# Tracking cognitive function with wearables during telerehabilitation: can nighttime sleep regularity and respiratory measures be used as sex-specific digital endpoints?

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## *Abstract*

While changes in brain structure are common across the lifespan, it is difficult to differentiate benign variations from early disease pathogenesis, especially in patients participating in home-based rehabilitation. Cognitive decline is frequently linked with normative aging, but its early detection can facilitate preventative interventions, particularly in patients at high risk of cognitive impairment, like older women. Although women have fewer modifiable risk factors for dementia than men, wearables have the potential to establish new digital endpoints that facilitate the management and/or prevention of abnormal brain aging. Sleep, which is necessary for maintaining overall brain health, is one behavior tracked via wearables, for which an ever-growing body of pilot and validation phase studies exists; yet, endpoints defining optimal sleep are not one-size-fits-all, as individual differences in chronotype necessitate new strategies to personalize care. Though sex-based differences in circadian rhythm are well established, little is understood about which sleep features and thresholds are uniquely important to cognitive function in women. In this editorial, we discuss recent findings on the use of wearables to track sleep and cognitive health in women, while highlighting the challenges and opportunities for implementing meaningful digital endpoints for future work.

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# Original Manuscript

## Editorial

# Tracking cognitive function with wearables during telerehabilitation: can nighttime sleep regularity and respiratory measures be used as sex-specific digital endpoints?

## Abstract

While changes in brain structure are common across the lifespan, it is difficult to differentiate benign variations from early disease pathogenesis, especially in patients participating in home-based rehabilitation. Cognitive decline is frequently linked with normative aging, but its early detection can facilitate preventative interventions, particularly in patients at high risk of cognitive impairment, like older women. Although women have fewer modifiable risk factors for dementia than men, wearables have the potential to establish new digital endpoints that facilitate the management and/or prevention of abnormal brain aging. Sleep, which is necessary for maintaining overall brain health, is one behavior tracked via wearables, for which an ever-growing body of pilot and validation phase studies exists; yet, endpoints defining optimal sleep are not one-size-fits-all, as individual differences in chronotype necessitate new strategies to personalize care. Though sex-based differences in circadian rhythm are well established, little is understood about which sleep features and thresholds are uniquely important to cognitive function in women. In this editorial, we discuss recent findings on the use of wearables to track sleep and cognitive health in women, while highlighting the challenges and opportunities for implementing meaningful digital endpoints in future telerehabilitation programs.

**Keywords:** Sleep; wearables; digital health; women's health; cardiopulmonary health; cognition; dementia; telerehabilitation

With the rapid adoption of wearables in home-based rehabilitation, also known as telerehabilitation, programs, there is an emerging need to establish clinically meaningful digital endpoints. For patients with neurologic or functional deficits, like those with hospitalizations for stroke or chronic obstructive pulmonary disease (COPD), who participate in telerehabilitation programs, existing research has shown the effectiveness of interventions to monitor and track exercise through digital endpoints, like steps per day derived from wearable

pedometers [1,2]. Although the technology to personalize exercise recommendations for these patients exists, barriers to participation in home-based rehabilitation programs remain, including high drop-out rates [3,4]. To better understand patient behavior, researchers in the wearable device space should investigate the link between sleep measures and changes in mood and cognition, particularly in women, who are at a higher risk of cognitive decline, including Alzheimer's disease and dementia [5]. This is exceptionally helpful for clinicians overseeing rehabilitation cohorts, wherein deficits might emerge over time and not be accurately captured in surveys due to participant self-report bias or cognitive decline [6]. Rather than provide a comprehensive review of wearables in the telerehabilitation space, the aim of this editorial is to emphasize specific aspects of recent wearables research that may be translated into telerehabilitation and other home-based monitoring programs, helping investigators formulate novel digital endpoints related to sleep.

A growing number of recent publications highlight potential use cases for sleep digital endpoints relevant to telerehabilitation. In one such article, Swanson et al. used a wearable to examine relationships between cognitive performance and sleep features in older adult women [7]. Their cross-sectional analysis involved a subsample of participants enrolled in the Study of Women's Health Across the Nation (SWAN) who completed an at-home wearables study during follow-up visit 15 in 2015-16 (n = 1,177; mean age = 65) [8]. Participants were instructed to wear an Actiwatch-2 (AW-2; Philips Respironics, Bend, OR) on their non-dominant wrist for 7 days to record critical sleep features: timing (average midpoint from sleep onset to wake) and regularity (midpoint standard deviation). Cognitive performance was measured via motor, visual, learning, and memory questions in these validated assessments: the East Boston Memory Test, Symbol Digit Modalities Test, and Digit Span Backwards exam.

Metabolic burden in participants was high, with 63.5% hypertensive and 17.6% diabetic. The majority of participants had two or more comorbidities (54.9%) and a waist circumference indicating central obesity (59.9%). Importantly, at baseline, the average participant was at intermediate risk for a heart attack or stroke within the decade (mean Atherosclerotic Cardiovascular Disease risk score (ASCVD) = 9%). The authors adjusted linear regression models for relevant covariates to explore associations between sleep and cognition. Importantly, irregular sleep timing was linked with improved working memory ($\beta$ = 0.50; p = 0.004) and worse delayed ($\beta$ = -0.36; p= 0.006) and immediate verbal memory ($\beta$ = -0.29; p = 0.020). While late sleep timing, defined as a midpoint after 4:00 AM, was associated with decreased processing speed ($\beta$ = -1.80; p = 0.008), early sleep timing (a midpoint before 2:00 AM) was associated with worse delayed verbal memory ($\beta$ = -0.37; p = 0.047). Notably, a sensitivity analysis revealed that the magnitude of the effect of sleep irregularity on working memory was greater in hypertensive participants (interaction $\beta$=--3.35, p=.039). In addition, as the magnitude of ASCVD risk increased, so did the strength of the association between early sleep timing and delayed verbal memory (interaction $\beta$=-8.83, p=.026), drawing attention to the impact of cardiovascular disease (CVD) risk factors on sleep and cognitive decline in older women.

Swanson et al.'s study builds upon current literature specific to aging by highlighting relevant modifiable sleep measures for endpoint analysis and considering a range of CVD risk factors [7]. Only ASCVD and hypertension revealed significant interactions with sleep-cognition associations in this study, both of which are linked with increasing white matter hyperintensity (WMH) volume in middle-age [7,9]. It is plausible that the lack of associations for some factors, such as diabetes which is a known risk factor for dementia, represents an age-related baseline

for otherwise “healthy” women. The circadian clock controls blood pressure and the hypothalamic-pituitary-adrenal (HPA) axis, which regulates blood glucose levels. As age and dementia risk increase, the circadian clock weakens [10]. After hypertension emerges, vascular changes influence the development of WMHs, amyloid-β deposits, and cerebrovascular disease (CeVD)-related atrophy, all contributing to cognitive decline [11]. Downstream these changes, HPA dysfunction may, in some cases, lead to diabetes or central obesity via insulin resistance, which then modulates the association between some sleep factors and cognition [12, 13].

Despite the growing adoption of wearables for sleep monitoring, like the AW-2 used in Swanson et al.’s study, these studies reflect significant heterogeneity with regard to methodologies and primary endpoints, leaving researchers with no clear starting point for variables uniquely important to women’s health [14-16]. Additionally, deriving actionable information for women’s health from objective sleep data remains a challenge for multiple reasons. First, the proportion of participants in sleep studies with wearables has been overwhelmingly male (61%) [17]. This is complicated by the fact that individual sleep chronotypes change across the lifespan, necessitating robust methods that account for within-person variability and establish patient-specific baseline measures, rather than rely on population-based thresholds [18]. Such an approach is appropriate for dynamic monitoring in real-world settings, automatically accounting for variability in environment.

Using the SleepImage ring, Ding et al.’s study (n = 62; 67.7% women; mean age = 74; 80.5% cognitively intact) extended the results of Swanson et al’s work, finding that older adult participants without cognitive impairment exhibited more consistent respiratory markers during sleep [19]. For instance, mean $SpO_2$ (intraclass correlation coefficient (ICC): 0.62-0.85) and minimum $SpO_2$ (ICC: 0.60-0.85) were found to be stable over 3 nights in participants without cognitive impairment. Further demonstrating that sex-specific sleep patterns can be captured by wearables, women exhibited more stable heart rate while men exhibited more stable sleep duration. Considering these findings, researchers should explore sleep as a multidimensional health metric, looking at sleep regularity, pulmonary measures, and cardiovascular measures when selecting digital endpoints to assess. Although this study is limited by its small sample size recruited from Boston University Alzheimer’s Disease Research Center, which annually administers the Montreal Cognitive Assessment to participants to adjudicate cognitive status, it is plausible that digital endpoints to track sleep health remotely – and their associated clinically meaningful improvement thresholds - will be unique for men and women [20].

The recent results from Nikbakhtian et al also highlight the importance of considering sex-specific CVD markers when tracking sleep health remotely [21]. They investigated the role of sleep onset in CVD development using a large population cohort study, the UK Biobank (n = 103,712; 57.9% female; aged 43-79), which used 1 week of wearable accelerometer data to capture sleep measures. In contrast to male participants, who mostly experienced sleep onset later in the night, women primarily experienced sleep onset between 10:00 and 11:00 PM, the sleep onset time associated with the lowest incidence of CVD. Adjusting for CVD risk factors, sleep regularity, and sleep duration, the associations between sleep onset time and CVD risk persisted, yielding Cox proportional hazards ratios of 1.25 (1.02-1.52; $p$ = 0.03), 1.24 (1.10-1.39; $p$ < 0.005), and 1.12 (1.01-1.25; $p$ = 0.04) for sleep onset times of ≥ 12:00 AM, < 10:00 PM ,and 11:00-11:59 PM. Notably, in sex-specific models, the associations between sleep onset times of < 10:00 PM (1.63; 1.20-2.21; $p$ <0.005) and ≥ 12:00 AM (1.63; 1.20-2.21; $p$ < 0.005) were more pronounced in females. In contrast, only the association between sleep onset time

of <10:00 PM and CVD was significant in males. Beyond Ding et al's finding that breathing measures may inform useful digital endpoints of cognitive health, these results highlight the need for researchers to pay closer attention to CVD-related risk factors when interpreting sleep data, particularly in women.

Combined, these studies introduce innovative perspectives for interpreting sleep data from wearables; however, two current bottlenecks to developing clinically meaningful endpoints for wearables remain: (1) the lack of standardized and validated algorithms for data from different devices and (2) the lack of longitudinal sleep data captured beyond one-week periods [22-24]. Accurate longitudinal monitoring is especially relevant when conducting aging research in dementia, when prevalence rates change drastically over short epochs. For instance, dementia prevalence is <1% in adults under the age of 65 [25]. After 65, that number shifts to between 3-11% and climbs to over 30% in adults over 85 [25]. Additionally, studies with less than 1 week of data should be cautiously interpreted, as the limited datasets may not be representative of an individual's sleep routine.

Multiple aspects of these methodologies employed in these studies may have implications for the future of sleep monitoring research in detecting cognitive impairment and dementia in women. First, establishing specific sensor-based measures that are clinically useful for identifying cognitive changes in women is crucial to developing digital endpoints for tracking brain health across the lifespan. By identifying correlates between sleep measures and cognitive survey scores, future researchers can develop predictive models for participants who may miss survey response dates. Next, the influence of cardiovascular and pulmonary risk factors on the association between sleep and cognition underscores the importance of tracking comorbid burden to understand brain health [26]. Lastly, these remote monitoring approaches could reach women in rural areas who might otherwise be unable to participate in in-clinic monitoring, thereby addressing barrier and compliance issues by introducing enhanced flexibility in rehabilitation care for patients [27]. Also, considering that women's risk of CVD increases after menopause, these results may not generalize well to women of reproductive age [28].

Ultimately, these recent studies offer proof-of-concept evidence for unique sleep measures as potentially meaningful markers of cognitive health in women. The contributions of sleep and nighttime pulmonary measures to the development of cognitive decline in women should be explored further using wearables and adjusting for cardiovascular factors across middle- and late-adulthood. Considering that women are at a higher risk of dementia than men, these studies offer a significant step toward developing meaningful endpoints for longitudinal sleep studies tracking brain health and showcase how researchers might interpret real-world sleep data in the context of cardiovascular and pulmonary health in adult female cohorts.

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## Conflicts of Interest

SJZ is an associate editor of *JMIR Neurotechnology* at the time of this publication. EF and LJF have no conflicts of interest to report.

## Abbreviations

CVD = cardiovascular disease
COPD = chronic obstructive pulmonary disease
WMH = white matter hyperintensities
HPA = hypothalamic-pituitary-adrenal

## References


1. Miller A, Collier Z, Reisman DS. Beyond steps per day: other measures of real-world walking after stroke related to cardiovascular risk. *J Neuroeng Rehabil*. 2022;19(1):111. Published 2022 Oct 14. doi:10.1186/s12984-022-01091-7
2. Armstrong M, Winnard A, Chynkiamis N, Boyle S, Burtin C, Vogiatzis I. Use of pedometers as a tool to promote daily physical activity levels in patients with COPD: a systematic review and meta-analysis. *Eur Respir Rev*. 2019;28(154):190039. Published 2019 Nov 13. doi:10.1183/16000617.0039-2019
3. Brugin E, Palermi S, Pescatore V, et al. Effects of an exercise-based rehabilitation program in patients with minor ischemic non-disabling stroke or transient ischemic attack. *J Sports Med Phys Fitness*. 2025;65(7):932-938. doi:10.23736/S0022-4707.25.16408-6
4. Alhasani R, Janaudis Ferreira T, Marie-France Valois, Singh D, Ahmed S. Enrollment and dropout rates of individuals with chronic obstructive pulmonary disease approached for telehealth interventions: A systematic review and meta-regression analysis. *Heliyon*. 2023;10(1):e23776. Published 2023 Dec 22. doi:10.1016/j.heliyon.2023.e23776
5. Udeh-Momoh C, Watermeyer T; Female Brain Health and Endocrine Research (FEMBER) consortium. Female specific risk factors for the development of Alzheimer's disease neuropathology and cognitive impairment: Call for a precision medicine approach. *Ageing Res Rev*. 2021;71:101459. doi:10.1016/j.arr.2021.101459
6. Van Der Donckt J, Vandenbussche N, Van Der Donckt J, et al. Mitigating data quality challenges in ambulatory wrist-worn wearable monitoring through analytical and practical approaches. *Sci Rep*. 2024;14(1):17545. Published 2024 Jul 30. doi:10.1038/s41598-024-67767-3
7. Swanson LM, Hood MM, Thurston RC, et al. Sleep Timing, Sleep Timing Regularity, and Cognitive Performance in Women Entering Late Adulthood: The Study of Women's Health Across the Nation (SWAN). *Sleep*. Published online February 16, 2025. doi:10.1093/sleep/zsaf041
8. Santoro N, Sutton-Tyrrell K. The SWAN song: Study of Women's Health Across the Nation's recurring themes. *Obstet Gynecol Clin North Am*. 2011;38(3):417-423. doi:10.1016/j.ogc.2011.05.001
9. d'Arbeloff T, Elliott ML, Knodt AR, et al. White matter hyperintensities are common in midlife and already associated with cognitive decline. *Brain Commun*. 2019;1(1):fcz041. doi:10.1093/braincomms/fcz041
10. Hood S, Amir S. The aging clock: circadian rhythms and later life. *J Clin Invest*. 2017;127(2):437-446. doi:10.1172/JCI90328

11. Pålhaugen L, Sudre CH, Tecelao S, et al. Brain amyloid and vascular risk are related to distinct white matter hyperintensity patterns. *J Cereb Blood Flow Metab*. 2021;41(5):1162-1174. doi:10.1177/0271678X20957604
12. Barone MT, Menna-Barreto L. Diabetes and sleep: a complex cause-and-effect relationship. *Diabetes Res Clin Pract*. 2011;91(2):129-137. doi:10.1016/j.diabres.2010.07.011
13. Wingenfeld K, Wolf OT. HPA axis alterations in mental disorders: impact on memory and its relevance for therapeutic interventions. *CNS Neurosci Ther*. 2011;17(6):714-722. doi:10.1111/j.1755-5949.2010.00207.x
14. Berryhill S, Morton CJ, Dean A, et al. Effect of wearables on sleep in healthy individuals: a randomized crossover trial and validation study. *J Clin Sleep Med*. 2020;16(5):775-783.
15. Wallace ML, Lee S, Stone KL, et al. Actigraphy-derived sleep health profiles and mortality in older men and women. *Sleep*. 2022;45(4):zsac015. doi:10.1093/sleep/zsac015
16. Anchouche K, Elharram M, Oulousian E, et al. Use of Actigraphy (Wearable Digital Sensors to Monitor Activity) in Heart Failure Randomized Clinical Trials: A Scoping Review. *Can J Cardiol*. 2021;37(9):1438-1449. doi:10.1016/j.cjca.2021.07.001
17. Nebel RA, Aggarwal NT, Barnes LL, et al. Understanding the impact of sex and gender in Alzheimer's disease: A call to action. *Alzheimers Dement*. 2018;14(9):1171-1183. doi:10.1016/j.jalz.2018.04.008
18. Foy BH, Petherbridge R, Roth MT, et al. Haematological setpoints are a stable and patient-specific deep phenotype. *Nature*. 2025;637(8045):430-438. doi:10.1038/s41586-024-08264-5
19. Ding H, Madan S, Searls E, et al. Exploring nightly variability and clinical influences on sleep measures: insights from a digital brain health platform. *Sleep Med*. 2025;131:106532. doi:10.1016/j.sleep.2025.106532
20. Besser L, Kukull W, Knopman DS, et al. Version 3 of the National Alzheimer's Coordinating Center's Uniform Data Set. *Alzheimer Dis Assoc Disord*. 2018;32(4):351-358. doi:10.1097/WAD.0000000000000279
21. Nikbakhtian S, Reed AB, Obika BD, et al. Accelerometer-derived sleep onset timing and cardiovascular disease incidence: a UK Biobank cohort study. *Eur Heart J Digit Health*. 2021;2(4):658-666. Published 2021 Nov 9. doi:10.1093/ehjdh/ztab088
22. Druiven SJM, Riese H, Kamphuis J, et al. Chronotype changes with age; seven-year follow-up from the Netherlands study of depression and anxiety cohort. *J Affect Disord*. 2021;295:1118-1121. doi:10.1016/j.jad.2021.08.095
23. Carpi M, Fernandes M, Mercuri NB, Liguori C. Sleep Biomarkers for Predicting Cognitive Decline and Alzheimer's Disease: A Systematic Review of Longitudinal Studies. *J Alzheimers Dis*. 2024;97(1):121-143. doi:10.3233/JAD-230933
24. Evans MA, Buysse DJ, Marsland AL, et al. Meta-analysis of age and actigraphy-assessed sleep characteristics across the lifespan. *Sleep*. 2021;44(9):zsab088. doi:10.1093/sleep/zsab088
25. 2023 Alzheimer's disease facts and figures. *Alzheimers Dement*. 2023;19(4):1598-1695. doi:10.1002/alz.13016
26. Zawada SJ, Ganjizadeh A, Conte GM, Demaerschalk BM, Erickson BJ. Accelerometer-Measured Behavior Patterns in Incident Cerebrovascular Disease: Insights for Preventative Monitoring From the UK Biobank. *J Am Heart Assoc*. 2024;13(11):e032965. doi:10.1161/JAHA.123.032965
27. Fischer MJ, Scharloo M, Abbink JJ, et al. Participation and drop-out in pulmonary rehabilitation: a qualitative analysis of the patient's perspective. *Clin Rehabil*. 2007;21(3):212-221. doi:10.1177/0269215506070783

28. Wang W, Qian J, Cho Y, Guo Z, Yu X, Li J. Trajectories of sleep health during the perinatal period: a systematic review and meta-analysis. *Sleep*. 2025; 48, (7):zsaf095, https://doi.org/10.1093/sleep/zsaf095