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Bidirectional association between physical activity and sleep in healthy Japanese super-seniors: the Japan Healthy Aging Study (J-HAS)

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To address the challenges of an ageing population, it is important to promote health by identifying factors for healthy ageing. The aim of this study was to investigate the bidirectional association between physical activity (PA) and sleep in healthy Japanese super-seniors over the age of 80. For approximately 1 year, 124 participants wore wearable devices and answered daily lifestyle questionnaires. PA was defined as daily step count and minutes in light activity. Sleep was measured using 24-h total sleep time (TST) and time in bed (TIB). Associations were analysed bidirectionally using multilevel mixed-effects linear regression models. Fully adjusted models revealed significant and inverse associations between sleep and PA from the same 24-h period. Similarly, the results were significant and inverse with PA from the day before as exposure and the next 24-h sleep measures as outcome. The between-individual associations between sleep measures and PA from the subsequent day were significant and inverse. However, there was a positive within-individual association between TST and step count from the subsequent day. The study suggests that associations between PA and sleep in super-seniors differ from patterns previously described in younger adults. Very old individuals with increasing 24-h total sleep time may compensate for a lower step count on one day by increasing their step count the following day.

The world's elderly population is currently growing at a rapid rate. Both developed and developing countries are experiencing a sustained demographic shift toward older ages, a process known as population ageing[1]. Currently, 8.5% of the global population is 65 years and older, and this group is expected to compose one-fifth of the global population by 2050[2]. While the demographic shift towards older ages reflects great achievements in modern medicine, it also brings significant challenges. Studies from several countries, including Japan, Sweden, and 12 OECD countries, observe increasing prevalence of chronic conditions such as heart disease, diabetes and arthritis among the elderly[3–5]. Thus, disease structures change in conjunction with demographic change, which consequently affects the demand for medical care.

In order to harness the positive opportunities and mitigate the challenges that arise with an ageing population, policymakers and professionals need to develop strategies that are tailored to the needs of the elderly. One approach is to identify factors that promote health and protect against age-related diseases. Previous studies have shown that certain behaviours, such as physical activity (PA) and healthy sleeping patterns, significantly reduce all-cause mortality risks[6]. Extensive research suggests that PA, together with proper nutrition, avoidance of smoking and engagement in social activities, lead to healthier longevity and higher quality of life (QoL) among older adults[7,8].

The relationship between different domains of sleep and healthy ageing, however, is not as clear. Older people tend to have more difficulty

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initiating and maintaining sleep due to frequent arousals and more time spent in lighter stages of sleep. This results in less efficient sleep, and the sleep schedule is generally shifted forward, increasing early-morning awakenings[9]. Previous studies suggest a U-shaped relationship between sleep duration and QoL, where both shorter (≤5 h) and prolonged (≥9 h) sleep duration are associated with poor health and frailty among elderly[10]. Although older age does not necessarily equate with poor sleep, current research demonstrates that sleeping well improves overall health.

In addition to the many benefits of regular exercise, evidence suggests that PA positively affects sleep by enhancing relaxation and energy expenditure in older adults[11,12]. Hence, PA may be utilised as an accessible and non-pharmaceutical treatment option to improve sleep. Current guidelines underscore the importance of exercise for good health, but recommendations for sleep have long been debated, and the opposite directional relationship has mostly been overlooked[13]. This highlights the need for further research as it enables the development of health recommendations that could promote well-being in the elderly population. This paper therefore aims to evaluate the bidirectional between- and within-individual associations between objective measures of sleep and physical activity in a sample of healthy Japanese super-seniors over 80 years old.

Results

Participant characteristics

A total of 124 participants were included in the analyses, and the characteristics are presented in Table 1. Mean (± standard deviation [SD]) age was 85 (±4.5) years, and 50.8% of participants were men. The sample had an average of 6400 (±3300) daily steps and 166.3 (±61.5) minutes in light physical activity. The participants had an average 24-h sleep duration of 384.8 (±61.6) minutes (6.4 h) and spent 441.9 (±69.9) minutes (7.4 h) in bed. The mean sleep record was 1.3 (±0.3) occasions, and the median (±interquartile range [IQR]) score for sleep quality was 1.5 (±1.0). On average, the participants consumed 1–2 cups of caffeine-containing products daily. 46.8% of the participants had hypertension, and the average BMI was 22.7 (±3.1) kg/m^2. The majority, 83.1%, did not receive any care service, and the average grip strength was 24.3 (±7.8) kg.

Table 1 | Participants' characteristics (*n* = 124)

Variables	Mean (SD) or % (*n*)	Median (IQR)
Age	85.4 (4.5)	
Sex, male	50.8% (63)	
Daily steps (per thousand)	6.4 (3.3)	
Lightly active (minutes)	166.3 (61.5)	
Total sleep time (minutes)	384.8 (61.6)	
Time in bed (minutes)	441.9 (69.9)	
Sleep records	1.3 (0.3)	
Sleep quality		1.5 (1.0)
Caffeine consumption[a]		2 (1)
Hypertension	46.8% (58)	
BMI	22.7 (3.1)	
Care level		
Care-level 0	83.1% (103)	
Care-level 0–Care-support level 2	8.9% (11)	
Care-support level 2–Care-need level 1	7.3% (9)	
>Care-need level 1	0.8% (1)	
Grip strength (kg)	24.3 (7.8)	

SD standard deviation, *IQR* interquartile range, *BMI* body mass index. [a] Caffeine consumption is categorised into three categories, category 1 indicates 0 cups, category 2 indicates 1 to 2 cups and category 3 indicates 3 or more cups per day.

Physical activity and the association with sleep parameters

Association between step count from the day before and TST. Within- and between-individual associations between PA the day before and TST the day after are presented in Table 2. As a between-individual association, more step counts on the day before were significantly and inversely associated with sleep duration (Model 1: −5 min; 95% CI: −8.3, −1.7). The association was slightly attenuated in Model 2 (−3.6 min; 95% CI: −7.0, −0.2) and strengthened in Model 3 (−4.5 min; 95% CI −7.9, −1.1). The associations remained inverse and significant throughout the inclusion of all covariates (Model 4: −4.4 min; 95% CI: −7.8, −1.0), as presented in Fig. 1a. No significant within-individual association was observed.

Association between lightly active minutes from the day before and TST. The within-individual association between lightly active minutes and TST was significant and inverse (Model 1: -5.9×10^{-2} min; 95% CI: -10×10^{-2}, -1×10^{-2}) and attenuated in Model 2 (-5.0×10^{-2} min; 95% CI: -8.8×10^{-2}, -1.3×10^{-2}). The coefficient strengthened slightly in Model 3 (-5.1×10^{-2} min; 95% CI: -8.8×10^{-2}, -1.3×10^{-2}) but was later attenuated in Model 4 (-5.0×10^{-2} min; 95% CI: -8.7×10^{-2}, -1.3×10^{-2}). Similarly, the between-individual association between lightly active minutes and TST was significant and inverse in Model 1 (-35×10^{-2} min; 95% CI: -51.5×10^{-2}, -18.7×10^{-2}), attenuated in Model 2 (-24.3×10^{-2} min; 95% CI: -41.8×10^{-2}, -6.9×10^{-2}) and strengthened in Model 3 (-27.4×10^{-2} min; 95% CI: -44.4×10^{-2}, -10.3×10^{-2}). This association remained significant throughout the last model (Model 4: -27.0×10^{-2} min; 95% CI: -43.9×10^{-2}, -10.1×10^{-2}), as illustrated in Fig. 1b.

Association between step count from the day before and TIB. When comparing step count with TIB during the next 24-h, as presented in Table 3 and Fig. 1c, no statistically significant within-individual association was observed. A significant and inverse between-individual association was observed in Model 1 (−5.1 min; 95% CI: −8.8, −1.4), but the significance was lost in Model 2 (−3.6 min; 95% CI: −7.5, 0.2). The association strengthened in Model 3 (−4.6 min; 95% CI: −8.5, −0.8), and remained significant in Model 4 (−4.6 min; 95% CI: −8.4, −0.8).

Association between lightly active minutes from the day before and TIB. With lightly active minutes as the exposure, all models showed a sustained and significant inverse association with TIB. The within-individual association in Model 1 (-7.69×10^{-2} min; 95% CI: -12.7×10^{-2}, -2.6×10^{-2}) was attenuated in Model 2 (-6.78×10^{-2} min; 95% CI: -11.1×10^{-2}, -2.5×10^{-2}). The association was marginally strengthened in Model 3 (-6.81×10^{-2} min; 95% CI: -11.1×10^{-2}, -2.5×10^{-2}) and slightly attenuated in Model 4 (-6.78×10^{-2} min; 95% CI: -11.0×10^{-2}, -2.6×10^{-2}), presented in Fig. 1d. The between-individual association showed a similar change where the coefficient attenuated from Model 1 (-35.6×10^{-2} min; 95% CI: -54.4×10^{-2}, -16.8×10^{-2}) to Model 2 (-24.4×10^{-2} min; 95% CI: -44.4×10^{-2}, -4.5×10^{-2}), strengthened slightly in Model 3 (-28.9×10^{-2} min; 95% CI: -47.6×10^{-2}, -8.5×10^{-2}) and attenuated in Model 4 (-27.5×10^{-2} min; 95% CI: -46.8×10^{-2}, -8.3×10^{-2}).

Sleep parameters and the association with physical activity

Association between sleep parameters and physical activity measures from the same day. As presented in Supplementary Tables 1 and 2 and Supplementary Fig. 1, the between- and within-individual associations between sleep parameters (TST and TIB) and PA measures from the same day (step count and minutes in light activity, respectively) were significant and inverse. A detailed description of these results can be found in Supplementary Notes 1–4.

Association between TST and step count the following day. Table 4 and Fig. 2a presents a positive within-individual association between TST

Table 2 | Coefficients and 95% confidence intervals for the association between physical activity measures from the day before and total sleep time ($n = 124$)

Total sleep time (minutes)	Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Steps yesterday (per thousand)								
Within-individual effects	-18.9×10^{-2}	-74.2×10^{-2}, -36.4×10^{-2}	-20.7×10^{-2}	-70.1×10^{-2}, 28.0×10^{-2}	-21.8×10^{-2}	-70.6×10^{-2}, 3.9	-20.6×10^{-2}	-68.9×10^{-2}, -27.7×10^{-2}
Between-individual effects	**−5.03****	−8.31, −1.74	**−3.61***	−6.99, −0.22	**−4.47****	−7.88, −1.06	**−4.41****	−7.77, −1.04
Intercept	**601*****	390, 811	**598*****	367, 828	**417****	135, 699	**410****	132, 688
Lightly active (minutes)								
Within-individual effects	**-5.91×10^{-2}** **	-10.3×10^{-2}, -1.49×10^{-2}	**-5.03×10^{-2}** **	-8.78×10^{-2}, -1.29×10^{-2}	**-5.06×10^{-2}****	-8.80×10^{-2}, -1.32×10^{-2}	**-5.03×10^{-2}****	-8.73×10^{-2}, -1.35×10^{-2}
Between-individual effects	**-35.1×10^{-2}*****	-51.5×10^{-2}, -18.7×10^{-2}	**-24.3×10^{-2}****	-41.8×10^{-2}, -6.94×10^{-2}	**-27.4×10^{-2}****	-44.4×10^{-2}, -10.3×10^{-2}	**-27.0×10^{-2}****	-43.9×10^{-2}, -10.1×10^{-2}
Intercept	**639*****	439, 839	**638*****	411, 866	**472*****	191, 755	**467*****	188, 745

β coefficient, *CI* confidence interval. Bold values denote statistically significant results. [a]Adjusted for sex and age. [b]Additionally adjusted for sleep records, sleep quality and daily caffeine consumption. [c]Additionally adjusted for BMI, hypertension, grip strength and care level. [d]Additionally adjusted for total sleep time the day before. $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

and step count the following day. The association was marginally non-significant in Model 2 (0.54×10^{-3} steps per thousand; 95% CI: -4.05×10^{-7}, 1.08×10^{-3}) but became significant and slightly strengthened in Model 3 (0.55×10^{-3} steps per thousand; 95% CI: 4.96×10^{-6}, 1.08×10^{-3}). In Model 4, the association was strengthened further (0.77×10^{-3} steps per thousand; 95% CI: 0.26×10^{-3}, 1.27×10^{-3}). The between-individual association was significant and inverse in all models. The coefficient was gradually strengthened between Model 1 (-1.28×10^{-2} steps per thousand; 95% CI: -2.13×10^{-2}, -0.43×10^{-2}), Model 2 (-1.29×10^{-2} steps per thousand; 95% CI: -2.14×10^{-2}, -0.44×10^{-2}) and Model 3 (-1.48×10^{-2} steps per thousand; 95% CI: -2.30×10^{-2}, -0.65×10^{-2}). The association was attenuated but remained significant in Model 4 (-1.27×10^{-2} steps per thousand; 95% CI: -2.01×10^{-2}, -0.55×10^{-2}).

Association between TIB and step count on the following day. There was no significant within-individual association between TIB and step count the following day throughout all models, except in Model 4 which was significant and positive (0.50×10^{-3} steps per thousand; 95% CI: 0.06×10^{-3}, 0.09×10^{-3}), illustrated in Fig. 2b. The between-individual association was significant and inverse, and strengthened between Model 1 (-1.02×10^{-2} steps per thousand; 95% CI: -1.78×10^{-2}, -0.27×10^{-2}), Model 2 (-1.03×10^{-2} steps per thousand; 95% CI: -1.78×10^{-2}, -0.28×10^{-2}) and Model 3 (-1.22×10^{-2} steps per thousand; 95% CI: -1.95×10^{-2}, -0.48×10^{-2}), but attenuated in Model 4 (-1.05×10^{-2} steps per thousand; 95% CI: -1.70×10^{-2}, -0.40×10^{-2}).

Association between TST and lightly active minutes the following day. As presented in Table 5, the within-individual association between TST and lightly active minutes the following day was significant and inverse in Model 1 (-1.3×10^{-2} min; 95% CI: -2.6×10^{-2}, -0.1×10^{-2}) but not significant throughout the remaining models. The between-individual association was inverse and significant throughout all models. The coefficient was slightly attenuated between Model 1 (-36.0×10^{-2} min; 95% CI: -51.0×10^{-2}, -20.1×10^{-2}) and Model 2 (-35.7×10^{-2} min; 95% CI: -51.1×10^{-2}, -20.3×10^{-2}, strengthened in Model 3 (-39.8×10^{-2} min; 95% CI: -55.1×10^{-2}, -24.5×10^{-2}) and strongly attenuated in Model 4 (-26.8×10^{-2} min, 95% CI: -37.5×10^{-2}, -15.9×10^{-2}), presented in Fig. 2c.

Association between TIB and lightly active minutes on the following day. The within−individual association between TIB and lightly active minutes the following day was significant and inverse in Model 1 (-1.4×10^{-2} min; 95% CI: -2.5×10^{-2}, -0.4×10^{-2}), Model 2 (-1.2×10^{-2} min; 95% CI: -2.3×10^{-2}, -0.1×10^{-2}) and Model 3 (-1.2×10^{-2} min; 95% CI: -2.3×10^{-2}, -0.1×10^{-2}). There was no significant within−individual association in the fully adjusted model, illustrated in Fig. 2d. The between-individual association was significant and inverse throughout all models. The association was strengthened in Model 1 (-28.8×10^{-2} min; 95% CI: -42.5×10^{-2}, -15.1×10^{-2}), Model 2 (-28.9×10^{-2} min; 95% CI: -42.5×10^{-2}, -15.3×10^{-2}) and Model 3 (-32.8×10^{-2} min; 95% CI: -46.4×10^{-2}, -19.3×10^{-2}), but attenuated in Model 4 (-21.7×10^{-2} min; 95% CI: -31.4×10^{-2}, -12.1×10^{-2}).

Discussion

The objective of this study was to examine the bidirectional within- and between-individual associations of sleep parameters and physical activity measures in healthy super-seniors over 80 years old. When looking at the between-individual association between daily step count as exposure and sleep as outcome, the results suggest that an increase in step count is associated with shorter TST and TIB within the next 24-h period, respectively. This indicates that guidelines for the general public may show an association at a population level, but it might not indicate an association between PA and sleep on an individual level. Indeed, intra-individual factors such as physical fitness and habitual activity levels may influence sleep[14,15]. A

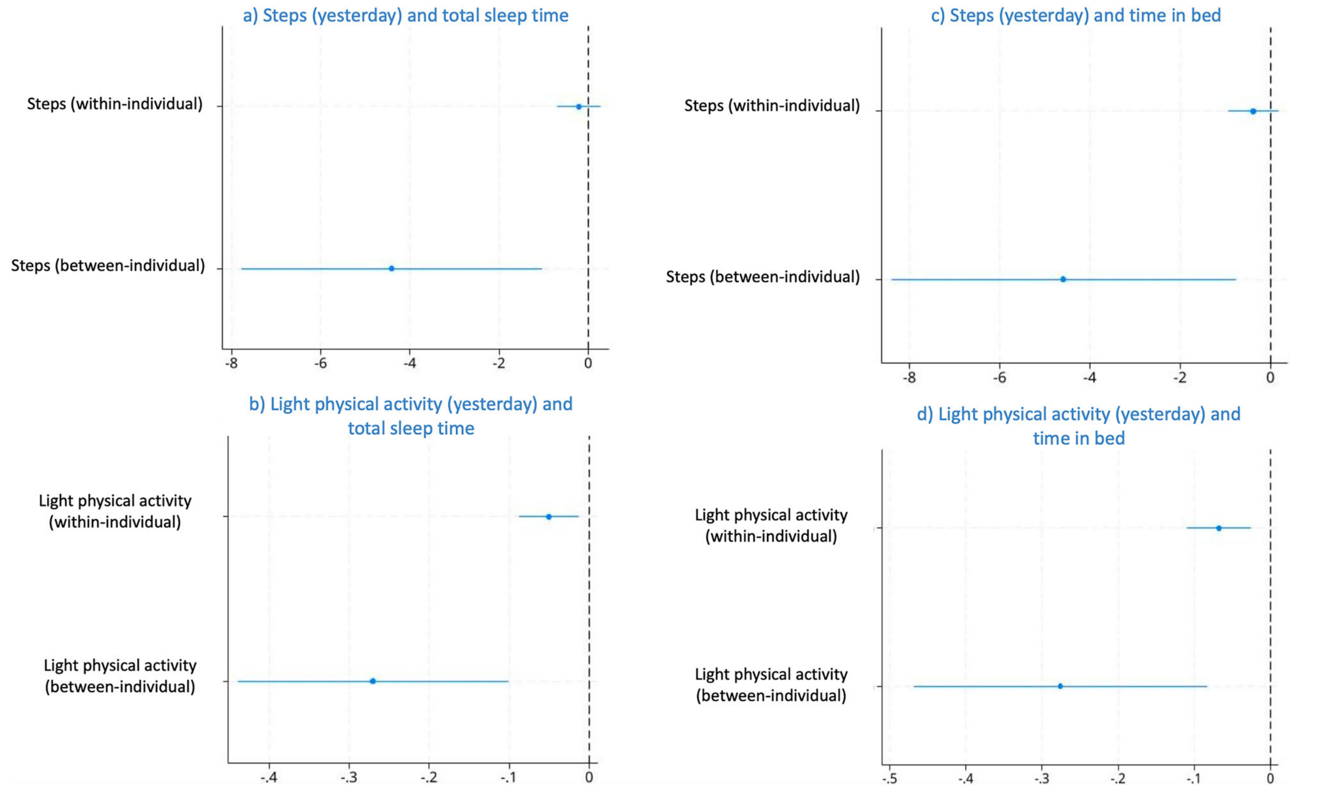

Fig. 1 | Coefficient plots for the associations between physical activity from the day before and sleep parameters. Coefficient plots with beta coefficients and confidence intervals for the association between **a** total steps yesterday and total sleep time, **b** minutes in light physical activity yesterday and total sleep time, **c** total steps yesterday and time in bed, and **d** minutes in light physical activity yesterday and time in bed. Note the differing scales of the *x*-axes. Full model details, including intercepts, are available in the corresponding tables (Tables 2 and 3).

nuanced approach is therefore warranted, as a one-size-fits-all strategy may not be effective for everyone in this particular age group.

Notably, albeit marginally non-significant, the between-individual association between step count and TIB weakened in Model 2, suggesting the presence of relevant confounders. With the inclusion of BMI, hypertension, grip strength and care-level as covariates in Model 3, the association became stronger and regained statistical significance. This change in direction could possibly be attributed to negative confounding. When the association is unadjusted, negative confounders may weaken or hide the true association between the variables, introducing underestimation bias[16]. In Model 4, adjustment for autocorrelation was considered, but based on these results, it did not affect the association noticeably. Instead, it seems that the covariates that were indicators of health and frailty had a more important role in the association between PA and sleep among very old adults. Indeed, prior studies have demonstrated that individuals with higher BMI have an increased risk of obstructive sleep apnoea and insomnia[17], which in turn has been associated with poor control of hypertension due to increased nocturnal activity of the sympathetic nervous system and the hypothalamic-pituitary-adrenal (HPA) axis[18]. Similarly, those with low grip strength and long-term care services tend to be more physically inactive and suffer from sleep disruptions[19,20]. Thus, further exploration is required to understand the interactions between health-related variables and the association between PA and sleep in this age group.

The results reveal a reciprocal inverse association between lightly active minutes and sleep parameters. For within-individual association analyses, each participant's daily deviation from the cluster mean was inversely associated with the next 24-h TST and TIB. Similarly, between-individual association analyses suggest that an increase in minutes spent in light activity was associated with shorter TST and TIB, respectively, the following day. These results differ from some studies conducted on younger populations, where a greater amount of PA was associated with longer sleep duration and better sleep quality[21,22]. Existing evidence suggests that changes in body temperature[23], cortisol secretion[24], and heart rate[25] may be potential mechanisms through which PA influences sleep. The findings in this study might differ due to several reasons related to these theories. It has been proposed that PA increases core body temperature and normally, the body temperature decreases before and during sleep, as a way to conserve energy and reduce metabolism[23]. This process is partially mediated by the autonomic nervous system (ANS), where reductions in the sympathetic tone induces heat loss, which in turn characterises sleep onset[26]. However, during the ageing process, an imbalance occurs in the ANS where the parasympathetic nervous system becomes diminished and the sympathetic nervous system becomes overactive[27]. The sympathetic hyperactivity among older adults may therefore affect thermoregulation and consequently sleep onset[26]. Similarly, cortisol secretion has been theorised to decrease in line with the preceding exercise-intensity[24]. Due to dysfunction in the HPA axis with advancing age, the reduction in cortisol levels may not be as extensive as seen in younger adults, resulting in a limitation of de-arousal, which is needed for good sleep[27,28]. Lastly, it has been proposed that regular exercise enhances vagal modulation and bradycardia, which improves sleep[25]. However, the same effect might not be applicable to older adults, as this group may have a different vagal response compared with younger adults[27]. Indeed, a few studies have seen a similar inverse association between PA and sleep parameters, where increased activity during the day was associated with shorter sleep duration and longer total wake time[13,29,30].

Shorter sleep duration does not necessarily equate with worse perceived sleep. Extensive research has shown that PA significantly improves sleep quality, sleep latency and sleep efficiency among older adults[31,32]. Furthermore, the Ministry of Health, Labour and Welfare in Japan recently updated their sleep guidelines, where it was advised for the elderly to sleep at

Table 3 | Coefficients and 95% confidence intervals for the association between physical activity measures from the day before and total time in bed ($n = 124$)

Total time in bed (minutes)	Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Steps yesterday (per thousand)								
Within-individual effects	-36.0×10^{-2}	-99.4×10^{-2}, 27.3×10^{-2}	-37.8×10^{-2}	-94.2×10^{-2}, 18.5×10^{-2}	-39.1×10^{-2}	-95.6×10^{-2}, 17.3×10^{-2}	-37.5×10^{-2}	-93.1×10^{-2}, 18.2×10^{-2}
Between-individual effects	**−5.11****	−8.84, −1.38	−3.62	−7.46, 0.222	**−4.65***	−8.53, −0.765	**−4.58***	−8.40, −0.756
Intercept	**660*****	421, 900	**659*****	396, 921	**462****	141, 782	**452****	137, 768
Lightly active (minutes)								
Within-individual effects	$\mathbf{-7.69 \times 10^{-2}}$**	-12.7×10^{-2}, -2.64×10^{-2}	$\mathbf{-6.78 \times 10^{-2}}$**	-11.1×10^{-2}, -2.48×10^{-2}	$\mathbf{-6.81 \times 10^{-2}}$**	-11.1×10^{-2}, -2.51×10^{-2}	$\mathbf{-6.78 \times 10^{-2}}$**	-11.0×10^{-2}, -2.55×10^{-2}
Between-individual effects	$\mathbf{-35.6 \times 10^{-2}}$***	-54.4×10^{-2}, -16.8×10^{-2}	$\mathbf{-24.4 \times 10^{-2}}$*	-44.4×10^{-2}, -4.53×10^{-2}	$\mathbf{-28.9 \times 10^{-2}}$**	-47.6×10^{-2}, -8.50×10^{-2}	$\mathbf{-27.5 \times 10^{-2}}$**	-46.8×10^{-2}, -8.25×10^{-2}
Intercept	**697*****	467, 926	**701*****	441, 960	**518****	196, 840	**510****	193, 828

β coefficient, *CI* confidence interval. Bold values denote statistically significant results. [a]Adjusted for sex and age. [b]Additionally adjusted for sleep records, sleep quality and daily caffeine consumption. [c]Additionally adjusted for BMI, hypertension, grip strength and care level. [d]Additionally adjusted for total time in bed the day before. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 4 | Coefficients and 95% confidence intervals for the association between sleep time measures and total steps the following day ($n = 124$)

Steps (per thousand)	Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Total sleep time (minutes)								
Within-individual effects	0.28×10^{-3}	-0.24×10^{-3}, 0.80×10^{-3}	0.54×10^{-3}	-4.05×10^{-7}, 1.08×10^{-3}	$\mathbf{0.55 \times 10^{-3}}$*	4.96×10^{-6}, 1.08×10^{-3}	$\mathbf{0.77 \times 10^{-3}}$**	0.26×10^{-3}, 1.27×10^{-3}
Between-individual effects	$\mathbf{-1.28 \times 10^{-2}}$**	-2.13×10^{-2}, -0.43×10^{-2}	$\mathbf{-1.29 \times 10^{-2}}$**	-2.14×10^{-2}, -0.44×10^{-2}	$\mathbf{-1.48 \times 10^{-2}}$***	-2.30×10^{-2}, -0.65×10^{-2}	$\mathbf{-1.27 \times 10^{-2}}$***	-2.01×10^{-2}, -0.55×10^{-2}
Intercept	**31.5*****	20.9, 42.1	**31.5*****	20.7, 43.0	**21.7****	8.0, 35.4	**18.8****	6.6, 30.9
Total time in bed (minutes)								
Within-individual effects	0.09×10^{-3}	-0.36×10^{-3}, 0.54×10^{-3}	0.27×10^{-3}	-0.20×10^{-3}, 0.73×10^{-3}	0.27×10^{-3}	-0.19×10^{-3}, 0.74×10^{-3}	$\mathbf{0.50 \times 10^{-3}}$*	0.06×10^{-3}, 0.09×10^{-3}
Between-individual effects	$\mathbf{-1.02 \times 10^{-2}}$**	-1.78×10^{-2}, -0.27×10^{-2}	$\mathbf{-1.03 \times 10^{-2}}$**	-1.78×10^{-2}, -0.28×10^{-2}	$\mathbf{-1.22 \times 10^{-2}}$***	-1.95×10^{-2}, -0.48×10^{-2}	$\mathbf{-1.05 \times 10^{-2}}$***	-1.70×10^{-2}, -0.40×10^{-2}
Intercept	**30.8*****	20.2, 41.4	**31.1*****	19.9, 42.3	**21.2****	7.37, 35.0	**18.4****	6.19, 30.6

β coefficient, *CI* confidence interval. Bold values denote statistically significant results. [a]Adjusted for sex and age. [b]Additionally adjusted for sleep records, sleep quality and daily caffeine consumption. [c]Additionally adjusted for BMI, hypertension, grip strength, and care level. [d]Additionally adjusted for total steps from the day before. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

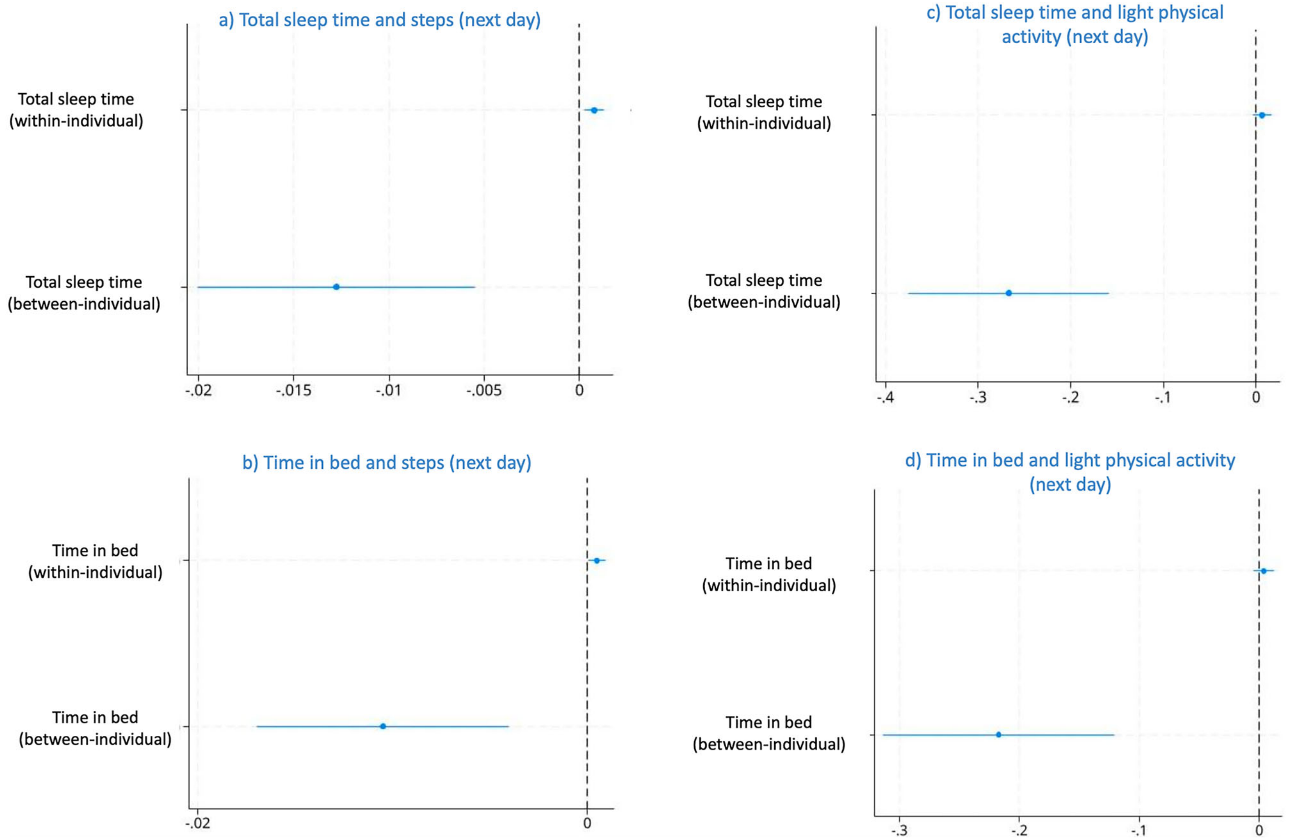

Fig. 2 | Coefficient plots for the associations between sleep parameters and physical activity the following day. Coefficient plots with beta coefficients and confidence intervals for the association between **a** total sleep time and steps the day after, **b** time in bed and steps the day after, **c** total sleep time and minutes in light physical activity the day after, and **d** time in bed and minutes in light physical activity the day after. Note the differing scales of the *x*-axes. Full model details, including intercepts, are available in the corresponding tables (Tables 4 and 5).

least 6 h and not more than 8 h a day[33]. Previous studies have shown that both short and long sleep durations are associated with increased all-cause mortality in older adults[34] and spending more time in bed may lead to worse health outcomes[35]. The results from our study, where increasing minutes in light activity is followed by shorter 24-h TST and TIB, might support the idea that PA improves several sleep aspects. One way to explore this theory would be to specifically analyse sleep quality, both with subjective and objective measures, among older adults.

When looking at sleep as exposure and PA as outcome, our findings show an inverse association between TST and TIB, respectively, with the same 24-h period's PA, in the form of lower step count and minutes spent in light activity. These associations were observed both within- and between-individuals, i.e., when the participant deviated from their cluster mean and from the respective TST and TIB means. Since the associations are examined in a 24-h cycle, spending more TIB would naturally reduce the time available to be physically active[36]. Similar inverse associations were observed between individuals when analysing sleep with the following day's step count, as well as both between- and within-individuals when analysing the following day's minutes in light activity. The results parallel previous studies where longer sleep was associated with fewer step counts and less time spent in light activity[37,38]. Longer sleep or higher sedentary behaviour has previously been suggested to be an indicator of underlying disease in older adults[39], which may reduce the likelihood of being physically active. The robust, significant inverse associations might be important to consider during cognitive behaviour therapy for sleep disorders, as the intervention may not only have an impact on the sleep disorder itself but also on PA, which in turn might have a reciprocal effect on sleep[40].

It is noteworthy that when participants' TST and TIB were longer than their individual average, the exposures were positively associated with the following day's step count. The results are similar to a study by Štefan et al., where greater sleep was associated with greater amounts of PA the subsequent day[41]. Although it is not possible to determine a causal relationship, longer sleep time may be restorative for an individual's step count the next day. Indeed, this would be in line with current literature, as sleep is needed for muscle repair, tissue growth and protein synthesis, all of which are important for physical activity[42]. Considering our results suggesting an inverse association between TST and TIB with step count within the same 24-h period, there may be a compensatory increase in step count the following day. Furthermore, the association became more positive and significant when adjusting for autocorrelation in Model 4, indicating that the previous day's step count may have a confounding effect. These results were only observed within individuals, which is relevant in the perspective of precision medicine, suggesting that treatments and intervention programmes should be customised according to each individual's needs and circumstances.

Despite the number of statistically significant results, the effect size is quite small, thus raising questions about the findings' generalisability. It is, however, important to note that the variables are observed within a day, and changes in PA and sleep are studied in minutes for this study. Lifestyle changes such as these are often required to be repeated for a longer period of time in order to present detectable results[43]. This continuous build-up of repeated exposure creates a cumulative effect that grows to become a larger effect. Accordingly, it appears that both sleep and PA have cumulative effects on overall health[44,45]. Despite small effect sizes, it might still be

Table 5 | Coefficients and 95% confidence intervals for the association between sleep time measures and minutes in light physical activity the following day ($n = 124$)

Lightly active (min)	Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Total sleep time (min)								
Within-individual effects	**-1.3×10^{-2}****	-2.6×10^{-2}, -0.1×10^{-2}	-1.0×10^{-2}	-2.3×10^{-2}, 0.3×10^{-2}	-1.0×10^{-2}	-2.3×10^{-2}, 0.2×10^{-2}	0.6×10^{-2}	-0.4×10^{-2}, 1.6×10^{-2}
Between-individual effects	**-36.0×10^{-2}*****	-51.0×10^{-2}, -20.1×10^{-2}	**-35.7×10^{-2}*****	-51.1×10^{-2}, -20.3×10^{-2}	**-39.8×10^{-2}*****	-55.1×10^{-2}, -24.5×10^{-2}	**-26.7×10^{-2}*****	-37.5×10^{-2}, -15.9×10^{-2}
Intercept	**609*****	417, 802	**631*****	429, 833	**538*****	284, 793	**377*****	197, 557
Total time in bed (min)								
Within-individual effects	**-1.4×10^{-2}****	-2.5×10^{-2}, -0.4×10^{-2}	**-1.2×10^{-2}***	-2.3×10^{-2}, -0.1×10^{-2}	**-1.2×10^{-2}***	-2.3×10^{-2}, -0.1×10^{-2}	0.4×10^{-2}	-0.5×10^{-2}, 1.2×10^{-2}
Between-individual effects	**-28.8×10^{-2}*****	-42.5×10^{-2}, -15.1×10^{-2}	**-28.9×10^{-2}*****	-42.5×10^{-2}, -15.3×10^{-2}	**-32.8×10^{-2}*****	-46.4×10^{-2}, -19.3×10^{-2}	**-21.7×10^{-2}*****	-31.4×10^{-2}, -12.1×10^{-2}
Intercept	**588*****	395, 780	**609*****	406, 812	**514*****	258, 770	**364*****	182, 546

β coefficient, *CI* confidence interval. Bold values denote statistically significant results. [a]Adjusted for sex and age. [b]Additionally adjusted for sleep records, sleep quality and daily caffeine consumption. [c]Additionally adjusted for BMI, hypertension, grip strength and care level. [d]Additionally adjusted for total steps from the day before. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

valuable to consider the association between PA and sleep when developing health guidelines for the elderly.

This study has several strengths. First, this is the only study that has investigated the bidirectional PA-sleep association in super-seniors for a period of 1 year with clinical follow-ups, which provides extended and detailed information about this particular age group. Second, the study has ecological validity as the participants were studied in a free-living environment with daily objective measures, which minimised the risk of recall bias and social desirability effect. Participants' personal experiences were taken into account by including daily subjective measures. Third, the data allows for the separation of between- and within-individual associations.

Despite its many strengths, the study has some limitations. First, even though adjustments were made for relevant variables, there might still be residual confounders to take into consideration, owing to the highly complex attributes of both PA and sleep. Other relevant factors include chronic pain conditions, respiratory diseases, sleep and mental health disorders, as well as use of sleep medications[46–48]. In this study, these factors are considered in the care-level variable, however, future studies may consider each variable specifically for a more detailed understanding of their impact on the PA–sleep association. Second, prior research suggests that there may be gender differences in age-related sleep changes, which were not examined in this study[49]. Third, despite the prospective nature of the study, the analyses are cross-sectional and do not provide information about changes over time. The observational nature of the study does not allow for causal inference. Finally, even though the wearable device has shown a sufficient ability to measure PA, previous comparisons with accelerometer-derived data have shown that the wearable device is prone to variability and overestimation of PA–intensity levels[50]. However, intensity is only one of the measures considered for PA in this study, and the device has shown high agreement for step count[51]. According to existing research, overestimation seems to be more specific for higher intensity levels, such as MVPA[52,53], which was omitted in the current study. With the constant development of wearable technology, the accuracy of wearable devices will likely improve, and future studies may include higher PA-intensity levels for a more elaborate understanding of the association with sleep in very old adults.

The findings of this study suggest a reciprocal inverse association between PA and sleep in very old adults. Thus, PA–sleep patterns previously explored in younger adults may not be applicable to the very old. An increase in total sleep time over a 24-h period at the individual level may lead to compensatory behaviour, whereby a lower step count on one day is offset by an increased step count on the subsequent day. Future studies should consider measures of health and intra-individual factors when investigating the association between PA and sleep in very old adults.

Material and methods

Study design

The participants of this study were part of the Japan Healthy Ageing Study (J-HAS), a prospective cohort study. The data, including digital, clinical, and self-reported measures, were collected between October 2022 and December 2023. The baseline population consisted of 150 healthy Japanese men and women aged 80 or over. Throughout a one-year study period, participants were asked to respond to daily and monthly lifestyle questionnaires on a tablet, as well as to continuously use wearable devices in their free-living environment. More detailed questionnaires were conducted when participants visited the University of Tokyo Hospital for clinical examinations at baseline and after 1 year of follow-up.

Study population

A total of 150 healthy community-dwelling older adults (50,313 observations) were eligible for participation. The inclusion criteria were: men and women aged 80 years or older; individuals who provided written informed consent to participate in the study; separately provided written consent for genetic testing; ability to wear the wearable device during sleep; ability to

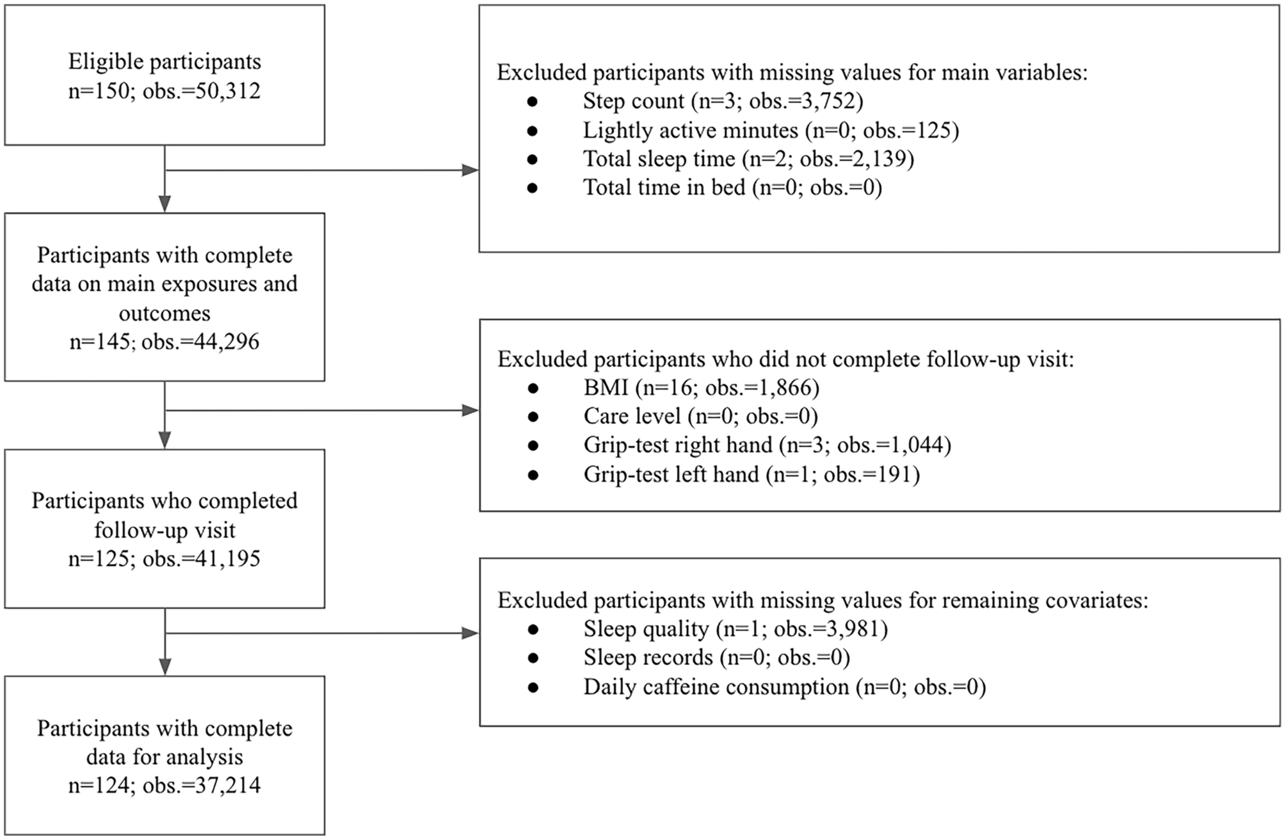

Fig. 3 | Flowchart illustrating the inclusion and exclusion of participants (*n*) and observations (obs.) in the present study.

charge the wearable device; ability to perform simple touchscreen operations on a provided tablet device. The exclusion criteria were: individuals certified as requiring long-term care services according to the Japanese long-term care insurance system; evident cognitive impairment; medical history or current condition that could lead to cognitive impairment; clinically significant diseases; participation in clinical research or clinical trials involving other pharmaceuticals or foods within the past month; deemed inappropriate as participants by the principal investigator or co-investigators. As illustrated in Fig. 3, participants and observations were excluded if they had missing values on main variables: daily step count ($n = 3$; 3752 observations), lightly active minutes ($n = 0$; 125 observations), and total sleep time ($n = 2$; 2139 observations). For any observations that were obtained during the first visit (i.e., baseline visit V1) and the 1-year follow-up visit (V2), the means of both measures were used ([V1 + V2]/2). Due to this, participants were further excluded if clinical check-ups for body mass index (BMI) ($n = 16$; 1866 observations), grip test for right ($n = 3$; 1044 observations) and left hand ($n = 1$; 191 observations) after 1 year of follow-up were not completed. Further exclusion occurred if participants did not answer the daily questionnaire for sleep quality ($n = 1$; 3981 observations). Hence, a total of 124 participants and 37,214 observations were included in the final analyses.

Wearable device

Continuous information about daily sleep and PA was obtained by the Fitbit Inspire2 (Fitbit Inc., San Francisco, CA, USA). The registered data were automatically uploaded to the research server with a pseudonymised research ID. The participants were asked to continuously wear the device as much as possible, except when taking a bath or when the device needed charging. The accuracy of consumer wearable devices has previously been investigated, and the results indicated that Fitbit could be used to measure step count and sleep time with high relative agreement and sensitivity compared to gold standard methods[51,54].

Physical activity measures

For PA measures, a daily number of steps and minutes in light activity were used as continuous variables in the analyses. Both measures were obtained from the wearable device. Activity measures were collected based on metabolic equivalents (METs) where lightly active minutes equal 1.5–3.0 METs[55]. In 2013, the Ministry of Health, Labour and Welfare of Japan published the Exercise and Physical Activity Reference for Health Promotion, where moderate-to-vigorous physical activity (MVPA, >3 METs) was recommended[56]. Recent data have questioned the reliability of MVPA as a PA measure among older adults, as it has mostly been used for younger adults, and the definition of MVPA varies between wearable devices[57]. Due to its uncertain reliability in very old adults, we chose not to use this as a variable in the analysis.

Sleep measures

Two measures were used to analyse sleep: 24-h total sleep time (TST) and 24-hour time in bed (TIB), calculated in minutes. Both were used as continuous variables obtained from the wearable device. As previously mentioned, with older age comes gradual deterioration of sleep quality and quantity. This results in the elderly spending more time in bed compared to younger adults. Due to the increase of daytime sleepiness, it is more common for elders to take naps throughout the day[58]. Using 24-hour TST and TIB instead of night-time TST and TIB, respectively, was considered to be more representative of the amount of sleep obtained throughout the entire day.

Covariates

Information about sex and age (continuous) was acquired through the baseline questionnaire. Sleep quality was assessed using daily questionnaires. Four binary Likert scale questions reminiscent of questions in the validated Athens Insomnia Scale and the Insomnia Severity Index were included[59,60]: "Was it difficult to fall asleep last night?", "Did you wake up during your sleep?", "Did you wake up earlier than planned?" and "Did you feel like you didn't get enough sleep?". The questions were dichotomised and possible outcomes were therefore "Yes" (1 point) or "No" (0 points), and a total score was calculated. A higher score would indicate poorer subjective sleep quality or insomnia. Hypertension was based on health questionnaires answered by the participants at baseline and analysed as a dichotomous variable. Daily caffeine consumption was categorised into 3 categories (no intake, 1 to 2 cups, and 3 or more cups daily).

Grip strength and BMI were clinically assessed at baseline (V1) and follow-up (V2). For each variable, individual means of the 2 visits were used for analysis. In order for the elderly aged 65 and over to utilise the long-term care insurance service in Japan, a care-need level certificate is required. Nursing care insurance level information for each participant was collected at each visit. The levels are divided into 7 categories, where the first 2 levels indicate care-support levels 1 and 2, which include nursing care prevention services. The remaining categories provide long-term care services and include care need levels 1–5[61]. A higher level indicates a greater need for care services and, indirectly, a lower level of functioning. When using this as an indicator of health, statistics are implemented to consider a 65-year-old person "healthy" until he or she is certified as requiring care-need level 2 or higher[62]. Since the current study focuses on healthy super-seniors, only participants with care need level 1 or lower at baseline were eligible for inclusion. Since each participant had one assessment for each clinical visit, a mean care level was calculated. The means were categorised into 4 different categories: mean of care-level 0 (no certificate), means from care-level 0 to care-support level 2, care-support level 2 to care-need level 1 and means above care-need level 1. Results from previous studies suggest that handgrip strength has a predictive validity for mortality, cognition, and mobility[63]. In this study, the mean grip strength from each participant's dominant hand was utilised for analysis.

Statistical analyses

Participant characteristics were analysed by calculating a group mean using the individual cluster means. For variables with skewed distribution, the median was used. Associations between PA and sleep measures were estimated using multilevel mixed-effects linear regression models, where goodness of fit was considered using likelihood-ratio tests. Models with random intercepts and random slopes were utilised in all analyses. To investigate the within-individual effect, the independent variables were defined as the daily deviation from the cluster mean. Between-individual effects were examined using the cluster means. Bidirectional associations between PA and sleep parameters were investigated as illustrated in Supplementary Fig. 2. When investigating the association between PA and sleep, the analysis considered sleep data from the same day and PA data from the preceding day. To investigate the association between sleep and PA, 2 separate analyses were performed. The first analysis included PA recorded during the day and sleep measures from the night preceding the PA day, and any sleep periods registered until the end of that PA day. The second analysis included sleep measures from the night preceding the day of the registered sleep periods, and PA measures from the following day. Potential confounders were considered in all statistical analyses. Model 1 included sex and age. Model 2 was additionally adjusted for sleep records, sleep quality and daily caffeine consumption. Model 3 was additionally adjusted for grip strength of the dominant hand, care level, BMI, and hypertension. Finally, Model 4 was additionally adjusted for the dependent variable from the previous day in order to consider autocorrelation. Autocorrelation represents the extent to which an observation at one point in time is predictive of an observation at another point in time, i.e., the potential relationship between a variable with a "lagged" value of itself[64]. This was included due to the temporal nature of the data, as it has previously been overlooked in other studies looking at similar variables[30]. All statistical analyses were performed using Stata/MP 18.0 (StataCorp LLC, College Station, TX, USA). A two-tailed p-value < 0.05 was considered to be statistically significant.

Data availability

We cannot provide public access to individual data due to participant privacy stipulations in accordance with ethical guidelines. Additionally, the written informed consent we obtained from study participants does not include a provision for the public sharing of data. Qualifying researchers may, upon reasonable request, apply to access an aggregated dataset by contacting the corresponding author.

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Author contributions

H.P. and T.S. designed the study concept. A.K.S. conducted clinical research as Principal Investigator. T.S. and A.K.S. provided the dataset. H.P. and T.S. analysed the data. H.P. drafted the paper. All authors interpreted the results, critically revised the paper for important intellectual content, and approved the final version.

Competing interests

The authors declare no competing interests.

Additional information

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