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CLINICAL REVIEW

The association between objective measurements of sleep quality and postural control in adults: A systematic review

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SUMMARY

We systematically reviewed the association between objective sleep quality and postural control based on objective measurements. We searched the electronic databases PUBMED, CINAHL, SCOPUS and Web of Science for studies assessing the relationship between objective measurements of sleep and postural control or gait performance among adults above age 18. All types of articles until April 2020 were considered. The search yielded 2967 articles, and out of these, inclusion criteria were met by five cross-sectional and two longitudinal studies (N = 7). Three studies found a positive correlation between sleep efficiency and gait speed, three studies found a negative correlation between wake time after sleep onset (WASO) and gait speed or postural control, and one study found no association between sleep parameters and gait speed. Objectively measured sleep quality parameters such as sleep efficiency and WASO were associated with objective measures of posture and gait. More studies with longitudinal designs are needed to expose causal pathways and mechanisms underlying these relationships.

Introduction

Both the proportion and absolute number of older people in populations around the world are increasing dramatically [1]. Adults 65 years and older are projected to make up nearly one-quarter of the population in the United States, and the number of people 85 years and older is expected to almost double by 2035 and nearly triple by 2060 to 19 million people [2]. Falling accidents are a major problem among older adults and have dramatic effects on their health status and quality of life. Falls cause 81–98% of hip fractures [3] and nearly 40% of all injury deaths [4]. An increased risk of falling is associated with impaired balance and reduced postural control, especially during walking (i.e., mobility limitations) [5]. Postural control is defined as the ability to control the body in space for two main purposes: balance and orientation [6,7]. Gait abnormalities and balance disturbances are common among 75% of people over 70 years old [8], and are associated with an increased risk of falls, loss of independence, morbidity, and mortality [9,10]. Thus, one of the major goals of the (emerging field of) geroscience is to identify populations at a higher risk for falls as early as possible.

Alarming findings indicate that older adults with poor sleep quality have as much as a 4.5-fold higher risk of falls [11,12] and for functional decline [13,14]. Self-reported poor sleep quality as measured by the Pittsburgh Sleep Quality Index (PSQI) is associated with a high risk of falls among community-dwelling older adults [13]. Symptoms of insomnia are prevalent among 20–50% of middle-aged and older adults [14], and have also been associated with falls [11,12]. Findings show positive associations between sleep (quality and quantity) and postural control, especially gait performance, even among relatively healthy adult populations [15]. The potential comorbidity between reduced sleep quality and balance problems has led to a growing interest in the study of the relationships between them [16].

Findings across different study designs consistently demonstrate a strong link between sleep quality and postural control and, specifically, gait quality. Yet potential mechanisms that may underlie these associations have been studied separately for sleep and for gait and are not fully understood. These include physiological mechanisms such as cardiometabolic risk factors [19,20], brain

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Abbreviations

ALS	Amyotrophic lateral sclerosis
BMI	Body mass index
CHF	Congestive heart failure
COP	Center of pressure
DT	Dual task
L5	Sum of activity of least active 5 h period in a day
OHS	Obesity hypoventilation syndrome
OSA	Obstructive sleep apnea
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
RDI	Respiratory disturbance index
REM	Rapid eye movement
SE	Sleep efficiency
SL	Sleep latency
ST	Single task
TST	Total sleep time
UARS	Upper airway resistance syndrome
WASO	Wake time after sleep onset

structure abnormalities such as reduced hippocampal volume [21,22], cognitive decline [23,24] and psychological distress [25,26].

One of the major obstacles that hinders our ability to generalize the conclusions of these studies is the use of *subjective* measurements to assess both sleep quality and gait/postural control performances [11,17]. Self-report data is limited by many factors such as setting (home vs. laboratory) [28], personality traits or constitutional factors such as trait anxiety [29] and psychosocial factors, such as lack of social support and depressive symptoms [30]. Evidence suggests that poorer psychosocial predispositions are associated with poorer subjective, but not objective sleep measurements. Although the limitations of subjective reports for sleep [19–21] and falls [13] are well documented, in clinical settings they have many advantages. For research purposes, *objective* measurements are required to better validate the presentation of both domains and to enable comparisons that overcome biases associated with various settings from different cultures [17]. An in-depth examination of objective sleep parameters and their association with respect to objective postural control measurements may enable us to explore potential shared mechanisms between them. Such an examination may shed light on the specific risk factors of falling and at the same time help pave the way for developing effective interventions [17].

The aims of this systematic review are to: 1) describe the comorbidity between sleep and postural control based on objective measurements; 2) offer potential mechanisms for the relationships between them; 3) discuss clinical implications; and 4) articulate future directions for the exploration of this relationship.

Methods

The review protocol was registered in the International Prospective Register for Systematic Reviews (PROSPERO, protocol CRD42020188536). Recommendations of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement were respectively followed [22].

Inclusion and exclusion criteria

A research study was eligible for our systematic review if the study's sample included community-dwelling adults aged 18 and above, and their sleep and posture parameters were objectively measured. Studies were excluded if they focused specifically on populations with neurological conditions [e.g., cerebrovascular disease, Parkinson's disease, dementia (of any type), amyotrophic lateral sclerosis (ALS)], sleep-related breathing disorders [upper airway resistance syndrome (UARS), obstructive sleep apnea (OSA) or obesity hypoventilation syndrome (OHS)], rapid eye movement (REM) sleep behavior disorder, congestive heart failure (CHF), or major physical disabilities. In studies that employed different selection criteria, thus rendering only part of their sample eligible for the present systematic review, authors were contacted with a request for differentiated data. If no response was received, the study was not included in the review.

Search strategy

The literature search was performed in April 2021 in PUBMED, CINAHL, SCOPUS and Web of Science. Key terms used in the search were synonyms for: “postural balance”, “posture”, “walking”, “gait”, “sleep”, “actigraphy”, and “polysomnography”. Additionally, manual searching was performed using references of already included studies and reviews in the identification of other potentially eligible studies. Results of the search were imported into Sciwheel.com (Sciwheel Limited, London, UK) for removal of duplicates and reference management. A complete description of the search strategy employed in this review is available in supplementary Table 1.

Screening of references and eligibility assessment

Two reviewers, Ma'ayan Agmon (MA) and Dani Kirshner (DK), searched electronic databases independently according to pre-set inclusion criteria and created a list of relevant articles. Based on the studies' titles and abstracts, each reviewer independently categorized each study as either: relevant, irrelevant or uncertain. All articles classified as irrelevant by both reviewers were excluded; articles which were classified as uncertain by at least one reviewer or as irrelevant by only one reviewer, were discussed by both reviewers until an agreement was reached on whether classification was irrelevant (excluded) or relevant. Subsequently, each of the reviewers independently reviewed all the non-excluded articles in full, and further classified them as relevant or irrelevant. Reasons for exclusion were then documented. If an article was deemed relevant but certain information or details about the sample or results were lacking—thus preventing the option of determining accordance with inclusion criteria—the authors were contacted to complete the missing information. If the missing information was provided and met the review's criteria, the article was included in the review, otherwise, it was excluded.

Data extraction and quality assessment

Data extraction from the selected references was performed blindly by two authors (MA and DK). Comparison of the data was then conducted, and inter-reviewer resolution was carried out if a disagreement occurred. Extracted data for each reference were: first author, year of publication, study location, study design, sample characteristics (e.g., sample size, setting, number of females, age), inclusion and exclusion criteria, objective and subjective sleep measurements, posture measurements, covariates, and main results.

Two authors (MA and DK) independently evaluated study quality using three domains of the Newcastle–Ottawa quality assessment scale (NOS): Selection of the population (S), comparability of groups (C) and assessment of the outcome (total score of nine points) (O). The selection (S) domain includes aspects that are associated with the cohort characteristics, level of representativeness, mode of selection, and the inclusion of a comparison group (i.e., exposed versus non exposed groups) in the study design. The comparability domain (C) evaluates the level in which control variables were considered. The assessment of the outcomes domain (O) evaluates the quality of the outcome, the follow up period and the potential for bias during follow-up [35].

Results

Fig. 1 depicts the PRISMA flow diagram. The search yielded 2967 articles (PUBMED: 1300, CINAHL: 163, Web of Science: 290, SCOPUS: 1214) with 819 duplicates. Of these articles, 2118 were excluded during screening: 1020 articles did not use an objective measurement of sleep or posture and 1098 included populations that did not meet the study criteria. The remaining 30 articles were reviewed in full. Of these, 23 studies were excluded. Eleven studies incorporated additional populations in their results that did not meet the inclusion criteria of this review and 12 studies did not describe the association between objective sleep quality variables and objective postural control (see Fig. 1). As a result, a total of seven studies matched the systematic review criteria.

All of the obtained studies were conducted among community-dwelling adults who were able to walk independently. The mean age of participants in five studies was above 70 years [15,24–27], and 52 years and 21 years in the remaining two studies [28,29], respectively. One study included only men [26], two studies included only women [24,25]. Five studies were conducted as cross-sectional studies [15,26–29] and two as longitudinal studies [24,25]. Six studies found significant associations between sleep characteristics and gait speed or posture [15,24–27,29]. Tables 1 and 2 summarize the characteristics and main results of the studies examined in this review.

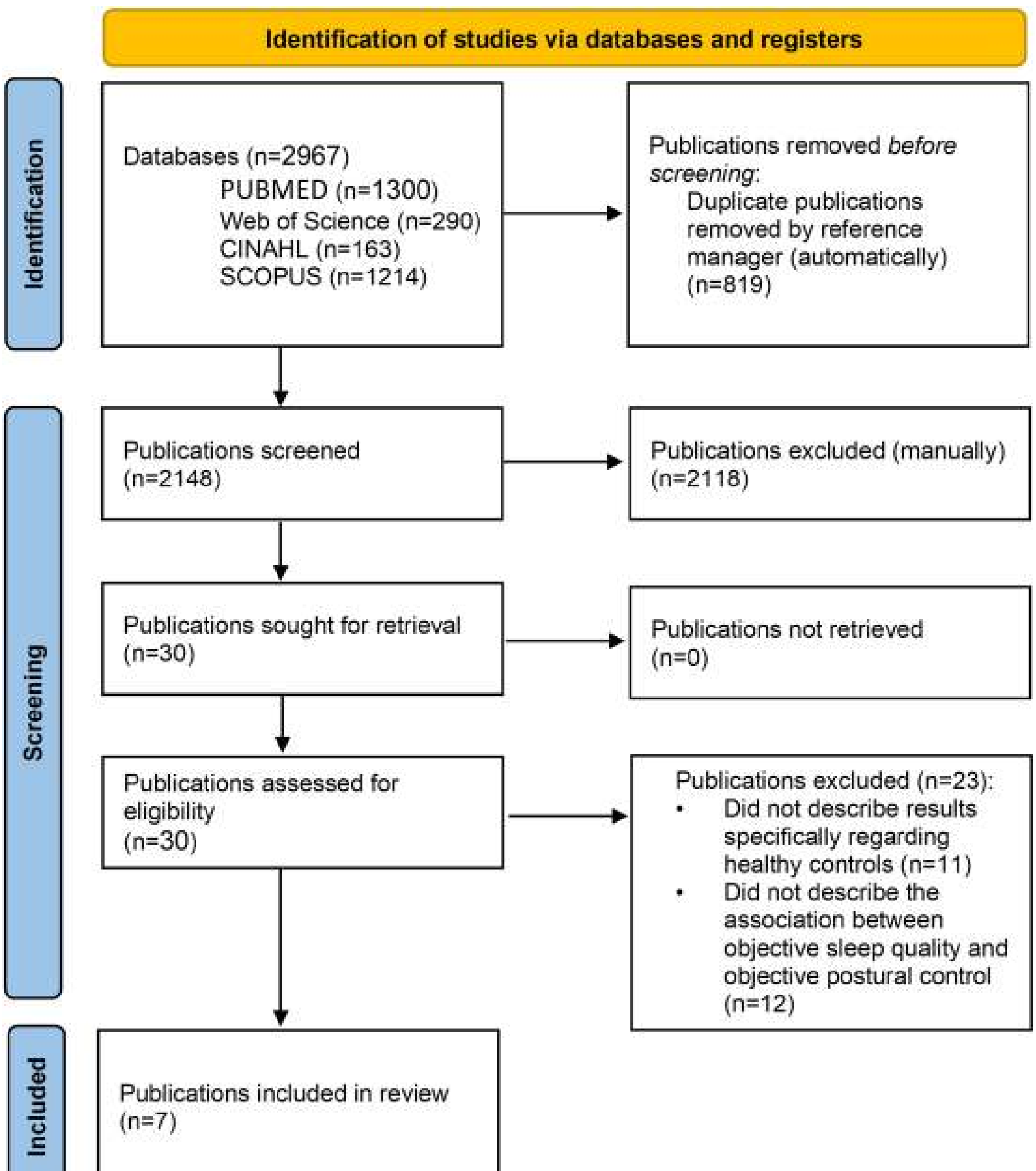

Fig. 1. PRISMA flow diagram of selected studies [22].

Inclusion and exclusion

All of the studies recruited only community-dwelling adults who were able to walk independently. Four studies excluded participants with cognitive impairments [15,24,27,28], and three studies excluded participants with a neurological diagnosis [15,27,28]. Only two studies described the use of hypnotic medications which were reported by a minority of participants [17,39] One study excluded participants with "a major medical condition" [26]. Among the exclusion criteria applied to studies in this systematic review (Table 1) were musculoskeletal, rheumatological or psychiatric diseases, any IADL (instrumental activities of daily living) difficulty at baseline, status post bilateral hip replacements, severe orthopedic limitations, inability to walk without assistance, use of any mechanical devices during sleep, or significant hearing or vision loss.

Covariates

All of the studies used age as a covariate in their analysis [15,24–29]. Five studies included BMI (body mass index) or diagnoses of obesity, depression or use of antidepressants as covariates in their analysis [24–26,28,29]. Three studies included objective cognitive measurement as a covariate in their analysis [15,24,25] (Table 2).

Sleep evaluation

Objective sleep parameters were assessed by actigraphy in all studies. Actigraphy systems used to evaluate sleep in the studies in this review consisted of a variety of commercially available brands. Six studies measured sleep by means of actigraphy for a period of 3–14 days [15,24,26–29] and one study employed the actigraphy device for an average of 24 h [25]. One study used a polysomnography (PSG) to measure respiratory disturbance index (RDI) and sleep architecture [26]. Total sleep time (TST) was described in six studies [15,25–29] and wake time after sleep onset (WASO) was described in six studies [24–29]. Sleep efficiency (SE) was described in five studies [15,24,26–28] and sleep latency (SL) was described in four studies [15,26,27,29] (Table 1).

Posture evaluation

Six studies measured gait speed using different protocols [15,24–27,29]. Two studies were conducted under both single task (ST) and dual task (DT) conditions [15,27]. The dual-task paradigm aims to explore attention resources that are associated with gait performance. To this end, the participants are asked to walk under two conditions: gait alone (ST) and gait simultaneously with another task (DT), typically a cognitive arithmetic task (in the above-mentioned study, the task was subtraction by three from a random number between 100 and 250 for 1 min). Additionally, the cognitive task is conducted alone (ST). Finally, the difference in gait and cognitive performance between single and dual-task is calculated and reflects dual-task interference or cost (DTC) [42]. One study used the center of pressure (COP) as an objective tool to assess posture [28], one study measured balance [26], and three studies also measured the ability to rise up from a chair [25,26,29]. Five studies (out of six which measured gait speed) described the mean walking speed of the sample group [15,25–27,29] (Table 1).

The associations between sleep measures and postural control measures

Five studies found associations between gait parameters i.e., speed [17,37–39,41], variability [17] and narrow walking [38] with sleep parameters. One paper found no association between gait speed and sleep parameters [36]. The two other studies found association of sleep parameters with chair stand [37] and control of posture, measured by postural sway (displacement of center of pressure) [40]. In some of these studies the results remained robust after adjustment for cognitive function [17,36,37], suggesting that the association between sleep and postural control is partially independent of cognitive function.

A summary of the findings is shown in Fig. 2.

Quality assessment

All of the studies received high ratings for most score components on the Newcastle–Ottawa scale. The most common missing components were in the selection section of the scale. Sample size was not justified and satisfactory, and the description of the response rate or the characteristics of responders and non-responders were missing in the majority of studies (Table 1).

Discussion

Overall, the studies included in the current review demonstrated independent associations between sleep characteristics and postural control, so that more favorable sleep characteristics were associated with better postural control, even after controlling for major covariates such as BMI, physical activity, comorbidities, use of antidepressants, and objective cognitive status. Sleep characteristics were associated with several aspects of postural control, including gait speed, standing balance, and stride-length variability (under dual task condition) [15,24–27,29].

Several explanations are offered for the association between sleep characteristics and postural control: 1) physiological and pathological mechanisms that influence sleep and postural systems, 2) neuroanatomical, 3) cognitive, and 4) psychological mechanisms (Fig. 3).

Physiological and pathological mechanisms

Various cardiometabolic risk factors have been linked to sleep disturbance [30] and gait deterioration [31,32]. For example, cumulative high blood pressure from young adulthood to middle age has been associated with reduced gait speed [31]. Cardiometabolic risk factors are characterized by long-term low-level systemic inflammation [33], which has also been demonstrated in people with sleep disturbances [34] and people with slower walking speed [35]. However, these associations between cardiometabolic risk factors, inflammation markers, sleep, and gait have yet to be incorporated into a comprehensive model that also takes long-term changes into account.

The association between OSA and falls is understudied and warrants further investigation. OSA has been shown to be associated with a twofold increased risk of vertebral fractures in postmenopausal women [49]. Nocturnal hypoxia, a hallmark of OSA, has been implicated as a risk factor for balance and gait disturbances as well as falls, and is suggested as an underlying mechanism [11,50].

Table 1
Characteristics of the sample.

Authors, year, reference	Design, setting, country	N (female: number, %) Age: mean ± SD	Sociodemo-graphic and clinical characteristics	Gait and posture characteristics	Sleep characteristics	Inclusion criteria	Exclusion criteria	Newcastle–Ottawa Scale
Dam et al. (2008) [38]	Cross-sectional Six clinical centers United States	2862 (0, 0%) 76.4 ± 5.5	91% Caucasian BMI - mean 27.2 + 3.8 kg/m^2 Comorbid disease (%) 1554 (54.3) Cardiovascular disease (%) 856 (29.9) Hypertension (%) 1435 (50.2)	Usual walking speed (m/s) 1.1 ± 0.2 Unable to do one chair stand (%) 142 (5.0) Unable to do narrow walk (%) 531 (18.6)	• Total sleep time (hrs) 6.4 ± 1.2 • Total sleep ≤6 h (%) 900 (31.4) • Total sleep 6–8 h (%) 1750 (61.2) • Total sleep ≥8 h (%) 212 (7.4) • Sleep efficiency (%) = 85.1 (77.9–89.9) • Sleep efficiency <80% (%) 878 (30.7) • Sleep latency (min) = 21.2 (12.2–37.0) • Sleep latency ≥30 min (%) 962 (33.6) • Wake after sleep onset (min) = 68.6 (46–101.0) • Wake after sleep onset ≥90 min (%) 916 (32.0)	Community dwelling men Age≥65 Independent ambulation Absence of a major medical condition	Bilateral hip replacements Use of any mechanical devices during sleep	S *** C ** O **
Goldman et al. (2007) [37]	16 years longitudinal study Community-dwelling women United States	2889 (2889, 100%) 83.5 ± 3.7	10.9% black, 89.1% white BMI 27.0 ± 5.0 Self-reported health status in %: Excellent 19.1% Good 56.5% Fair 22.5% Poor 1.9% Comorbid conditions (stroke, diabetes, Parkinson's disease, Alzheimer's disease, COPD, heart disease, congestive heart failure, and hypertension): None 27.4% One 41.1% Two 20.8% ≥ Three 10.7% Depression (GDS15) (mean ± SD) 2.4 ± 2.6 Anxiety (mean ± SD) 1.4 ± 2.2 Mini Mental Status Exam (mean ± SD) 27.9 ± 2.0	Gait speed (m/sec) (mean ± SD) 0.8 ± 0.2 Walks for exercise (n (%)) 1066 (37.4) Functional limitation (n (%) with no impairment) 1375 (47.5) Able to complete five chair stands (n (%)) 2021 (83.7)	• Mean TST (hr) (SD) 6.7 (1.3) • Mean WASO (hr) (SD) 1.3 (0.8) • Mean total daytime sleep (hr) (SD) 1.2 (1.1)	Community-dwelling women Living independently ≥65 years of age Ambulatory at the initial visit 1986-88	Bilateral hip replacements	S **** C ** O **
Agmon et al. (2016) [17]	Cross-sectional Community-dwelling older adults Israel	34 (22, 64.7%) 71.5 ± 5.8	Mean education: 14.3 ± 2.8 years Mean MoCA score: 24.0 ± 2.7 Mean TMT–B time was 132.9 ± 75.2 s Absence of, or very low levels of anxiety Four participants reported using sleep medications	Gait speed during single task (m/sec) (mean ± SD) 1.28 ± 0.17 Gait speed during dual task (m/sec) (mean ± SD) 1.15 ± 0.19	• Mean sleep duration was 400.9 min • Mean sleep latency was 10.1 min • Mean sleep efficiency was 94.1%	Age≥60 Walking independently Speak, understand, and read Hebrew Independent in BADL, IADL	Presence of neurologic diagnosis (cerebral vascular accident, Parkinson's disease, Alzheimer's disease or multiple sclerosis) Severe orthopedic restrictions (acute	S *** C * O **

(*continued on next page*)

Table 1 (continued)

Authors, year, reference	Design, setting, country	N (female: number, %) Age: mean ± SD	Sociodemo-graphic and clinical characteristics	Gait and posture characteristics	Sleep characteristics	Inclusion criteria	Exclusion criteria	Newcastle–Ottawa Scale
			more than three times per week				back pain, recent fractures, or a total hip replacement) Significant hearing or vision loss	
Spira et al. (2012) [36]	5-years prospec-tive cohort Commu-nity-dwelling women United States	817 (817, 100%) 82.4 ± 3.3 at baseline	103 (12.6%) were non-white 325 women (39.8%) had education beyond high school	N/A	• Mean sleep duration was 409.2 ± 66.0 min • Mean WASO was 65.9 ± 40.4 min • Mean sleep efficiency was 79.9% ± 9.9%	Enrolled from population-based listings during the Study of Osteoporotic Fractures (SOF), a prospective cohort study Age >65	Not participating in the five-year follow-up visit (1009) Any IADL difficulty at baseline Unable to walk without assistance Bilateral hip replacements Alzheimer's disease (AD) diagnosis or using an AD medication at baseline Missing follow-up data	S *** C ** O *
Furtado et al. (2016) [40]	Cross-sectional Commu-nity-dwelling young adults Brazil	30 (24, 80%) Group 1: 21 ± 2.57 Group 2: 22 ± 3.97	Mean height 1.62 m Mean weight 58.6 ± 6.8 kg Mean BMI 22.22 ± 1.73 (kg/m^2)	N/A	Group 1 (n = 19) • L5 low = higher sleep quality • Mean TST 494.26 ± 46.39 min • Mean WASO 7.02 ± 3.22 • Mean sleep efficiency 0.99 ± 0.005% Group 2 (n = 11) • L5 high = lower sleep quality • Mean height 1.65 m • Mean weight 66.79 ± 7.64 kg • Mean BMI 24.56 ± 2.18 (kg/m^2) • Mean TST 495.96 ± 58.98 min • Mean WASO 14.56 ± 9.19 • Mean sleep efficiency 0.97 ± 0.159%	Healthy volunteers	Medical history of musculo-skeletal, rheumato-logical, neurological, visual, vestibular, psychiatric diseases and/or with diabetes mellitus A body mass index (BMI) smaller than 18.5 or larger than 30 (obesity) kg/m^2	S ** C * O **
Teas & Friedman (2021) [41]	Cross-sectional Community-dwelling adults United States	664 (389, 58.6%) 52.54 ± 12.12	Education: High school/GED or less 29.07% Some college 30.12% College or more 40.81% Married 59.04% Obese (BMI > 30 kg/m^2) 47.89% Disease burden using a multimorbidity weighted index 2.79 (3.77)	N/A	Average sleep duration <6 h 40.66% 6–8 h 55.87% >8 h 3.46%	Community-dwelling adults aged 25-75	Not completing the objective measurements	S *** C ** O ***

Kirshner D. et al. (2021) [39]	Case control Community-dwelling older adults Israel	Group 1 Insomnia group 39 (28, 71.8%) 74 ± 6 Group 2 Non-insomnia (control) group 34 (21, 61.8%) 72 ± 6	Group 1 Insomnia group 38% use of sleep medicine Group 2 Non-insomnia (control) group 12% use of sleep medicine	N/A	Group 1 insomnia group • Sleep efficiency (%) = 72 • Sleep latency (min) = 17 • WASO (min) = 45 • Sleep duration (min) = 408 Group 2 Non-insomnia (control) group: • Sleep efficiency (%) = 93 • Sleep latency (min) = 9 • WASO (min) = 15 • Sleep duration (min) = 404	Group 1 insomnia group: Screened positive for insomnia based on standard DSM-5 criteria Group 2 Non-insomnia (control) group: No known sleep disturbances or complaints based on self-report	Presence of a neurologic diagnosis, such as cerebral vascular accident, Parkinson's disease, Alzheimer's disease or multiple sclerosis Severe orthopedic restrictions such as acute back pain, recent fractures, or a total hip replacement Significant hearing or vision loss Presence of obstructive sleep apnea or periodic limb movements in sleep	S *** C * O **

Abbreviations: IADL-Instrumental Activities of Daily Living.

Other potential physiological mechanisms may underlie the bidirectional link between sleep and frailty. Potential mechanisms underlying this link are particularly important and may also explain the link between sleep and postural control. For example, sarcopenia and increased inflammation markers can lead to frailty [51] and in the same vein to decline in postural control [52].

Neuroanatomical mechanisms

Several neuroanatomical regions, such as the pontine tegmentum, the pedunculopontine nucleus, and the medial medulla have been offered as potential structures that connect sleep-regulation nuclei and gait-controlling areas [36]. Additionally, reduced hippocampal volume was linked to poor sleep [37], reduced executive function [38], and reduced gait performance [39,40] in various studies that explored sleep, executive function or gait disturbances separately.

Cognitive mechanisms

Cognitive function is the factor most extensively linked to both sleep and gait, maybe due to the easier process of its measurement in relation to other factors. Inadequate or disturbed sleep negatively affects cognitive performance [41] and especially executive functions, including impairment of sustained attention [42], working memory, inhibitory control, and cognitive flexibility [43]. In turn, the decline in cognitive abilities, mainly executive function and attention [44], has been linked to an increased risk of falls [45,46] and gait impairment (reduced gait speed and increased gait variability), especially when walking is performed together with a cognitive task (i.e., dual-tasking) [44,47]. Gait control implicates a delicate equilibrium between automatic and executive systems [48]. People with insomnia may have inefficient attention allocation during walking, indicating an inefficient strategy of attention prioritization in adults with insomnia. This hypothesis may explain the higher risk of falls in this population. A model has been proposed in which the effects of sleep deprivation on cortical and subcortical systems involved in postural control are mediated by higher cognitive processes [49]. It is important to evaluate changes in cognition—and specifically executive functions—throughout one's lifespan to better understand risk factors for developing comorbid sleep and gait deterioration.

Psychological mechanisms

Psychological distress (anxiety and depression) and sleep are closely related [11]. Similarly, anxiety is associated with gait deterioration [50,51] and is linked to fear of falling [52], which can start a vicious cycle of limited mobility and consequently reduced gait performance [53]. In much the same manner, the relationship between gait and depression are likely to be bidirectional: slower gait speed and shorter step length predicted the incidence of clinical depression in a four-year longitudinal study [52], and older adults with depression had significantly higher dual-task cost during dual-task gait, probably due to reduced attention associated with depression [54].

The interplay between sleep and postural control/gait

Evidence of the association between sleep problems and falls among community-dwelling older adults is inconsistent in the literature. To date, most of the studies that addressed the relationship between sleep and postural control are cross-sectional and population-based observational studies. These studies demonstrated mostly linear associations between sleep disturbances and falls, whereby poorer sleep measures (poor sleep quality, short

Table 2
Outcome measures, covariates, and results.

Authors, year, reference	Relevant aim	Objective and subjective sleep measurement(s)	Posture measurement(s)	Covariates	Results
Dam et al. (2008) [38]	To determine whether measures of sleep are associated with slower walking speed and inability to complete a chair stand or narrow walk course	Objective 1. One night home-based unattended PSG measured RDI, sleep stage distribution 2. Five days actigraphy: TST, SE, SL, WASO Subjective Sleep diaries	1. Gait speed 2. Balance 3. Rise once from a standard chair	Age BMI Clinic site Antidepressant use Hypertension Comorbid disease (cardiovascular disease, osteoarthritis, diabetes, COPD and Parkinson's disease) Physical Activity Scale for the Elderly Smoking	Gait speed Lower SE was significantly associated with poorer walking speed. After adjustment for age, mean walking speed was 4.3% lower in men with WASO >90 min compared to men with WASO <90 min. Men with the least amount of REM sleep (<14.8%) had the slowest walking speed. No consistent associations were seen with stage 1, stage 2 or stage 3/4 sleep and physical function Narrow walk test Increased nighttime awakenings had 30% higher odds of not completing the narrow walk test (OR 1.3, 95% CI 1.1, 1.6). Similar odds ratios were seen in men with decreased sleep efficiency and increased sleep latency After multivariate adjustment, decreased nighttime sleep was ***not*** associated with decreased walking speed
Goldman et al. (2007) [37]	To examine the association of objective measures of sleep with objective measures of neuromuscular performance	Objective 1.Twenty-four h wrist actigraphy: TST, WASO, total sleep during the day Subjective 1. Sleep diary simultaneously with actigraph	1. Gait speed 2. Ability to rise up from a chair 3. Time to complete five chair stands	Age Race BMI Depression (GDS15) Anxiety (Goldberg Anxiety Score 0–9) Cognitive function (MMSE) Number of comorbidities (stroke, diabetes, Parkinson disease, Alzheimer disease, chronic obstructive pulmonary disease, heart disease	Gait Speed Women who averaged <6 h sleep per night had 3.5% slower gait speed. Women with over 1.6 h of WASO walked almost 10% slower than women who had less than three-quarters of an hour of nighttime wakening. Chair Stands Women who averaged ≥7.5 h of sleep per night took 4.1% longer to complete five chair stands than those who slept 6.8–7.5 h/night. Women who averaged <6 h and ≥7.5 h of TST were not at increased odds of being unable to complete the five chair stands. Women with over 1.6 h of WASO took 7.6% longer to complete five chair stands. Higher amounts of WASO were also associated with higher odds of not being able to complete 5 chair stands.
Agmon et al. (2016) [17]	To explore the associations between habitual sleep quality indices and gait quality, under single and dual-task conditions	Objective 1. Wrist actigraphs for one week measured SE, SL, and sleep duration. Subjective 1. Sleep logs for determination of sleep onset and sleep offset.	1. Gait speed 2. Stride-length variability under single task and dual task conditions	Age Cognition	Gait Speed Significant positive correlation between SE and gait speed Stride-length variability Negative correlation between SE and stride-length variability during dual task ($rs = 0.35$; $p = 0.04$; $rs = 0.36$; $p = 0.03$,

Table 2 (*continued*)

Authors, year, reference	Relevant aim	Objective and subjective sleep measurement(s)	Posture measurement(s)	Covariates	Results
					respectively) Positive correlation between SL and stride length variability during dual task (rs = 0.38; p = 0.03) No correlations were found between sleep and gait measures during single task
Spira et al. (2012) [36]	To determine whether objectively measured sleep quality predicts five-year decline in gait speed in older women	Objective Wrist actigraph-measured TST, WASO and SE Subjective Sleep diaries	Gait speed	Age Obesity MMSE score Depression Anxiety Antidepressant use History of diabetes or coronary artery disease	No associations between sleep parameters and substantial decline in gait speed
Furtado et al. (2016) [40]	To assess the effects of the decrease of quality of sleep on postural control	Objective 1. Actigraph for more than a week measured TST, WASO, SE and L5 Subjective 1. Morningness—eveningness questionnaire 2. PSQI 3. Epworth Sleepiness Scale (ESS)	CoP Four testing protocols	Gender Age Height and weight Days with actigraphy Morning/evening chronotype questionnaire Level of physical activity	Chronic low sleep quality (TST, WASO and SE) affects the control of posture with eyes closed in healthy young Lack of vision impairs postural balance more deeply in subjects with chronic problems of sleep quality
Teas & Friedman (2021) [41]	To examine the relationship between objectively- measured sleep and functional capacity in adults	Objective Actigraph for 7 days. Measured TST, sleep onset latency, WASO Subjective PSQI	1. Gait speed 2. Chair stands	Age Sex Educational attainment Race Marital status Disease burden Obesity	Gait Speed Greater WASO predicted slower gait speed ($P < 0.05$)
Kirshner D. et al. (2021) [39]	To compare gait among community-dwelling older adults with and without insomnia	Objective Wrist-worn activity monitors during the night for two weeks ithe insomnia group and for one week in the non-insomnia group. Measured TST, SE, SL, WASO Subjective 1. Sleep logs for determination of sleep onset and sleep offset. 2. PSQI	Gait speed and variability under ST and DT conditions	Age	Gait Speed Older adults with insomnia have lower gait speed during single and dual tasks

Abbreviations: BMI-Body Mass Index; CoP-Center of Pressure; DL- Dual Task; L5-the sum of the activity of the least active 5-h period across a day; PSG-Polysomnography; PSQI-Pittsburgh Sleep Quality Index; RDI-Respiratory Disturbance Index; SE-Sleep Efficiency; SL-Sleep Latency; ST-Single Task; TST-Total Sleep Time; WASO-Wake Time After Sleep Onset.

sleep duration) are associated with poorer gait measures (e.g., slower gait speed and increased gait variability) [11,12,55]. Most studies have only examined relationships between sleep and gait speed rather than investigate other aspects of postural control and gait such as variability in stride length, step time, step length, and step stance time [56]. Furthermore, most studies have narrowly focused on specific dimensions of sleep, i.e., measures of sleep quality (e.g., WASO) and/or quantity (TST). It is notable that not all associations are linear. Short sleep duration has been associated with increased risk of falls [57–60], yet longer TST (>7.5-h) was associated with poorer chair stand performance [37]. This latter finding is in line with studies demonstrating an inverted U shaped relationship between habitual sleep duration and health outcomes [75]. A small group of controlled laboratory studies demonstrated that lab-induced sleep deprivation is associated with reduced postural control; this is consistent with results from observational cross-sectional studies [49,62,63]. Nevertheless, more nuanced associations between sleep and gait are difficult to delineate and are an important agenda for future research.

Limitations and confounding factors

Several limitations were identified in the reviewed articles. These limitations concern methods for sleep evaluation, methods for postural control evaluation, and research designs.

Sleep evaluation limitations

Sleep was objectively measured by actigraphy in all of the studies in the current review. One study used polysomnography for the evaluation of sleep stages. There was a significant difference among studies regarding the duration of actigraphy recordings, which ranged between 24 h to more than a week. Actigraphy for at least seven, but ideally 14 days, including work/school days and

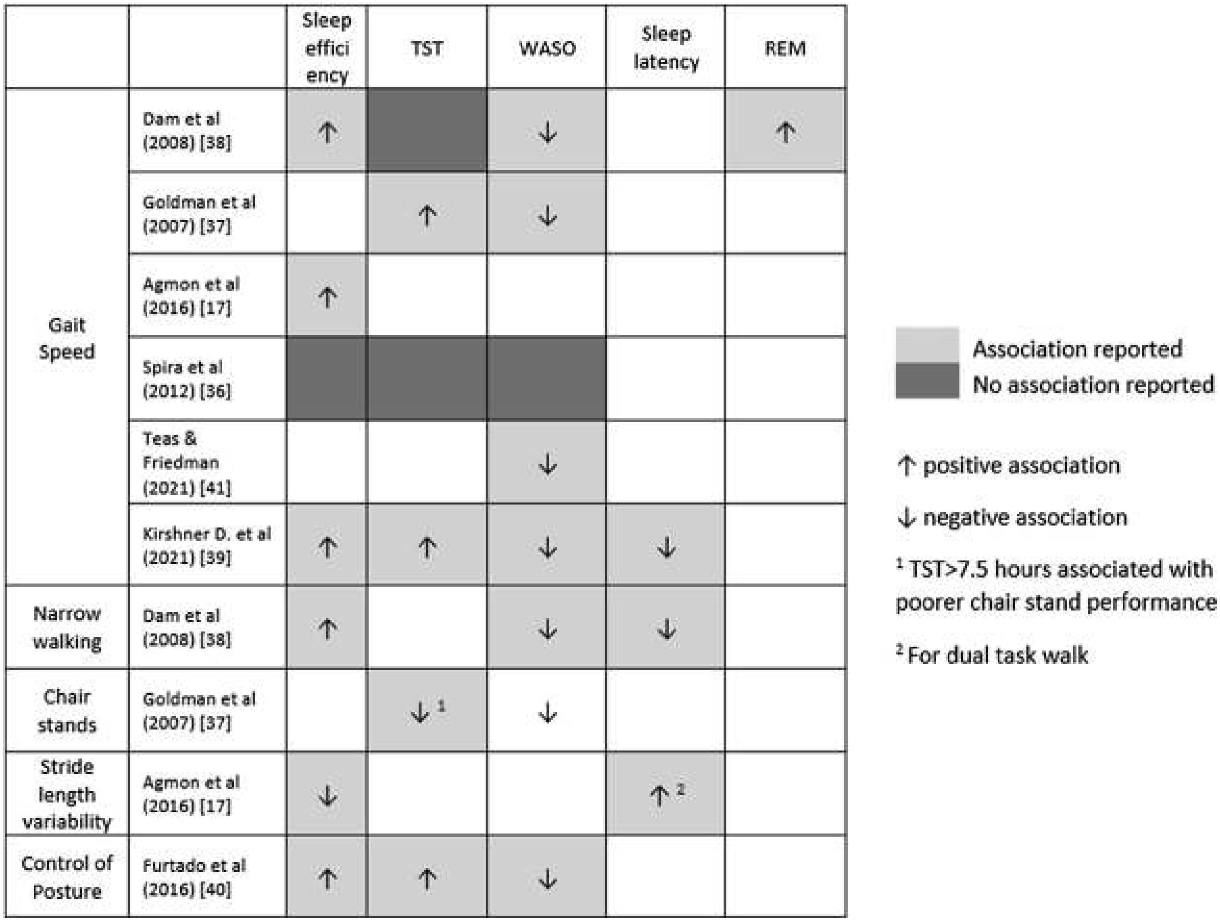

Fig. 2. Summary of results.

weekends/leisure time, is recommended as a diagnostic tool of sleep-wake rhythm disorders [64].

Postural control evaluation limitations

Although all of the studies in the current review included objective measurements of some aspects of postural control, these measurements gave rise to some limitations. Operationalization of postural control was inconsistent across studies. In general, postural control can be objectively assessed by application of behavioral scales and can be quantitatively measured by means of force platforms. Force platforms (or force plates) are considered to be the most reliable evaluation method [65]. Among the studies included in the current review, only one used a force platform for postural evaluation [28].

Gait is a central functional concept of postural control. In this systematic review, we found six studies that assessed postural control through different gait performance metrics, such as the time to complete a 6-m walk [24–26], walking on a narrow support base [26], gait speed [16,29], and gait variability [16,29]. Three studies assessed postural control by measuring the ability to rise up from a chair [25,26,29].

Although these measurements provide valuable information, in recent years a plethora of studies have proposed gait performance as tested by the dual-task paradigm to be a sensitive behavioral marker of various health conditions, such as Parkinson's and Alzheimer's diseases [67], falls [46], and cognitive decline in aging [68]. Only two studies assessed the association between sleep characteristics and postural control under both single and dual conditions [17,39].

Limitations in research design

The studies included in the current review used various design methodologies, limiting our ability to synthesize their findings. Most studies included in this review were cross-sectional studies [15,26,28,29]. Most of them consisted of relatively small samples. Two studies included more than 2000 participants [25,26] and two studies were longitudinal [24,25]. Thus, the overall level of evidence of these studies is relatively weak. It is important to note that there is a broad range of ages of participants in the studies under review, limiting our ability to generalize and understand this link among different age groups throughout the aging process. Additionally, methodological heterogeneity limited our ability to pool data and compare between studies, and, indeed, to understand the underlying mechanisms of these relationships. The longitudinal effects of the physiological, anatomical, cognitive, and psychological pathways that assumedly underlie the relationships between sleep and gait require more study in order to advance the development of a comprehensive model that incorporates age-related changes in these pathways.

Confounders

Several factors may confound the association between sleep quality and postural control. Addressing these factors may shed light on the nature of this relationship. The studies composing the current review considered the effect of major risk factors such as age, gender, BMI, cognitive status, depression and anxiety, and disease burden. Of the studies included in the current review, only one evaluated self-reported use of medications [27]. In addition, five out of seven

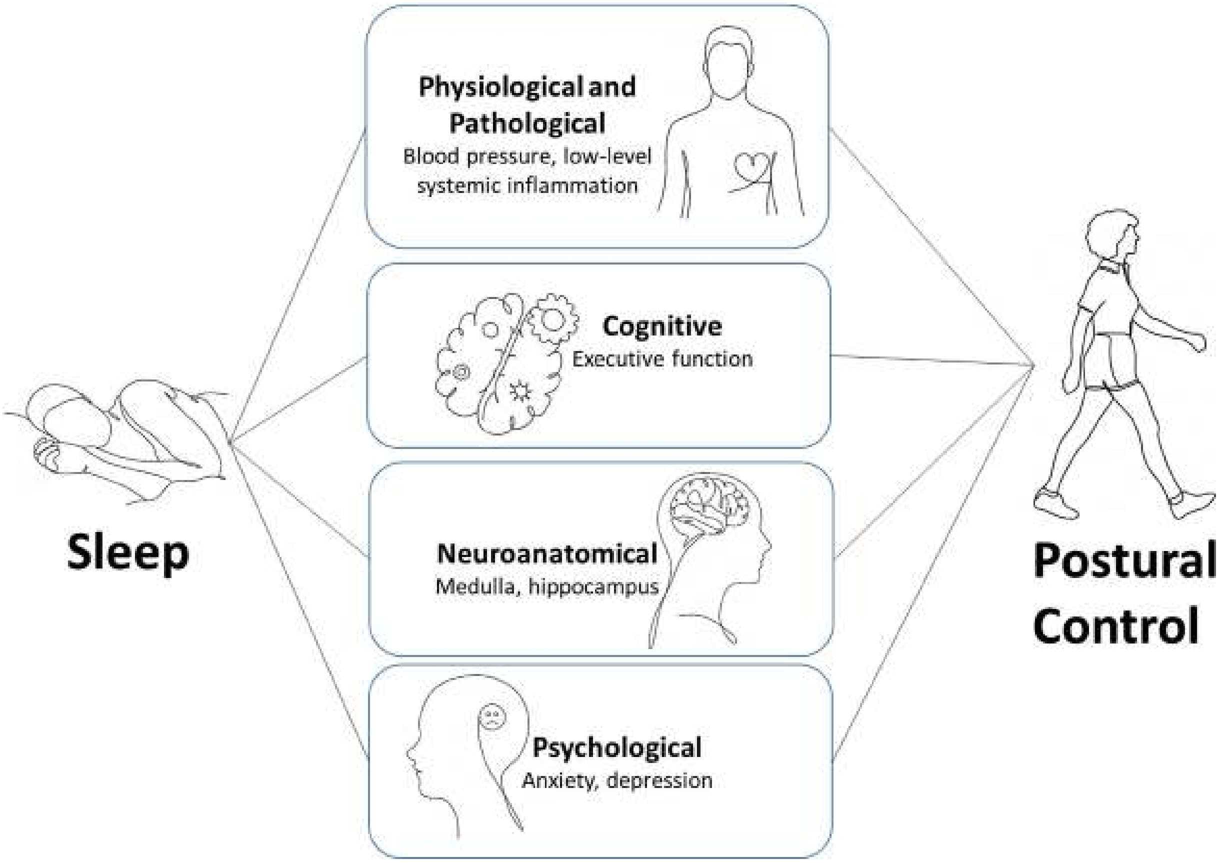

Fig. 3. Prospective mechanisms for the association between sleep characteristics and postural control.

studies evaluated gait and balance under single-task conditions. Nevertheless, tests of gait variability and gait speed, as well as balance tests during dual tasks, were overlooked although they are considered an early marker for future falls [5,36,48,69]. None of the studies controlled for the use of hypnotic medications in their analysis. Indeed, until recently, it had been widely accepted that sleep medication use in older adults was a major risk factor for falls [83], although findings were inconsistent [84]. Newer findings suggest that sleep disturbance itself and not only sleep medications increases the risk for falls in older adults [85].

Clinical implications

Based on the current review, a relationship between postural control and sleep in adults is suggested, resulting in possible implications for diagnosis and management of both behaviors. In light of the crucial role that sleep plays in adult health, early detection of sleep and gait abnormalities is vital. Most falls result from a reduction in postural control, especially during walking (i.e., mobility limitations) [5]. Therefore, it is possible that improving sleep quality and postural control may also be beneficial for reducing falls. However, the exact influence of improving or rehabilitating one modality, or the other, as well as the relationship between them, has not been fully explored.

Conclusions

The current review provides evidence linking sleep characteristics to reduced postural control in adults. However, most studies were cross-sectional, which limited the ability of the researchers to infer causality. The identification of the mechanisms underlying this relationship has yet to be elucidated. The suggested physiological, anatomical, cognitive, and psychological mechanisms are capable of existing independently but are more likely to interact with one another.

The studies included in this review point to critical directions for future research, which will most likely contribute to our growing theoretical understanding of the nature of the relationship between sleep and postural control. Future studies should include high-level randomized clinical trials with objective measures of both sleep characteristics and postural control. Standardization and optimization of measurements may enable researchers to compare and combine studies and arrive at more generalizable and conclusive insights. Another interesting direction for future research would be to examine the development of sleep and gait abnormalities simultaneously throughout the individual's lifespan and to describe the pattern and development of their relationship. Such an investigation would enable the design of effective early interventions which are necessary in order to address these public health priority conditions.

Although findings across different study designs consistently demonstrate a link between sleep quality and postural control, and, specifically, gait quality, significant gaps in knowledge and mechanisms remain: 1) inconsistent quantification of postural control, 2) a lack of studies on sleep architecture and gait in healthy adults, 3) a shortage of longitudinal studies, and 4) the lack of a comprehensive model addressing factors underlying the sleep—gait relationship.

Practice points

1. More favorable objective sleep characteristics are associated with better objective postural control parameters.
2. Physiological, neuroanatomical, cognitive, and psychological mechanisms may explain the association between sleep characteristics and postural control.
3. The suggested relationship between postural control and sleep in adults may enable early detection of poor sleep quality and higher risk of falls, since most falls result from a reduction in postural control.

Research agenda

1. The effects of improving or rehabilitating one modality with respect to the other (i.e., sleep quality with respect to postural control and vice versa) have not been fully explored.
2. Most falls result from a reduction in postural control. Future studies should explore whether improvement of sleep quality and postural control may be beneficial for reducing falls.
3. Future studies should include high-level randomized clinical trials with objective measures of both sleep characteristics and postural control in order to increase our understanding of the nature of the relationship between them.
4. Simultaneously examining the development of sleep and gait abnormalities throughout the individual's lifespan and describing the pattern and progress of their relationship should be studied.
5. Identifying more nuanced associations between specific sleep and specific gait measures is necessary in order to recommend and prioritize informed intervention.

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Conflicts of interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smrv.2022.101633.

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