PAPER II

Paper II

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 $kg \cdot m^{-2}$, 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 $kg \cdot m^{-2}$) [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 $\geqslant$25<42 $kg \cdot m^{-2}$); 3) inactive (not participating in an exercise programme at baseline); and 4) diagnosed with mild-to-moderate SDB (AHI $\geqslant$5<30.0; objective snore $\geqslant$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 $\geqslant$5<30.0; objective snore $\geqslant$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 $kg \cdot m^{-2}$, 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 cofounding 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

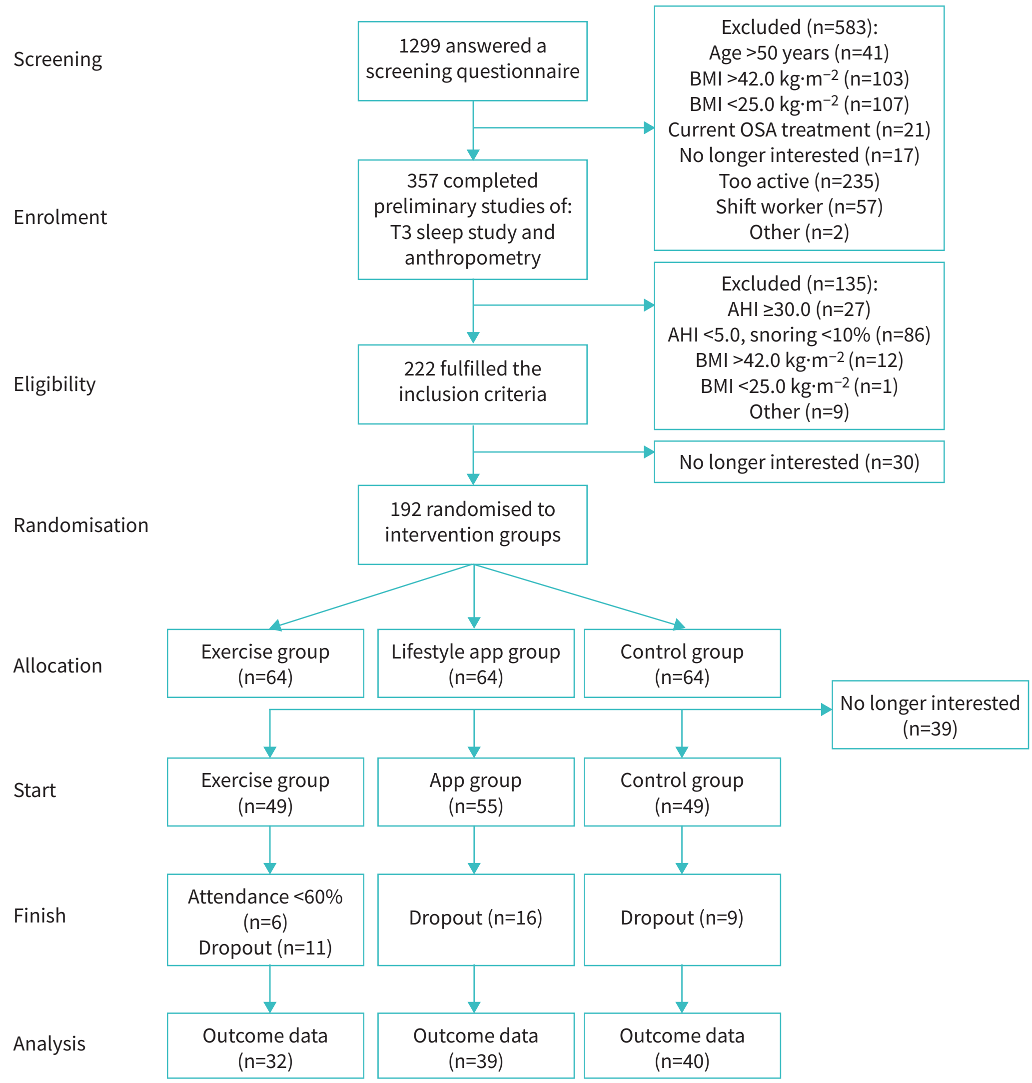

FIGURE 1 Summary of participant flow through the study. AHI: apnoea-hypopnea index; BMI: body mass index; OSA: obstructive sleep apnoea.

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 α >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 ($F=9.318$, $p\leqslant0.001$), BMI ($F=9.302$, $p\leqslant0.001$), body fat percentage ($F=4.756$, $p=0.01$), body fat mass ($F=5.916$, $p=0.004$) and skeletal muscle mass ($F=9.3601$, $p\leqslant0.001$). 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

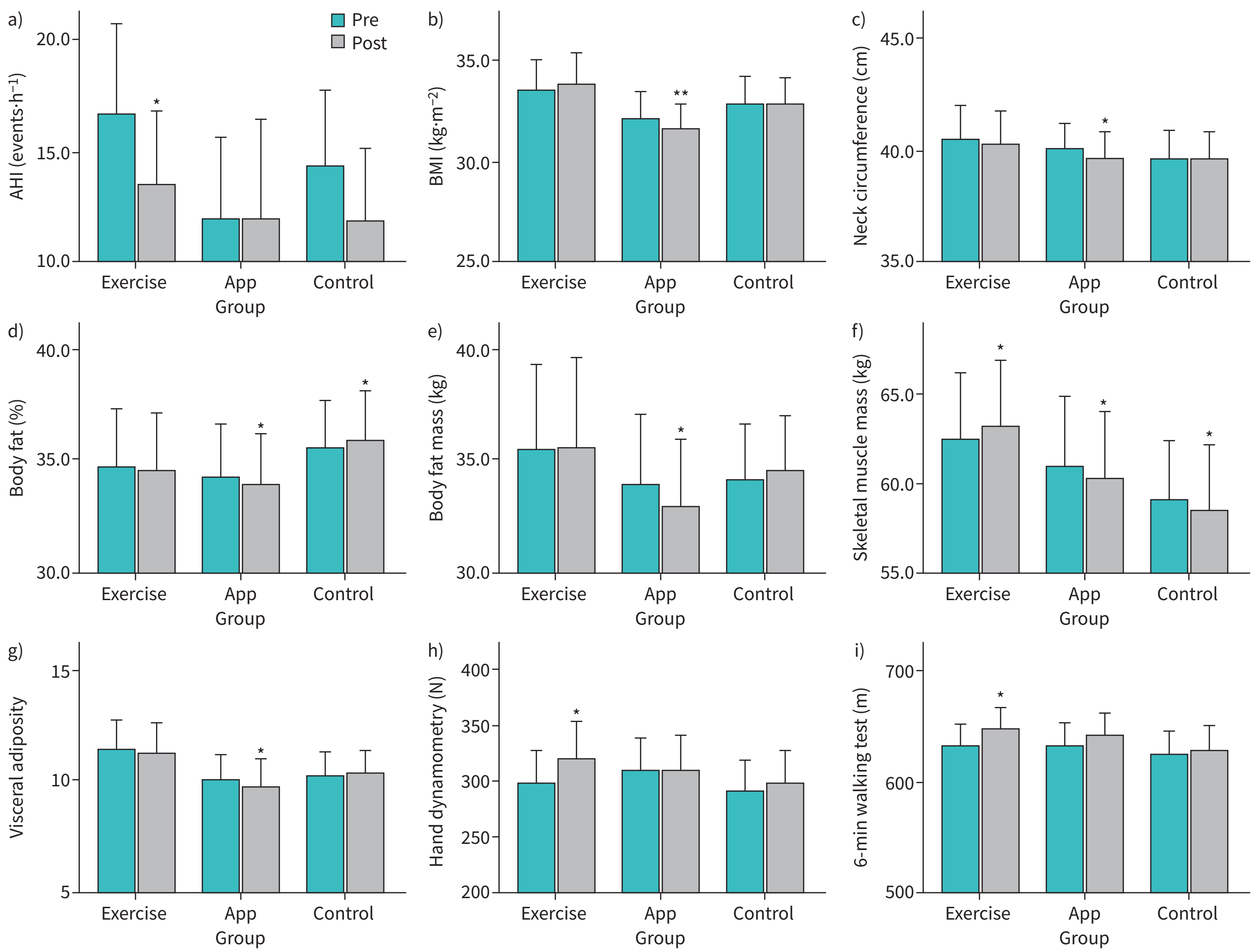

FIGURE 2 Intragroup differences between pre- and post-measures of sleep disordered breathing severity, and physical health: a) apnoea–hypopnea index (AHI), b) body mass index (BMI), c) neck circumference, d) body fat percentage, e) body fat mass, f) skeletal muscle mass, g) visceral adiposity, h) hand 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 × 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***	
AG	87.2±9.4	92.8±9.2	**6.33**	**<0.001****	0.335
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***	
AG	71.6±33.2	82.8±30.0	15.67	0.072	0.196
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	
AG	70.1±34.9	75.9±37.7	8.20	0.511	0.479
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***	
AG	38.6±18.2	51.6±18.3	**33.48**	**0.002***	0.073
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	
AG	71.7±11.3	73.5±13.5	2.51	0.290	0.203
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	
AG	76.3±21.0	79.3±20.7	3.95	0.554	0.746
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	
AG	71.1±19.8	76.1±17.4	7.03	0.364	0.693
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***	
AG	59.5±11.7	65.0±12.2	**9.28**	**0.010***	0.874
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,

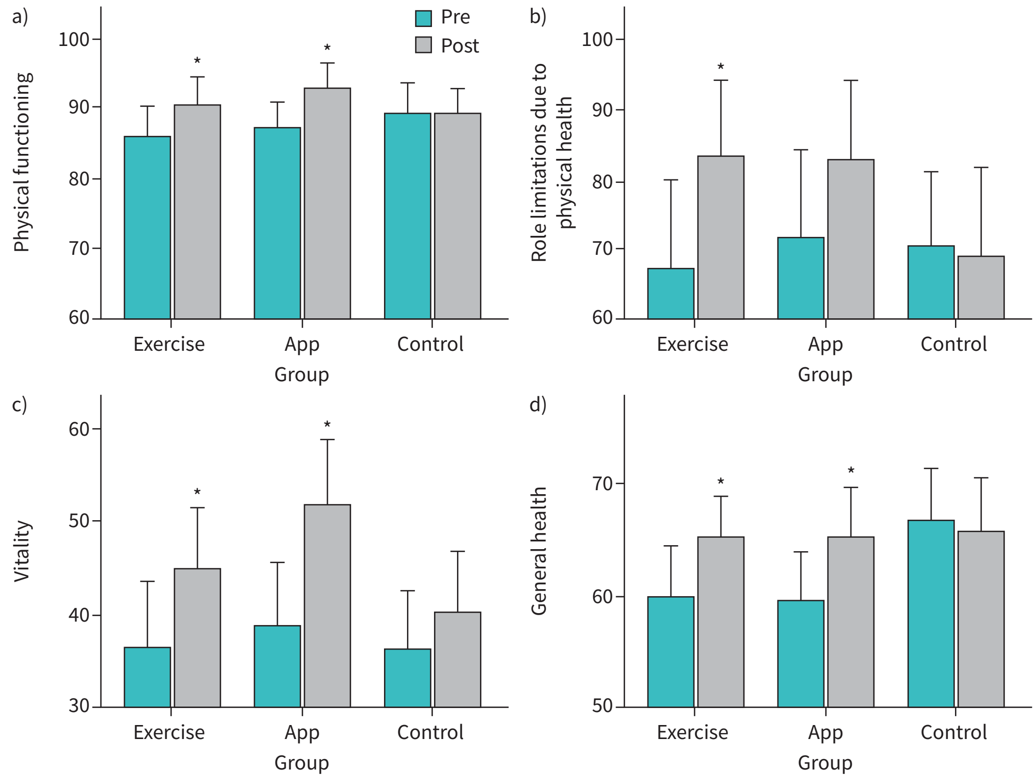

FIGURE 3 Intragroup differences between pre- and post-measures of health-related quality of life: a) physical functioning, b) role limitation due to physical health, c) vitality and d) general health. *$p<0.05$.

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 ∼3–8% 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 × 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 ($mL \cdot min^{-1} \cdot kg^{-1}$) (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.

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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).

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PAPER III

Paper III

THE EFFECTS OF AN EXERCISE PROGRAM AND A LIFESTYLE APP ON SLEEP HEALTH IN PEOPLE WITH MILD TO MODERATE SLEEP-DISORDERED BREATHING: ISRCTN 16974764

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ABSTRACT

Background. The objective of this randomized controlled trial was to assess the effects of a 12-week exercise program and a lifestyle app on sleep health in 18 to 50-year-olds with mild-to-moderate sleep-disordered breathing (SDB). **Methods.** One-hundred-ninety-two participants (age 37.4±6.3years, body mass index 33.3±4.2kg/m², 52.6% males) with mild-to-moderate SDB (apnea-hypopnea index [AHI]≥5<30.0 events/hour and/or objective snore ≥10%) were randomized into exercise (three times/week, 60 minutes), app, and control groups. The assessments included subjective sleep health measures (Pittsburgh Sleep Quality Index [PSQI] and Epworth Sleepiness Scale [ESS]) and objective sleep measures (three-night self-applied polysomnography). Wilcoxon signed-rank, Kruskal-Wallis H tests, repeated ANOVA, and chi-square were used to analyze the changes. **Results.** Intra-group changes were observed in the PSQI global score and subscales for sleep quality, sleep latency, sleep disturbances, and daytime dysfunction, as well as in the prevalence of poor sleepers (PSQI>5). A time effect was observed in wake after sleep onset (p<0.001), arousal index (p=0.003), and N2 sleep (p=0.027). A time x group interaction was found in N1 (p=0.015) and N3 (p=0.030) sleep stages.

Conclusions. The exercise program improved subjective sleep health, reflected in the PSQI global score and three PSQI subscales, without changes in objective sleep health. The lifestyle app improved subjective sleep health in the daytime dysfunction subscale of PSQI, decreased wake after sleep onset, increased N2, and decreased N3 sleep parameters of objective sleep health. The subjective sleep health improvements did not differ between the groups, but the N3 sleep stage differed between the app and control groups.

Keywords: Aerobic exercise, resistance training, obstructive sleep apnea, apnea-hypopnea index, sleep quality, snoring.

1. INTRODUCTION

Sleep-disordered breathing (SDB) is a highly prevalent sleep disorder (Benjafield et al., 2019) characterized by abnormalities in breathing during sleep, with manifestations ranging from loud and frequent snoring to repeated partial (hypopnea) or complete (apnea) airway obstruction (Panossian & Daley, 2013), termed obstructive sleep apnea (OSA). OSA is characterized by respiratory interruptions that can cause intermittent hypoxemia and fragmented, non-restorative sleep (Eckert & Younes, 2014).

Good sleep health is essential for overall health and well-being (Sejbuk et al., 2022). It encompasses a multidimensional pattern of sleep and wakefulness that aligns with individual, social, and environmental demands, promoting both physical and mental well-being (Buysse, 2014). Key indicators of optimal sleep health include satisfaction with sleep, appropriate timing, adequate duration, high efficiency, and sustained daytime alertness (Buysse, 2014). Generally, exercise programs have been demonstrated to improve both objective and subjective sleep quality in the general population (Zhou et al., 2025). While enhancing self-reported sleep quality and reducing perceived daytime sleepiness in OSA patients (C.-F. Lin et al., 2024; Lins-Filho et al., 2020; Peng et al., 2022). However, these subjective improvements are not always reflected in objective sleep parameters in OSA patients, as some studies have reported no (Schütz et al., 2013) or limited (Gokmen et al., 2019; Kline et al., 2011; Servantes et al., 2018) changes in objectively measured sleep health parameters despite improvements in subjective outcomes. Sleep architecture refers to the cyclical pattern of sleep, transitioning through different sleep stages, including non-rapid eye movement (NREM) and rapid eye movement (REM) sleep (Patel et al., 2024). NREM is further subdivided into three sub-stages: N1, N2, and N3 (American Academy of Sleep

Medicine, 2020). A sleep cycle typically commences in the lightest sleep stage, N1, and progressively advances through deeper NREM stages, culminating in the deepest sleep stage, N3, and ending with REM (Patel et al., 2024). The intermittent hypoxemia of OSA can alter sleep stages by increasing the number of sleep stage transitions (Bianchi et al., 2010), increasing N1, and reducing N3 sleep (Shahveisi et al., 2018). The effects of exercise programs on the sleep stages in OSA patients have not been widely studied. One meta-analysis of randomized controlled trials showed that exercise programs lasting ≥12 weeks decreased N2 sleep and increased N3 sleep in OSA patients (Chen et al., 2024). However, the results are inconsistent among studies (Kline et al., 2011; Lins-Filho et al., 2023; Schütz et al., 2013).

The emergence of smartphone applications (apps) that promote physical activity and healthy lifestyle behaviors (Schoeppe et al., 2016), presents a novel opportunity for interventions using these apps as a potential treatment option for OSA patients (Cho et al., 2018). However, studies on this topic remain limited within the SDB population (Cho et al., 2018; Fridgeirsdottir et al., 2024). Although current studies indicate that lifestyle apps have no effect on OSA severity in individuals with SDB (Cho et al., 2018; Fridgeirsdottir et al., 2024). In contrast, one recent study demonstrated an intra-group reduction in AHI following a six-month lifestyle app intervention (Lin et al., 2024). The impact of these lifestyle apps on sleep health in OSA patients remains understudied, highlighting the need for further studies. In a previous study with the same cohort, the apnea-hypopnea index (AHI) lowered by 19% without changes in body mass index (BMI) in the exercise group. In contrast, the app group did not achieve changes in AHI despite a significant reduction in BMI (Fridgeirsdottir et al., 2024).

In this context, the objective of this study was to assess the effects of a 12-week exercise program and a lifestyle app intervention compared to controls on subjective and objective sleep health in 18 to 50-year-olds with mild-to-moderate SDB.

2. METHODS

2.1 Design

This study was a 12-week RCT with three groups (exercise, app, and control). The study was registered in ISRCTN [*16974764*]. The independent variable was the type of intervention (exercise program, lifestyle app program, or no intervention). The dependent variables were categorized into subjective and objective sleep health parameters. Subjective sleep health included the Pittsburgh Sleep Quality Index (PSQI) global score and its subscales: sleep quality, sleep latency, sleep disturbances, sleep medication, and daytime dysfunction, as well as the Epworth Sleep Scale (ESS) score. Objective sleep health included total sleep time (TST), sleep efficiency (SE), sleep onset latency (SOL), wake after sleep onset (WASO), arousal index, and sleep stages (NREM, N1, N2, N3, and REM) presented in minutes as % of TST. All the dependent variables were evaluated immediately before and after the interventions.

2.2. Participants

One thousand two hundred ninety-nine subjects responded to the online advertisement to participate in this study. The inclusion criteria were: (i) adults aged 18 to 50 years, (ii) overweight or obese (BMI 25-42 kg/m²), (iii) inactive (not participating in an exercise program at baseline), and (iv) diagnosed with mild-to-moderate SDB (AHI ≥5<30.0 and/or objective snore ≥10%). Four hundred twenty-two subjects met the inclusion criteria of i, ii, and iii. These subjects were invited to the Reykjavik University Sleep Institute (RUSI), Reykjavik, Iceland, for a preliminary type 3 single night sleep study (T3 device, Nox Medical, Reykjavík, Iceland) to confirm (iv) mild-to-moderate SDB (AHI ≥5<30.0 and/or objective snore ≥10%). SDB parameters were manually scored from a minimum of four hours of wearable O_2 measures and other sleep study signals according to the current American Academy of Sleep Medicine (AASM) criteria (2020). Subjects that were currently treated for OSA, pregnant, shift workers, or were unable to exercise for any reason were excluded. 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 randomized into exercise, app, and control groups. The randomization was stratified by age, sex, and BMI from preliminary studies to minimize potential confounding effects on study outcomes. This process was implemented using Python (version 3.10.6.) and the A* Pathfinding algorithm, an artificial intelligence-based method that groups individuals based on similarity, ensuring balanced stratification. The algorithm also aimed to prevent any variable from exceeding specified limits. Given the small study population in Iceland, which increased the risk of bias, this algorithmic approach was chosen for its robustness. The algorithm first balanced the gender distribution across the three groups (exercise, app, and control), then calculated a "score" for each group, reflecting the differences in the average and standard deviation of key variables compared to the total sample, as well as the female and male subgroups. When gender distribution was not a factor, the algorithm used the "score" to ensure overall group balance. Out of the 103 participants who completed pre- and post-sleep studies, two control group participants with abnormal differences in AHI pre- and post-intervention were considered outliers and excluded from all analyses. In total, 101 participants were analyzed, representing a dropout rate of 47.4%. The flowchart is shown in

Figure 1. Additionally, Table 1. displays the characteristics of the sample before the interventions (baseline) and the results of Levene's test.

****Figure 1 near here****

**** Table 1 near here****

2.3. Interventions

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

2.3.1 Exercise program intervention.

The exercise program was implemented thrice weekly, with each session lasting 60 minutes over a 12-week intervention period. This duration aligns with the most commonly used timeframe in similar studies (da Silva et al., 2022; Gokmen et al., 2019; Kline et al., 2011; Lins-Filho et al., 2023; Sengul et al., 2011; Servantes et al., 2018). The program structure was developed following the guidelines and findings from previous studies (Agner et al., 2018; Saavedra et al., 2021; Timmons et al., 2018). Each session included a 5-10-minute warm-up focusing on mobility and activation, 15-22 minutes of circuit training, 8-14 minutes of brisk walking, and a 5-10-minute cooldown.

2.3.2 Lifestyle app intervention.

Participants assigned to the lifestyle app program were asked to complete daily tasks within the app [*Sidekick Health, Reykjavík, Iceland*] during the 12-week intervention period. The tasks encouraged healthy behaviors through goal setting, self-monitoring, and completing health-related tasks in four categories: diet, physical activity, sleep, and stress management. Participants earned points that unlocked virtual and altruistic rewards, such as badges and charitable water donations, by completing tasks aimed at enhancing motivation and engagement. Additionally, participants received personalized support and feedback from a live coach via text messages within the app. This app has previously demonstrated effectiveness in promoting weight loss among individuals with overweight and obesity (Thorgeirsson et al., 2022), improving glycemic control and psychological well-being in obese patients with type II diabetes (Hilmarsdóttir et al., 2021), and enhancing metabolic health in individuals with multiple conditions, such as metabolic syndrome, type 2 diabetes, and non-alcoholic fatty liver disease (Björnsdottir et al., 2024).

2.4. Measurements

Subjective and objective measures of sleep health were conducted.

2.4.1 Subjective sleep health.

Subjective sleep health was assessed using two questionnaires: PSQI and ESS. PSQI is a self-reported questionnaire encompassing seven subscales: sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, use of sleep medication, and daytime dysfunction (Buysse et al., 1989). Scores range from 0-21, with scores from 5-10 indicating poor sleep and above 10 indicating sleep disorders. ESS assesses the likelihood of falling asleep in eight different situations commonly encountered in everyday life (Johns, 1991). The total score ranges from 0-24, with scores above 10 suggesting excessive daytime sleepiness. The questionnaire data were collected and managed using REDCap electronic data capture tools hosted at Reykjavík University, Reykjavík, Iceland. REDCap (Research Electronic Data Capture) is a secure, web-based software platform designed to support data capture for research studies (Harris et al., 2019). Participants answered questionnaires in Icelandic or, for non-native speakers, in English.

Objective sleep health was assessed using TST, SE, SOL, WASO, arousal index, and the percentage of different sleep stages (Krystal & Edinger, 2008).

2.4.2 Objective sleep health

All participants underwent a three-night polysomnography (PSG) using self-applied polysomnography PSG using A1s, Nox Medical, Reykjavík, Iceland. The setup included frontal electroencephalogram (AF4, AF3, AF8, and AF7) and electrooculography (E1, E2, E3, and E4) recordings (Rusanen et al., 2024). Nasal airflow was detected with a cannula, oxygen saturation with oximetry, heart rate with electrocardiography and oximetry, respiratory movements with respiratory inductance plethysmography, thorax- and abdominal belts, body position with an accelerometer, and leg movements with left and right anterior tibialis electromyography. Additionally, an audio recording was conducted to detect snoring. Expert sleep technologists manually scored all sleep studies with a minimum of four hours of wearable oxygen (O_2) measures and other sleep study signals, following the current recommendations of the American Academy of Sleep Medicine (AASM) manual version 2.6 (American Academy of Sleep Medicine, 2020). All sleep parameters were defined and calculated following these recommendations and are presented as average values derived from completed sleep studies.

2.5. Procedure

Participants were recruited from the general population via media advertisements, where they completed a screening questionnaire covering information about sex, height, weight, shiftwork, previous OSA diagnosis, current OSA treatment, and physical activity. Those meeting the inclusion criteria were invited to a preliminary assessment, including a single night type 3 sleep study and anthropometric measurements. Eligible participants were randomized into exercise, app, and control groups. The exercise group participants were consulted about their preferred exercise timing to tailor the schedule to their needs. Given that the group assignment was randomized, participants in the exercise group may not have had an initial interest in exercise. Because participants were inactive and either overweight or obese, the program set an adherence target of around two sessions per week, requiring at least 60% attendance for analysis. Participants in the app group were instructed to install the lifestyle app (Sidekick Health, Reykjavík, Iceland) on their smartphones. The exercise program, conducted at the Sports Science Laboratory of Reykjavik University, was designed by the work package leader (JMS), supervised by the PhD student (KYF), and implemented by MSc and third-year BSc students in Sports Science. Following the initial study phases, the postdoctoral researcher (CMJ) joined the research team, taking on coordinator responsibilities under the guidance of the principal investigator (ESA) and the work package leader (JMS). All participants were informed about the purpose of this study, and written consent was a prerequisite for participation. The study was approved by the National Bioethics Committee of Iceland and the Icelandic Data Protection Authority *[ref. No. 22-082*] and respected the Declaration of Helsinki.

2.6. Statistical analysis

All variables were assessed for homoscedasticity using Levene's variance homogeneity test and normality using the Kolmogorov-Smirnov test. Descriptive statistics, including means and standard deviations, were calculated. A logarithmic transformation was applied for variables with non-normal distribution; if normality was not achieved, non-parametric tests were used. The Wilcoxon signed-rank test assessed the changes in subjective sleep health parameters (PSQI and ESS) pre- and post-intervention. Post-intervention PSQI and ESS scores across the three groups were compared using the Kruskal-Wallis H test. Changes in the prevalence of poor sleep (PSQI>5) and excessive daytime sleepiness (ESS>10) within each group were evaluated using the Chi-square test. Repeated measures ANOVA, with the Bonferroni post hoc test, were performed to summarize the changes in the objective sleep health variables. Additionally, the main effects of the group, time, and group × time interaction were analyzed. Missing data was excluded from the analysis. Statistical significance was set at $p<0.05$ for all tests, and analyses were performed using IBM SPSS Statistics 28.

3. RESULTS

Table 2. presents nonparametric test results for the subjective sleep health parameters (PSQI and ESS). The exercise program improved the PSQI global score ($p=0.021$), as well as sleep quality ($p=0.025$), sleep latency ($p=0.04$), and sleep disturbance ($p=0.033$). Similarly, the control group showed improvements in global score ($p=0.001$), sleep quality ($p=0.034$), and sleep latency ($p=0.001$). The lifestyle app program improved daytime dysfunction (p=0.005). However, PSQI parameters did not differ between the groups after the interventions ($p>0.079$). Figure 2 shows the intra-group comparison of subjective sleep health outcomes.

**** Table 2 near here****

**** Figure 2 near here****

Table 3. presents the prevalence of poor sleepers (PSQI>5) across the groups. In the exercise group, the prevalence of poor sleepers significantly decreased ($p=0.015$), with 23.3% transitioning from poor to good sleepers (figure 3a). Similarly, in the control group, the prevalence decreased (p=0.007), with 19.4% experiencing better sleep (figure 3a). In contrast, in the app group, the prevalence of poor sleepers increased ($p=0.667$), with 6.9% improving and

10.3% worsening (figure 3a). The ESS score did not change in any of the groups. In the exercise group, the prevalence of excessive daytime sleepiness (ESS>10) decreased (*p*=0.252), with 13.8% showing improvement (figure 3b). In the control group, a decrease was observed (*p*=0.696), with 9.4% of participants improving (figure 3b). However, in the app group, the prevalence of daytime sleepiness increased (*p*=0.663), with 13.3 improving but 10% worsening (figure 3b). Figure 3. Illustrates the prevalence of participants showing no change, improvement, or worsening across the exercise, app, and control groups.

**** Table 3 near here****

**** Figure 3 near here****

Table 4. summarizes the basic descriptive statistics and repeated ANOVA measures, including time, group, and time x group interaction effects and intra-group comparison for objective sleep health variables. The app intervention decreased WASO, increased N2 sleep, and reduced N3 sleep post-intervention and when compared to the control group (*p*=0.038). A reduced WASO, and decreased N1 sleep was observed in the control group. A time effect was found for WASO (F=19.334, *p*<0.001), arousal index (F=9.240, *p*=0.003), and N2(%) (F=5.064, *p*=0.027). A time x group interactions were observed in N1(%) (F=4.414, *p*=0.015), and N3(%) (F=3.644, *p*=0.030). Figure 4. shows the intra-group changes in objective sleep health variables.

**** Table 4 near here****

**** Figure 4 near here****

4. DISCUSSION

The objective of this randomized controlled trial was to assess the effects of a 12-week exercise program and a lifestyle app on sleep health in 18 to 50-year-olds with mild-to-moderate sleep SDB. To our knowledge, this is the largest randomized controlled trial to examine these parameters in an SDB population. The main findings of this study indicate that the exercise program improved subjective sleep health, as reflected in the PSQI global score and three PSQI subscales. The lifestyle app intervention enhanced subjective sleep health in one PSQI subscale and decreased WASO. However, these improvements were not reflected in other objective sleep health parameters, as N2 sleep increased and N3 sleep reduced. A time x group interactions were observed in N1 and N3 sleep stages variables.

With respect to the subjective sleep health parameters, the exercise group showed a 1.1-point reduction (improvement) in the PSQI global score (pre 7.5 *vs* post 6.4, p=0.021) (table 2, figure 2a). Comparable to the 1.5-point improvement reported in a previous 12-week aerobic and resistance training program conducted on a smaller sample of participants with moderate-to-severe OSA (Kline et al., 2011). Other studies using high-intensity interval training (Lins-Filho et al., 2024), T'ai Chi and Qigong (Gokmen et al., 2019), and an intense 4-week program combining health education, diet, and aerobic and resistance training (Desplan et al., 2014) have reported greater reductions (2.64 to 3.5 points). However, in these studies, the baseline PSQI global score was higher than in the current one (ranging from 8.4 to 8.9 *vs* 7.5), which may explain the difference in the results. Furthermore, the exercise group showed improvements in PSQI subscales for sleep quality, sleep latency, and sleep disturbance (figures 2b, 2c, and 2d), findings that partially align with previous research (Lins-Filho et al., 2020). Additionally, it is worth noting that the prevalence of poor sleepers (PSQI>5) significantly reduced in the exercise group from 83.3%

to 66.7% (p=0.015) (table 3), with 23.3% improving from poor to good sleep after the intervention (figure 3a). The app group demonstrated improvement in the daytime dysfunction subscale (figure 2e) despite no change in the PSQI global score. Furthermore, in the app group, there was an increase in the prevalence of poor sleepers, from 72.4% to 75.9% (p=0.667) (table 3), with 6.9% improving and 10.3% worsening following the intervention (figure 3a). Although no prior studies have specifically utilized the PSQI in lifestyle app interventions for SDB patients, subjective sleep metrics like the PSQI have been recommended for sleep self-management apps (Choi et al., 2018). Interestingly, the control group also exhibited improvements in the PSQI global score (figure 2a), as well as in the subscales for sleep quality and sleep latency (figures 2b and 2c). Additionally, in the control group, the prevalence of poor sleepers decreased from 80.6% to 61.3% (p=0.007) (table 3), with 19.4% improving from poor to good sleep despite no intervention (figure 3a). These findings have not been reported in prior studies (Desplan et al., 2014; Kline et al., 2011; Lins-Filho et al., 2024). However, the improvements of the current study, observed in subjective health assessed using PSQI, did not differ between the three groups. This could potentially be explained by the reduction in AHI in the exercise group, reported in a previous study conducted on the same cohort (Fridgeirsdottir et al., 2024). In that study, the AHI was reduced in the control group, although the reduction was not significant. Therefore, reduced AHI may partly explain the improvements in subjective sleep health observed in both the exercise and control groups. Notably, the sleep latency and sleep disturbance subscales of PSQI have been found to correlate with AHI (Lusic Kalcina et al., 2017). Consequently, reducing AHI will likely positively influence the subjective sleep health parameters assessed by the PSQI.

Continuing with the subjective parameters of sleep health, no changes were found in ESS in any of the groups, which is consistent with the findings of a study on mild-to-moderate OSA

(Sengul et al., 2011). However, this contrasts with prior findings of systematic reviews (C.-F. Lin et al., 2024; Lins-Filho et al., 2021; Lins-Filho et al., 2020; Peng et al., 2022) and studies (Bughin et al., 2020; Desplan et al., 2014) on moderate-to-severe OSA, which reported a reduction in daytime sleepiness following exercise interventions. Notably, participants in this current study, recruited from the general population, had lower baseline ESS scores than in previous studies (Bughin et al., 2020; Desplan et al., 2014; Lins-Filho et al., 2024). Furthermore, it is worth mentioning that among the groups, the exercise group showed the largest reduction in the prevalence of excessive daytime sleepiness (ESS>10), decreasing from 37.9% to 27.6% (table 3), with 13.4% improving following the exercise program (figure 3b).

Regarding objective sleep health, WASO decreased in all three groups (figure 4a), with a time effect observed (table 4). However, the reduction in the exercise group was not statistically significant (p=0.109). These results partially align with a previous study that reported no change in WASO in either the exercise group or stretching control group following a 12-week exercise program (Kline et al., 2011). Notably, while that earlier study relied on single-night laboratory PSG, this study utilized a three-night self-applied home polysomnography. A similar reduction in WASO over three consecutive nights using self-applied home polysomnography has been reported (Ferretti et al., 2024), which may explain the results. In terms of sleep stages, no change was observed in the exercise group, despite the 19% reduction in AHI reported (Fridgeirsdottir et al., 2024). These results are consistent with findings from earlier studies, which reported no (Gokmen et al., 2019) or limited change (Kline et al., 2011) in sleep stages despite improvements in AHI. However, some research has reported different effects, such as decreased light sleep (N1 and N2) and increased N3 sleep (Bughin et al., 2020) or an increase in both N3 and REM sleep (Lins-Filho et al., 2023). These discrepancies highlight the variability in how exercise interventions may influence sleep stages depending on design, exercise type, and participant characteristics. In the app group, the proportion of N2 sleep increased while N3 sleep decreased (figures 4c and 4d), with a significant reduction in N3 sleep compared to controls (time x group interaction, table 4). Although previous studies have not specifically examined the effects of lifestyle apps on sleep stages, the reduction in N3 sleep observed in the app group might partially explain the slight increase in poor sleep (PSQI>5) and excessive daytime sleepiness (ESS>10), which rose from 72.4% to 75.9% and 23.3% to 26.7%, respectively (table 3). Interestingly, in the control group, the proportion of N1 sleep decreased (p=0.012) (figure 4b), findings not reported in prior exercise intervention studies (Gokmen et al., 2019; Kline et al., 2011; Lins-Filho et al., 2023). These notable improvements in the control group, both in subjective and objective sleep health occurred despite receiving no intervention. Recruitment from the general population and the non-blinded study design may have heightened health awareness, leading to self-initiated changes through the Hawthorne effect (French, 1953), which can enhance behaviors like physical activity, even in control groups (Waters et al., 2012). These results indicate that further studies with larger sample sizes are needed to determine whether three weekly 60-minute aerobic and resistance training sessions over 12 weeks are sufficient to improve objective sleep health parameters in 18 to 50-year-olds with mild-to-moderate SDB.

This study's strengths include the largest RCT sample, the first to assess both a structured exercise program and an evidence-based lifestyle app on individuals with mild-to-moderate SDB, using comprehensive objective and subjective sleep health parameters. The exercise program, tailored for sedentary individuals, incorporated aerobic and resistance training, with perceived exertion measured in every session. The use of state-of-the-art three-night PSG recordings at baseline and follow-up allowed for better assessment of night-to-night variability, which is particularly high in mild-to-moderate OSA compared to severe OSA and healthy individuals (Punjabi et al., 2020).

There are some limitations. First, the three-night PSG was performed at home without controlling for bed-sharing partners to keep the sleep routine as close to normal as possible. Second, as this study focused on adults aged 18-50 (mean age 37.4), the findings may not generalize to older populations with SDB or should be interpreted with caution. Finally, the dropout rate was high (47.4%), although prior studies showed dropout rates from 4.3% (da Silva et al., 2022) to 44.4% (Schutz et al., 2013), with an average of 16.8%. This suggests that the interventions, while effective, were demanding and required high participant commitment.

5. CONCLUSION

The conclusions of this study were (i) the 12-week exercise intervention demonstrated significant benefits by improving subjective sleep health, as reflected in the PSQI global score and three PSQI subscales, despite no change in objective sleep health parameters and (ii) The lifestyle app intervention showed more targeted improvements, including reduced daytime dysfunction in subjective sleep health (PSQI), decreased WASO, but also increased N2 sleep, and reduced N3 deep sleep.

These findings highlight the potential benefits of incorporating 60 minutes of aerobic exercises and resistance training three times per week for individuals with SDB with the aim of improving perceived subjective sleep health assessed by PSQI. In contrast, the lifestyle app provided more modest improvements in subjective sleep health and specific objective sleep metrics, suggesting its value as a complementary tool alongside other treatment options. These approaches emphasize the importance of adopting multidimensional strategies tailored to address individual needs and priorities for effective SDB management.

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AUTHOR CONTRIBUTIONS

Conceptualization: JMS, ESA; Data Curation: KYF, CJM; Formal Analysis: KYF, JMS; Funding Acquisition: ASI, HH-S, JMS, ESA; Methodology: KYF, CJM, ASI, HH-S, JMS, ESA; Project Administration: JMS, ESA; Supervision: JMS, ESA; Writing original draft preparation: KYF, JMS, ESA; Writing – Review & Editing: All authors.

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Table 1. Baseline characteristics of eligible participants in each group and Levene's test results.

Variable	Participants (N= 101)			F	*P*
	Exercise group (N=32) M±SD	App group (N=34) M±SD	Control group (N=35) M±SD		
General information					
Age (years)	37.8 ± 6.0	37.8 ± 6.9	37.5 ± 6.3	0.467	0.628
Males (%)	56.3	44.1	40.0		
BMI (kg/m^2)	33.4 ± 4.3	31.8 ± 3.8	32.6 ± 3.9	0.795	0.454
AHI	16.6 ± 11.1	12.1 ± 10.4	13.2 ± 8.3	0.698	0.500
Subjective sleep health					
PSQI global score	7.7 ± 2.4	7.6 ± 3.0	8.5 ± 3.4	2.830	0.064
ESS score	8.9 ± 4.4	8.1 ± 4.3	8.5 ± 5.0	1.140	0.324
Objective sleep health					
Total sleep time (min)	396 ± 46	398 ± 50	401 ± 53	0.299	0.742
Sleep efficiency (%)	92.7 ± 3.7	91.7 ± 4.7	92.2 ± 4.8	0.731	0.484
SOL (min)	8.8 ± 7.8	7.6 ± 5.3	7.6 ± 5.6	1.733	0.182
WASO (min)	29.1 ± 16.2	31.8 ± 21.5	30.2 ± 22.6	0.588	0.557
Arousal index	15.4 ± 5.8	13.1 ± 4.2	13.3 ± 4.5	1.073	0.346
NREM (%)	75.5 ± 4.3	77.0 ± 4.8	76.0 ± 5.2	0.144	0.866
N1 (%)	10.6 ± 5.4	10.8 ± 4.8	10.8 ± 5.0	0.118	0.889
N2 (%)	44.0 ± 8.2	45.9 ± 6.0	44.9 ± 7.9	2.349	0.101
N3 (%)	20.9 ± 8.0	20.3 ± 7.2	20.3 ± 7.3	0.875	0.420
REM (%)	24.4 ± 4.1	22.9 ± 4.8	24.3 ± 5.2	0.405	0.688

BMI, Body mass index; ESS, Epworth Sleepiness Scale; NREM, non-rapid eye movement sleep; N1, non-rapid eye movement sleep stage one; N2, non-rapid eye movement sleep stage two; N3, non-rapid eye movement sleep stage three; PSQI, Pittsburgh sleep quality index; REM, rapid eye movement sleep; SOL, sleep onset latency; WASO, wake after sleep onset.

Table 2. Mean ± standard deviation, Wilcoxon signed rank, and Kruskal-Wallis H tests for subjective sleep health parameters (PSQI and ESS) for the exercise group (EG), app group (AG), and control group (CG).

Variable	Group	Time			Wilcoxon signed-rank test	Kruskal-Wallis H
		Pre-intervention	Post-intervention	Δ%	*p*	*p*
PSQI						
Global Score	EG	7.5 ± 2.2	6.4 ± 2.2	**-14.32**	**0.021**	
	AG	7.8 ± 2.8	7.0 ± 2.6	-10.98	0.065	0.576
	CG	8.7 ± 3.4	7.2 ± 3.4	**-16.99**	**0.001**	
Sleep Quality	EG	1.7 ± 0.6	1.4 ± 0.6	**-19.41**	**0.025**	
	AG	1.4 ± 0.6	1.2 ± 0.6	10.14	0.285	0.137
	CG	1.7 ± 0.6	1.6 ± 0.6	**-10.92**	**0.034**	
Sleep Latency	EG	1.0 ± 0.9	0.6 ± 0.7	**-38.14**	**0.040**	
	AG	1.5 ± 1.0	1.1 ± 1.0	-24.14	0.084	0.114
	CG	1.7 ± 1.0	1.0 ± 1.0	**-39.39**	**0.001**	
Sleep Duration	EG	1.0 ± 0.7	1.0 ± 0.7	3.4	0.739	
	AG	0.9 ± 0.9	0.8 ± 0.8	-8.00	0.564	0.169
	CG	1.1 ± 0.9	0.7 ± 0.8	-30.39	0.092	
Sleep efficiency	EG	0.6 ± 0.7	0.5 ± 0.6	-7.00	0.822	
	AG	0.7 ± 0.9	0.8 ± 0.9	20.00	0.363	0.462
	CG	0.8 ± 0.9	0.6 ± 0.8	-24.69	0.196	
Sleep Disturbances	EG	1.6 ± 0.6	1.4 ± 0.6	**-15.95**	**0.033**	
	AG	1.5 ± 0.7	1.5 ± 0.5	0	1.00	0.712
	CG	1.6 ± 0.6	1.5 ± 0.7	-3.80	0.527	
Sleep Medication	EG	0.2 ± 0.4	0.3 ± 0.7	35.00	0.516	
	AG	0.5 ± 0.9	0.5 ± 0.9	-13.46	0.414	0.609
	CG	0.5 ± 1.0	0.5 ± 1.0	-6.25	0.705	
Daytime dysfunction	EG	1.4 ± 0.6	1.2 ± 0.5	-12.14	0.096	
	AG	1.5 ± 0.6	1.1 ± 0.5	**-26.20**	**0.005**	0.079
	CG	1.4 ± 0.6	1.4 ± 0.6	0	1.00	
ESS						
ESS score	EG	9.1 ± 4.3	8.6 ± 3.7	-5.32	0.425	
	AG	8.5 ± 4.3	8.0 ± 3.7	-5.49	0.436	0.833
	CG	8.1 ± 4.7	8.1 ± 3.9	-0.39	0.601	

AG, app group; CG, control group; EG, exercise group; Ess, Epworth Sleepiness Scale; PSQI, Pittsburgh Sleep Quality Index.

Table 3. Change in the prevalence of poor sleepers and excessive daytime sleepiness pre- and post-intervention and Chi-square for the exercise group (EG), app group (AG), and control group (CG).

Variable	Group	Time Pre-intervention	Time Post-intervention	Chi-square Within-group *p*	Chi-square Between-group *p*
PSQI					
Poor sleepers (%) (PSQI>5)	EG	83.3%	66.7%	**0.015**	0.204
	AG	72.4%	75.9%	0.667	
	CG	80.6%	61.3%	**0.007**	
ESS					
Excessive daytime sleepiness (%) (ESS>10)	EG	37.9%	27.6%	0.252	0.655
	AG	23.3%	26.7%	0.663	
	CG	28.1%	25.0%	0.696	

AG, app group; CG, control group; EG, exercise group; Ess, Epworth Sleepiness Scale; PSQI, Pittsburgh Sleep Quality Index.

Table 4. Mean ± standard deviation and repeated measures ANOVA results for objective sleep health parameters corresponding to the exercise group (EG), lifestyle app group (AG), and control group (CG), pre- and post-intervention, and main effects and interaction.

Variable	Group	Time			Time effect		Group effect		Time x Group effect	
		Pre-intervention	Post-intervention	Δ%	F	p	F	p	F	p
Objective Sleep health										
TST (min)	EG	394 ± 47	380 ± 41	-3.55						
	AG	398 ± 50	389 ± 62	-2.26	3.296	0.073	0.393	0.676	0.109	0.897
	CG	401 ± 53	392 ± 52	-2.24						
SE¶ (%)	EG	92.8 ± 3.7	93.3 ± 3.4	0.57						
	AG	91.6 ± 4.8	93.4 ± 3.2	1.90	0.260	0.611	0.324	0.724	1.154	0.320
	CG	92.2 ± 4.8	92.9 ± 4.6	0.74						
SOL¶ (min)	EG	8.2 ± 7.1	7.5 ± 5.6	-8.57						
	AG	7.6 ± 5.4	7.1 ± 7.4	-5.96	1.795	0.184	0.448	0.641	0.903	0.409
	CG	7.6 ± 5.6	6.8 ± 5.5	-10.27						
WASO¶ (min)	EG	29.1 ± 16.5	23.3 ± 13.5	-19.87						
	AG	32.2 ± 21.7	22.9 ± 12.3	**-29.11***	19.334	**<0.001**	0.386	0.681	0.694	0.502
	CG	30.2 ± 22.6	23.5 ± 17.5	**-22.42***						
Arousal index¶	EG	15.6 ± 5.8	14.5 ± 6.0	-7.09						
	AG	13.0 ± 4.2	12.5 ± 6.0	-4.09	9.240	**0.003**	2.446	0.092	0.014	0.987
	CG	13.3 ± 4.5	12.1 ± 4.6	-8.98						
NREM (min)	EG	296.3 ± 35.2	293.2 ± 33.2	-1.05						
	AG	306.9 ± 38.0	296.2 ± 49.4	-3.50	2.373	0.127	0.382	0.683	0.260	0.771
	CG	303.2 ± 36.0	297.1 ± 39.8	-2.01						
NREM (%)	EG	75.4 ± 4.3	77.3 ± 5.0	2.54						
	AG	77.1 ± 4.9	76.1 ± 4.1	-1.31	0.003	0.957	0.517	0.598	2.522	0.086
	CG	76.0 ± 5.2	75.2 ± 6.3	-1.07						
N1¶ (%)	EG	10.7 ± 5.4	12.3 ± 6.1	14.36						
	AG	10.9 ± 4.8	10.6 ± 5.3	-2.79	0.263	0.609	0.488	0.615	4.414	**0.015**
	CG	10.8 ± 5.0	9.6 ± 4.7	**-11.03***						
N2 (%)	EG	43.8 ± 8.3	45.2 ± 7.4	3.19						
	AG	46.1 ± 6.0	49.0 ± 5.9	**6.40***	5.064	**0.027**	1.915	0.153	1.172	0.314
	CG	44.9 ± 7.9	45.3 ± 9.0	0.84						
N3 (%)	EG	20.8 ± 8.1	19.9 ± 7.1	-4.50						
	AG	20.2 ± 7.2	16.5 ± 6.6	**-18.13*[a]**	3.434	0.067	1.212	0.302	3.644	**0.030**
	CG	20.3 ± 7.3	21.1 ± 8.4	3.84						
REM (%)	EG	24.5 ± 4.2	22.7 ± 5.0	-7.31						
	AG	22.9 ± 4.8	23.8 ± 4.1	3.97	0.484	0.488	0.377	0.687	1.930	0.151
	CG	24.3 ± 5.2	24.0 ± 5.2	-1.11						

AG, app group; CG, control group; EG, exercise group; NREM, non-rapid eye movement sleep, REM, rapid eye movement sleep; SE, sleep efficiency; SOL, sleep onset latency; TST, total sleep time; WASO, wake after sleep onset; Δ%, percentages change from pre- to post-intervention, * $p<0.05$; [a], significantly different from control group post-intervention $p<0.05$.

Figure 1. Participant's flow chart

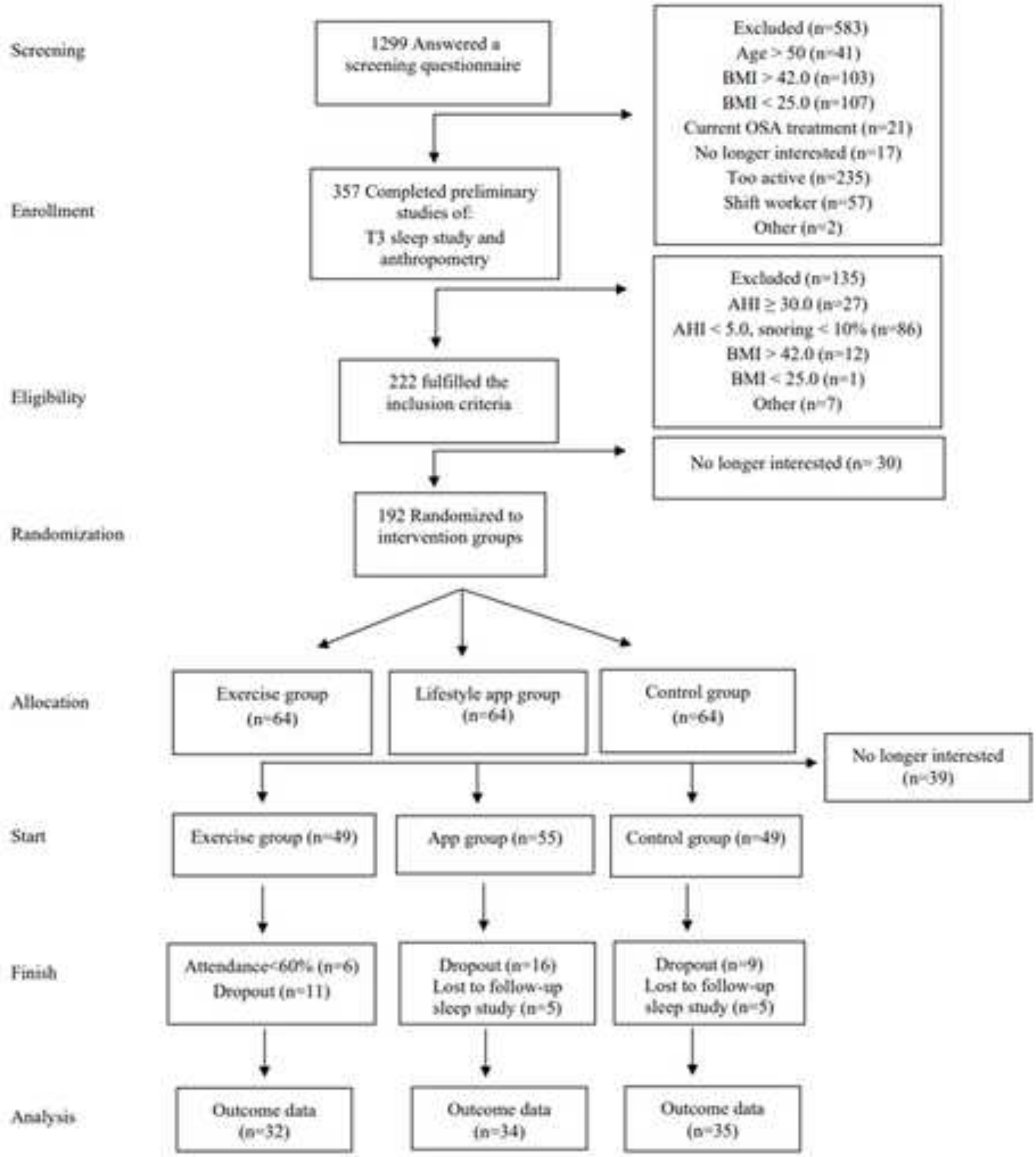

Figure 2. Intra-group comparison of subjective sleep health outcomes across exercise, app, and control groups

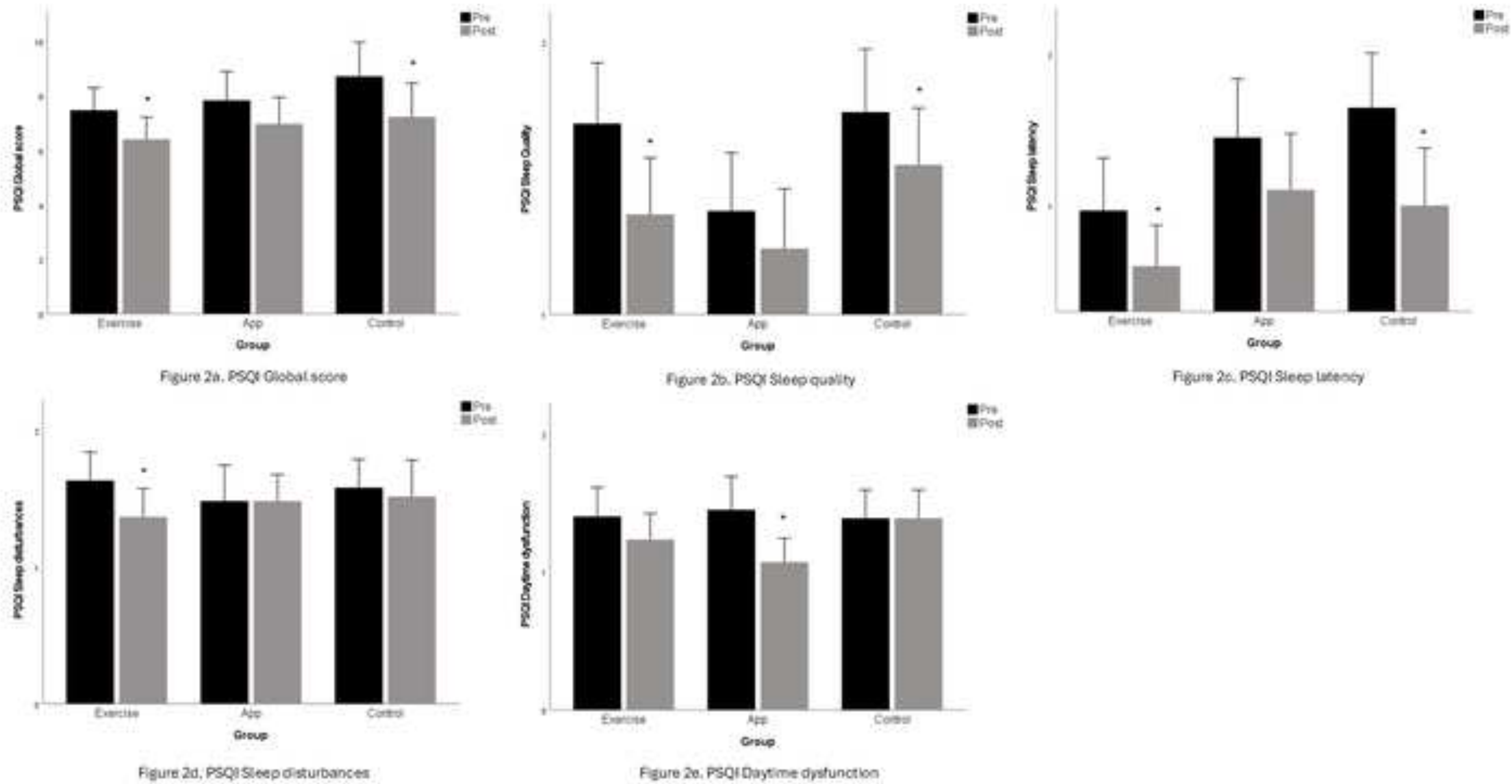

Figure 3. The prevalence of participants showing no change, improvement, or worsening in poor sleep (PSQI>5) and excessive daytime sleepiness (ESS>10) across

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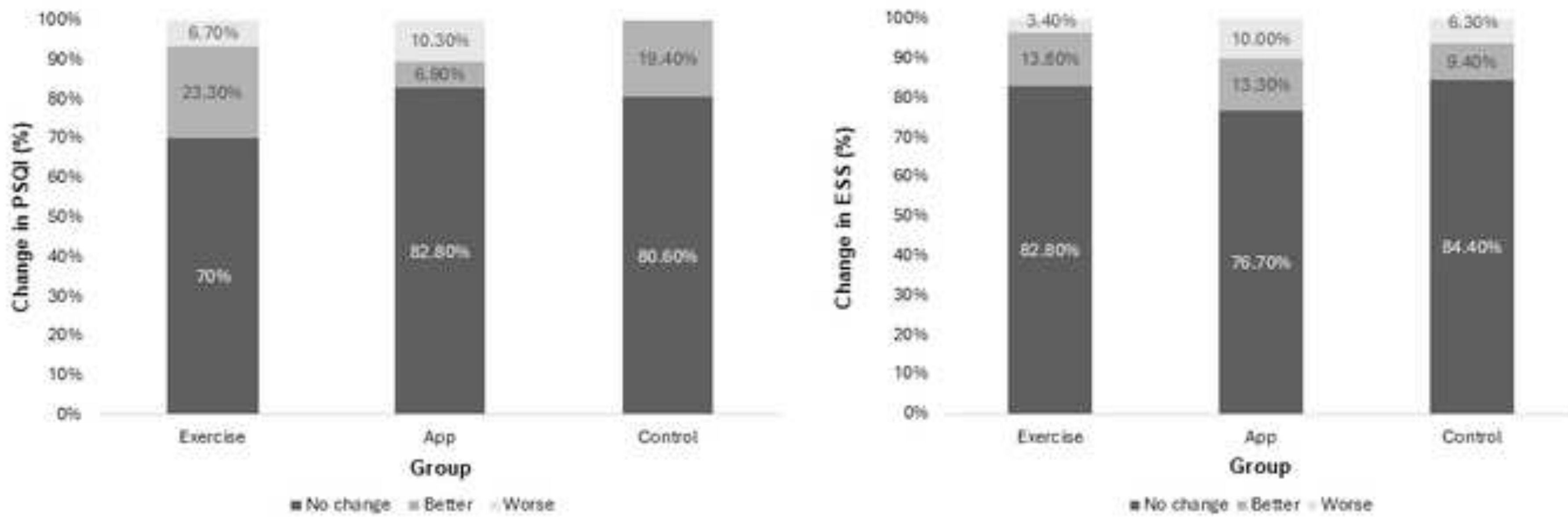

Figure 3a. Change in PSQI

Figure 3b. Change in ESS

Figure 4. Intra-group comparison in objective sleep health parameters across exercise, app, and control groups.

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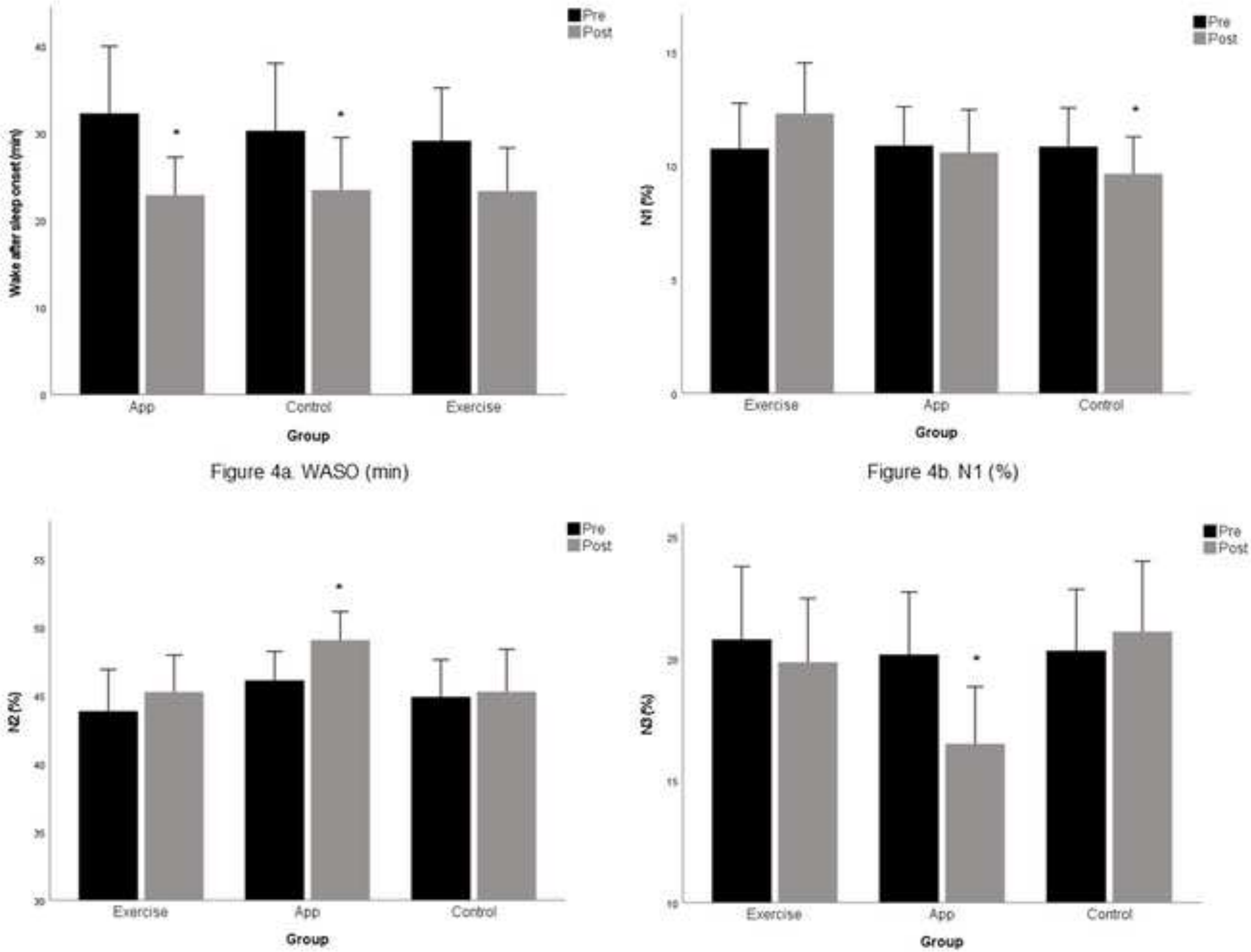

Figure 4a. WASO (min)

Figure 4b. N1 (%)

Figure 4c. N2 (%)

Figure 4d. N3 (%)