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Standing balance and spatiotemporal aspects of gait are impaired upon nocturnal awakening in healthy late middle-aged and older adults

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Abstract

Study Objectives: Nocturnal awakenings may constitute a unique risk for falls among older adults. We describe differences in gait and balance between pre-sleep and mid-sleep testing, and whether changes in the lighting environment during the mid-sleep testing further impact gait and balance.

Methods: Twenty-one healthy, late middle-aged and older (64.7 ± 8.0 years) adults participated in this repeated-measures design consisting of four overnight laboratory stays. Each night, participants completed baseline visual acuity, gait, and balance testing. After a two-hour sleep opportunity, they were awakened for 13 minutes into one of four lighting conditions: very dim white light (<0.5 lux); dim white light (~28.0 lux); dim orange light (~28.0 lux); and white room-level light (~200 lux). During this awakening, participants completed the same sequence of testing as at baseline.

Results: Low contrast visual acuity significantly decreased with decreasing illuminance conditions ($F(3,45)=98.26$, $p<0.001$). Our *a priori* hypothesis was confirmed in that variation in stride velocity and center of pressure path length were significantly worse during the mid-sleep awakening compared to pre-sleep baseline. Lighting conditions during the awakening, however, did not influence these parameters. In exploratory analyses, we found that over one-third of the tested gait and balance parameters were significantly worse at the mid-sleep awakening as compared to baseline ($p<0.05$), and nearly one-quarter had medium to large effect sizes (Cohen's $d \geq 0.5$; $r \geq 0.3$).

Conclusions: Balance and gait are impaired during mid-sleep awakenings among healthy, late middle-aged and older adults. This impairment is not ameliorated by exposure to room lighting, when compared to dim lights.

Key Words: (3-10): Nocturia, balance, gait, older adults, falls, light

Current Knowledge/Study Rationale: Approximately one-third of adults over the age of 65 experience at least one fall each year, and over one-quarter of these occur during the night. This study was conducted to determine whether mid-sleep arousals impair gait and standing balance, and whether changes in the lighting environment during the mid-sleep arousal could impact gait and standing balance.

Study Impact: This is to our knowledge the first study to report impairment of several aspects of both standing balance and gait during mid-sleep awakenings among healthy late middle-aged and older adults. This impairment is not ameliorated by exposure to room lighting, when compared to dim light.

Introduction

Approximately one-third of adults over the age of 65 experience at least one fall each year,[1] and the 2-year prevalence of self-reported falls has increased over the past decade.[2] The consequences of a fall for an older adult can be debilitating or even life-threatening. Falls accounted for 78% of injury admissions to hospitals in the United States among adults over 65 years in 2009,[3] are the leading cause of fatal injuries among adults over 65,[4] and result in premature institutionalization[5] and substantial psychological morbidity including activity restriction[6] and fear of falling.[7] Falls are also costly; direct medical costs in adults over 65 years totaled $200 million for fatal falls and $19 billion for non-fatal fall-related injuries in the U.S.[8]

Nocturia, or the frequent need to wake at night to void, is considered a risk factor for falls among older adults.[9] A cohort study of 135,433 older adults reported that the presence of nocturia and urinary incontinence were the strongest predictors of falls, after increased age, female sex, and a history of falls.[10] These studies did not examine the time of day in which the fall occurred, so it is unknown whether nocturia increased daytime fall risk (potentially as a result of daytime sleepiness), nighttime fall risk, or both. However, an independent study reported that over one-quarter of falls among older adults occur during the night.[11] In most individuals the majority of the nighttime hours are spent asleep with relatively low levels of activity compared to the daytime hours.[12] Presumably, this decrease in activity also decreases fall opportunity overnight, making the fact that one-quarter of falls occur at night an even more substantial proportion. Of these nocturnal falls, over half were related to a visit to the toilet.[11] Thus, it is likely that nocturnal awakenings, especially those with nocturia, pose a unique fall risk to the older adult.

The ability to maintain postural stability under different environmental conditions is critical to the ability to safely perform activities of daily living. Postural stability is a multi-sensory motor task that depends on reliable input from the vestibular, somatosensory and visual systems. Deficits in one or more of these sensory systems, all of which undergo age-related changes, are likely to contribute to nocturnal falls in older individuals. Increased fall risk is linked to poor vision through impaired depth perception,

contrast sensitivity, visual acuity, and visual fields.[13] Dim lighting reduces the ability to acquire this visual information, thus may impair postural and gait stability. It is well-established that complete removal of visual input decreases postural stability;[14,15] however, the effects of graded light on postural stability in late middle-aged or older adults is not well known. One study demonstrated that reduced ambient light significantly impaired standing balance,[14] while another study demonstrated reduced gait stability in low light.[16]

A low illuminance lighting environment, and its potential concomitant negative consequences on balance, is common upon arousal from sleep when arising to use the toilet. Additional sources of balance impairment might include incomplete arousal from sleep (i.e., sleep inertia), use of benzodiazepine hypnotic medications, and changes in blood pressure regulation. Two studies have assessed whether awakening from nocturnal sleep decreases standing balance and success on a tandem walk test among older adults. Neither study found an influence of awakening from sleep,[17,18] but the effect of nocturnal awakening on spatial and temporal parameters of gait is unknown. No previous study has examined the impact of nocturnal awakening and different levels of environmental light conditions on gait and balance in healthy, late middle-aged and older adults. Based on repeated associations with fall risk,[19–22] the *a priori* primary outcome measures of interest for gait and standing balance were, respectively: (1) stride velocity variability at self-selected pace and (2) center of pressure (COP) displacement during standing with eyes open and eyes closed. We hypothesized that there would be greater variation in stride velocity and greater COP displacement during the mid-sleep awakening and in the dimly lit environments compared to baseline and room-level light, respectively. We also measured changes in visual acuity pre-sleep and during the mid-sleep awakening, and across lighting conditions, with the hypothesis that vision would not change between the two time points, but would be progressively worse with decreasing illuminance. Finally, to direct future research on which balance and gait parameters were most impacted by mid-sleep awakenings, we ran exploratory analyses on twenty-nine balance and gait parameters in only the room-level white light condition to identify the parameters with the largest effect sizes.

Methods

The protocol was approved by the Stanford University Institutional Review Board and all procedures adhered to the principles outlined in the Declaration of Helsinki. Written informed consent and Health Insurance Portability and Accountability Act authorization were obtained from participants prior to study participation. The study was posted on www.clinicaltrials.gov (#NCT01350505) on 05/06/11.

Participants

Twenty-one healthy, late middle-aged and older adults without sleep, balance, or psychiatric disorders (see Table 1 for demographics) were recruited through advertisements in local community newspapers, articles in senior newsletters, posters at local Veterans Affairs clinics, posters at local businesses, and word of mouth. Participants were included in the study based on successfully completing the first three lines of the 25% low contrast visual acuity chart in very dim light (corrected-to-normal vision allowed) (Early Treatment Diabetic Retinopathy Study, ETDRS, charts [Precision Vision Inc., La Salle, IL]), normal 30° visual fields (Octopus 900, Haag-Streit, Mason, OH), stable health, no cognitive impairment (Mini Mental Examination Scores >23 [23]), non-smoker, good sleeper (Pittsburgh Sleep Quality Index scores ≤5 [24]), no clinically significant symptoms of depression (Geriatric Depression Scale ≤5 [25]), normal color vision (Ishihara's Test for Colour Deficiency), normal hearing, no alcohol abuse (Alcohol Use Disorders Identification Test ≤19 [26]) with proximal use tested upon admission to the laboratory (Chematics, Alco-Screen 02), and no illegal drug use with proximal use tested upon admission to the laboratory (DrugCheck3, Express Diagnostics). While 81% of study participants were regularly taking some type of medication (including vitamins and/or herbal medications), medication use was stable in the month prior to study enrollment and throughout the duration of their participation in the study.

Procedure

In this repeated-measures design, all participants were admitted into the laboratory for four separate overnight stays. Each laboratory stay differed only in the lighting environment into which the participant was awakened during the night (see below). The four experimental lighting conditions were: very dim white light (<0.4 ± 0.2 lux); dim white light (27.9 ± 0.6 lux); dim orange light (27.7 ± 0.6 lux); and room-level white light (202.4 ± 4.1 lux). The spectral characteristics of the orange and white light used are illustrated in Figure 1. Lighting was delivered using dimmable ceiling mounted high power light emitting diodes (LED) mounted with a UV filter (Rosco Cinegel #3114 Tough UV Filter), a diffuser (Rosco Cinegel #3047, Light Velvet Frost) in addition to an orange filter (Rosco Roscolux #19, Fire) (Rosco, Sun Valley CA, USA) for the dim orange light. The order of the lighting condition was randomized across participants, except for the room-level white light, which occurred during participants' fourth and final visit, because this condition was added to the protocol after participants had completed the first three visits.

One week of at-home regular sleep-wake periods preceded each laboratory stay. Bed and wake times were selected upon consensus between the participant and research personnel and were at least 7-9 hours apart so as to ensure participants were not significantly sleep deprived upon laboratory admission. Participants were required to go to bed and arise within 30 minutes of the agreed upon bed and wake times. This schedule helps maximize the amplitude[27] and stabilize the phase angle[28] of the circadian system. Adherence was verified using self-reported sleep-wake logs and wrist actigraphy (Actiwatch 2, Philips Respironics). The average sleep midpoint during the at-home week was calculated and used as the midpoint for an 8-hour sleep opportunity in the laboratory.

Participants arrived at the Stanford University/VA Palo Alto Health Care System Sleep and Circadian Translational Research Laboratory three hours before their scheduled bedtime. A research assistant prepared them for polysomnography according to the established 10-20 system including electroencephalography (C3/4, O1/2) referenced to an electrically neutral auricular electrode, bilateral electro-oculogram, submental electromyogram, and electrocardiogram (Siesta, Compumedics).

Recordings were analyzed according to the American Academy of Sleep Medicine's rules for sleep stage scoring[29] using Prana Software (PhiTools, Chicago, IL). Participants remained in a time-isolation suite (no windows, no time cues, *en suite* bathroom, and regulated ambient temperature) for the duration of the stay until discharge the next morning. Lighting was maintained at normal room lighting (~150 lux, in the direction of gaze; ~250 lux maximal lighting) for the entire time they were in the time isolation suite, except during sleep periods (<0.03 lux) and the experimental lighting conditions. Lighting was controlled by a technician from outside of the room.

Participants underwent a pre-sleep baseline testing sequence consisting of (1) visual acuity testing, (2) standing balance testing, and (3) gait testing. The lights were turned off and participants were instructed to go to bed at the pre-calculated habitual bedtime. Two hours into this sleep opportunity, participants were awakened by a technician into one of the four experimental lighting conditions and were kept awake for 13 minutes. During this awakening, participants were examined using the same test battery as occurred prior to sleep. After the 13 minutes awakening, the lights were turned off and the participants were permitted to return to sleep until their habitual wake time. Upon awakening in the morning, participants were given breakfast and then discharged.

Visual Acuity

During visual acuity testing, participants read a low contrast ETDRS Chart from a distance of three meters. The low contrast ETDRS chart consists of fourteen rows of five letters each. Going from the top to the bottom row, letters become progressively smaller and there is equal spacing (on a log scale) between letters and rows. Participants were instructed to read the eye chart from the top to the bottom; participants were stopped after they finished a row where they were unable to correctly identify at least three letters within the same row. The total number of correct letters was used as the measure of visual acuity. The contrast of the chart was adjusted (10% or 25%) depending on the participant's low contrast visual acuity ability to avoid a ceiling or floor effect.

Standing Balance and Gait

Balance and gait parameters were evaluated using a Zeno Walkway (ProtoKinetics, Havertown, PA, USA). The Zeno Walkway is a 2' x 14' sensor pad with 16 levels of dynamic pressure detected through embedded 0.4" pressure sensors placed every 0.5". The walkway is connected to a laptop computer by a serial interface cable in order to process and store data using ProtoKinetics Movement Analysis Software. Balance-related metrics and temporal and spatial measures of gait are calculated by the software (PKMAS, version 5.07C7). This system has been validated[30] and previously used to assess gait in relationship to falls among older adults.[31] The output parameters used in the current study and their descriptive statistics are listed in Tables 2 and 3. All but 6 of the 27 parameters have been previously associated with fall risk among older adults.[20–22,32,33] We chose to include the six that have not been previously associated directly with fall risk (gait cycle time, %CoV gait cycle time, stance time, %CoV single support %, COP X Range, COP Y Range) based on their close relationship with parameters that have been associated with falls: gait cycle time and the %CoV gait cycle time were chosen based on their similarity to mean and variation in stride velocity; mean stance time is of interest as the variation in stance time has been associated with falls[22]; similarly %CoV of single support % is of interest because the mean single support time has been associated with falls[32]; and standing COP X and Y Range were chosen because previous work has related the root mean square amplitude of the medio-lateral and anterior-posterior acceleration to fall history.[32]

During the standing procedure, participants were asked to stand on the walkway in a comfortable foot position with their arms by their side and their eyes open for 30 seconds and then with their eyes closed for 30 seconds. Immediately after the standing procedure, participants walked along the walkway at a self-selected pace for three trials. One end of the walkway was positioned against a wall, such that participants performed a turn on the walkway at this end and the other end was open so that participants walked off the mat and continued walking for two meters. To reduce artifact due to slowing down to turn, only the three walks that occurred from the wall to the open end of the walkway were analyzed. The first

step of each walk was considered gait initiation and was excluded from analyses. These three walks were averaged together in the calculation of the gait parameters. ProtoKinetics Movement Analysis Software was used to derive all parameters.

Data Analysis

Data were analyzed using R version 3.1.3 [34] and the R package lme4.[35] A $p<0.05$ was considered statistically significant. Data were checked for homoscedasticity and normality by visual inspections of residual plots and Shapiro-Wilks test. Differences in low contrast visual acuity between pre-sleep and nocturnal awakenings in the room-level light condition were tested with a paired-samples t-test. Differences in low contrast visual acuity between the four lighting conditions during the nocturnal awakenings were tested with a repeated-measures analysis of variance (ANOVA) and *post hoc* paired t-tests with a Bonferroni correction for multiple comparisons ($p=0.008$).

Given each participant contributed multiple data points, we used hierarchical multilevel modeling (HLM) to test the hypotheses that parameters of gait and balance differ upon awakening from nocturnal sleep compared to pre-sleep baseline, and explore whether the change in values from pre-sleep to mid-sleep differed by the lighting into which they were awakened. Using a simple linear regression is insufficient in this analyses because our data do not satisfy the assumption of independence of observations. The advantage of using HLM is that it accounts for shared variance within participants while modeling differences between participants.[36] With four lighting conditions and two time points, the dataset featured eight stacked cases for the 17 subjects that completed the protocol, and six stacked cases for the four subjects that did not return for the final condition (or a total of 160 data points). Specifically, crossed random-effects models, an extension of the classical HLM, were used to accommodate the nesting of the gait/balance parameter (Level 1) in the combination of participant and condition random effects (Level 2). A full model was fitted with fixed effects of time (*i.e.,* are pre-sleep values different from values obtained after awakening, independent of lighting condition), condition (*i.e.,* is the slope of the values from pre-sleep to awakening different by the lighting condition into which they are awakened),

and random effects of intercept (accounts for differences of pre-sleep values among participants), and by-participant random slopes for time (accounts for differences in the change in values between pre-sleep and awakening among participants). An unstructured covariate matrix was chosen to allow for correlation between the random effects. The initial model was over-fitted, so the random slope term was removed from the model for subsequent analyses. The model tested for each dependent variable is:

Level 1 (item-level) model:

$(\text{Standing Balance/Gait Parameter})_{ij} = \beta_{0ij} + \beta_{1ij}(\text{Time}) + \varepsilon_{ij}$

Level 2 (participant-level) model:

$\beta_{0ij} = \gamma_{00} + \zeta_{0j}$

$\beta_{1ij} = \gamma_{10} + \gamma_{11}(\text{Condition})$

Positive skewness was noted for all three dependent variables: coefficient of variation in stride velocity and center of pressure path length (both open and closed eyes). However, since modeling with and without the variables transformed (logarithmically) to closer approximate normality assumptions did not substantively change the results, untransformed values were used to facilitate interpretation. Modeling was achieved using likelihood ratio testing to compare full with stepwise reduced models.

A wide variety of parameters derivable from examination of gait and standing balance have been previously reported as proxies for predicting future falls in older adults. As such, we chose to look at an assortment of parameters we gathered from the Zeno Walkway in secondary exploratory analyses. These analyses were used to identify which parameters had the largest effect sizes in our study. Paired samples *t*-tests were used to determine whether balance and gait parameters differed between pre-sleep and nocturnal awakenings in the room-level lighting condition. Wilcoxon's signed rank test was used when variables did not meet normality assumptions. Cohen's *d* (small=0.2, medium=0.5, large=0.8) and *r* (small=0.1, medium=0.3, large=0.5) were used to interpret effect sizes.[37,38]

Results

Four out of the twenty-one participants did not return for the fourth and final condition, the room level white light condition. The participants who did not return for the final condition did not differ in age, sex, race, or ethnicity from the participants that did return. During the two hour sleep opportunity prior to the mid-sleep awakening, participants slept, on average, for 90.7 minutes (SD±18.0); this total sleep time did not differ across lighting conditions.

Low Contrast Visual Acuity

Notably, there was no difference between baseline low contrast visual acuity obtained in the evening in normal room light and the low contrast visual acuity measurements made upon awakening into the room-level light condition ($t(16)=1.38$, $p=0.19$). There was a significant difference across the four lighting conditions ($F(3,45)=98.26$, $p<0.001$) such that low contrast visual acuity decreased with decreasing illuminance, as expected,[39] but did not differ in equiluminant white and orange light (Figure 2).

Variation in Stride Velocity

A full model was fitted with the percent coefficient of variation (%CoV) of stride velocity as the dependent variable with time (pre-sleep vs. mid-sleep awakening) and condition (four lighting conditions) as independent variables. A reduced model that removed the effect of condition was fitted, but did not significantly differ from the full model ($\chi^2(3)=4.24$, $p=0.24$). As such, the condition term was removed and the model with just the fixed effect of time was compared to an intercepts only model. This comparison was statistically significant ($\chi^2(1)=15.64$, $p<0.001$), supporting a significant effect of time on variation in stride velocity. The model with the fixed effect of time and random effect of participant intercept became the final model and is summarized in Table 4.

COP Path Length – Eyes Open (EO)

Similar to the model testing process for variation in stride velocity, a full model was fitted with COP Path Length during eyes open as the dependent variable and time (pre-sleep vs. mid-sleep awakening) and condition (four lighting conditions) as independent variables. A reduced model with the condition (lighting) term removed did not significantly differ from the full model ($\chi^2(3)=5.78$, $p=0.12$) so the condition term was removed from further analyses. Comparison of the reduced model to an intercept only model revealed a significant difference ($\chi^2(1)=7.66$, $p=0.006$), supporting a significant effect of time on COP path length during the eyes open condition. The reduced model became the final model and is described in Table 5.

COP Path Length – Eyes Closed (EC)

Finally, the same procedure was followed for modeling the effects of time and lighting condition on COP Path Length during the eyes closed condition. The reduced model without the condition (lighting) term did not significantly differ from the full model ($\chi^2(3)=3.74$, $p=0.29$), supporting no effect of condition. A significant difference was found between the reduced model containing only the fixed effect of time and an intercept only model ($\chi^2(1)=5.24$, $p=0.022$), supporting an effect of time on COP path length in the eyes closed condition. The final model is described in Table 6.

Gait and Balance

While we had *a priori* hypotheses concerning the importance of variation in stride length (gait) and center of pressure path length (standing balance), we wanted to also examine the degree to which awakening an individual, independent of the lighting environment, would impact a variety of measures of gait and standing balance. As such, we examined many parameters reflecting these two behaviors and compared them between the pre-sleep baseline in normal room light and the experimental awakening into identical lighting. Of the 27 measures of gait and balance, more than one-third (11) significantly differed upon a forced mid-sleep awakening and eight had medium to large effect sizes (Figures 3 & 4).

Discussion

Our data support that awakening from a nocturnal sleep episode impairs aspects of both gait and standing balance among healthy late middle-aged and older adults. To the best of our knowledge, this is the first study to test these particular spatial and temporal aspects of gait performance during a forced nocturnal awakening in late middle-aged and older adults; however, our standing balance findings are in contradiction to those previously reported.[17,18] These findings are contrary to two previous studies in which Frey et al.[17] found balance was not impaired during a nocturnal awakening on the difficult tandem walking task and Zammit et al.[18] reported no dynamic standing balance impairments as measured using a force plate during a nocturnal awakening. These studies were consistent with ours in participant health and age, and that the nocturnal awakenings all took place about two hours after habitual sleep time, however, all studies used different equipment, methods, and measured different output parameters. Further, Frey et al.'s[17] walking task was more difficult than our own, and it is possible that alertness circuits were sufficiently activated to more completely awaken their participants, minimizing differences from pre-sleep testing. Zammit et al.,[18] had fewer participants than our own study (n=12), and all but one of their participants was female. These variations may account for the disparities in results. We believe, however, that our participant population and walking task is more ecologically valid with respect to the risk of falls during nocturnal awakenings among late middle-aged and older adults.

Results from our hierarchical level models indicate that variation in stride velocity and normative path length (in both eyes open and eyes closed conditions) were significantly worse during a nocturnal awakening compared to pre-sleep baseline, supporting our hypothesis that gait and balance are impaired upon nocturnal awakenings. Contrary to our hypothesis, however, the change in gait and balance values between time points did not differ across lighting condition. This finding contradicts that of previous research that dim lighting impaired postural stability[14] and temporal and spatial measures of gait[16] when compared to room level lighting. Again, differences in protocols may provide an explanation for this disparity in results. Most notably, we tested the effects of light during a nocturnal awakening instead of during typical waking hours. It is possible that since balance and gait were significantly worse overnight

compared to daytime baseline testing, the influence of light was mitigated in our study due to a floor effect.

Interestingly, despite no changes in gait performance or standing balance, low contrast visual acuity decreased with decreasing illuminance. Despite the reduction in low contrast visual acuity, there was no associated change in gait performance or standing balance and it may be that other aspects of vision (e.g., visual field, depth perception) were not significantly affected by the lighting and were utilized to maintain consistent gait performance and standing balance.[40] It is also possible that, as our testing procedure involved walking on an even surface with no obstacles with evenly dispersed lighting throughout the room, low contrast visual acuity was not the critical visual function to successfully perform the gait and standing balance tasks. As this study was the initial pilot study to determine important factors, the experimental task was kept to main exploratory factors that would help guide future studies. It would be an important area of future research to understand how gait performance might differ in different lighting in environments where there are more challenging visual and gait tasks with more complicated factors such as hazards, uneven surfaces, or stairs, as all of these represent obstacles an older adult might face when walking from the bedroom to the toilet at night.

Given the variety of parameters used as a proxy for falls, and in order to not exclude any potential parameters, for our secondary analyses we ran a large number of exploratory tests with data only from the room-level white light condition. Through these analyses, we identified six parameters that were both statistically significant at the p=0.05 level and had medium to large effect sizes. Two of these were our *a priori* parameters of interest - variation in stride velocity and the standing balance COP path length (with eyes open). The remaining four parameters were variability in the gait parameters of double support time, single support time, swing percentage, and stance percentage. All four of these parameters are complimentary to each other in that they are related to the time in which the feet were either in contact or not in contact with the floor during the walking protocol. Greater variability in each of these temporal parameters has been previously associated with either retrospectively or prospectively-identified fallers

among older adults.[31,41–43] Our results support that inter-cycle variability in temporal parameters during walking assessments and deviation of the COP during standing assessments with eyes opened are increased during nocturnal awakenings. Several mean walking performance assessments - stride velocity, stride width, stride length, and step length – also statistically worsened from the pre-sleep to the nocturnal awakening assessments, but multiple comparisons without adjustment of *p*-values combined with small effect sizes caution us from concluding a meaningful difference in these parameters within the present study. Results from these exploratory analyses, along with previous work,[42] emphasize the importance of complementing mean assessments of gait with inter-cycle variability in parameters during walking assessments in future research, as it was the variability of specific parameters that had the largest effect sizes rather than the absolute average of the parameters.

We, however, only tested a single, approximate circadian phase and did not have a large enough sample size to discriminate the effect of awakening out of different sleep stages on measures of balance and gait. It is likely that balance and gait following a mid-sleep awakening will be impacted through non-linear interactions between circadian phase, homeostatic pressure, and sleep stage. Our forced awakenings, therefore, cannot be generalized to spontaneous awakenings resulting from nocturia. The current study's sample size also precluded the analyses of effects of demographics such as age, sex, and race on balance and gait. Future research should aim for sufficient power to consider sleep stage upon awakening and other important demographics factors that might influence gait and balance. Additional measurements, such as orthostatic blood pressure, could be incorporated into future studies to help further understand the multifactorial nature of falls in older adults.

The current findings suggest that balance and gait are impaired in the middle of the night even among healthy late middle-aged and older adults, but that this impairment is not mitigated by exposure to room lighting. These results suggest that mid-sleep awakenings are in and of themselves a risk factor for falls in the healthy aging population. Future research is necessary to understand how mid-sleep awakenings affect balance and gait in a population of adults with poor balance, as well as in less healthy

older adults, and whether specific types of nocturnal light exposure are useful countermeasures to such impairments in balance.

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Figure Legends

Figure 1. **Spectral characteristics of the lighting environments.**

Figure 2**. Differences in visual acuity across lighting conditions during the nocturnal awakening.** ***Post hoc*** **testing revealed graded difference by illuminance level.**

Figure 3**. Differences in normally-distributed gait performance and standing balance measurements between pre-sleep and nocturnal awakening in the room-level light condition expressed as Cohen's *d* effect sizes.** *=p<0.05; EC=Eyes closed; Shading indicates values during the nocturnal awakening that were lower than pre-sleep values; hatched columns indicate standing balance parameters.

Figure 4**. Differences in non-normally-distributed gait performance and standing balance measurements between pre-sleep and nocturnal awakening in the room-level light condition expressed as effect size *r*.** *=p<.05; EO=Eyes open; EC=Eyes closed; All parameter medians were higher during the nocturnal awakening compared to pre-sleep baseline; hatched columns indicate standing balance parameters.

Tables

Table 1. Demographics and Baseline Information

	Mean/Percentage ± Standard Deviation	Range
Age	64.7 ± 8.0	55-82
55-64	52.4%	
65-74	38.1%	
75-84	9.5%	
Sex		
Female	52.4%	
Race/ethnicity		
White	71.4%	
Black	4.8%	
Asian	4.8%	
Native Hawaiian	4.8%	
Biracial	9.5%	
Hispanic	14.3%	
BMI	26.9 ± 6.1	18.8-42.3
Baseline TST (hh:mm)	7:19 ± 0:44	5:58-9:04
Baseline SE (%)	91.9 ± 5.6	79.6-98.3
Owl & Lark Questionnaire	21.7 ± 5.1	11-27
Balance Self-Efficacy Scale (BES)	97.3 ± 3.0	88.3-100
Pittsburgh Sleep Quality Index (PSQI)	2.3 ± 1.4	0-5
Mini Mental State Examination (MMSE)	29.9 ± 0.3	29-30
Geriatric Depression Scale (GDS)	0.6 ± 0.9	0-3
Alcohol Use Disorders Identification Test (AUDIT)	1.5 ± 1.6	0-5
Health – Related Medication Use		
Hypertension	33.3%	
High Cholesterol	19.0%	
Vitamin	14.3%	
Cardiac Disease/Prevention	14.3%	
Inflammation	9.5%	
Hypothyroidism	4.8%	
Diabetes	4.8%	
Hormone Replacement Therapy	4.8%	
Erectile Dysfunction	4.8%	
Allergies	4.8%	

Table 2. Definition of the Zeno Walkway output parameters used.

Parameters	Definition
Gait	
Stride Velocity	The ratio of Stride Length by the Gait Cycle Time (cm/sec)
Stride Length	Distance from the heel of one foot to the following heel of the same foot (cm)
Step Length	Distance between corresponding successive points on the heel of opposite feel measured parallel to the direction of progression for the ipsilateral stride of which it is the second part (cm)
Stride Width	Distance between a line connecting the two ipsilateral foot heel contacts (the stride) and the contralateral foot heel contact between those events and is measured perpendicular to the stride (cm)
Step Time	The period of time taken for one step; is measured from first contact of one foot to the first contact of the following other foot (sec)
Gait Cycle Time	The period of time from first contact of one foot to the following first contact of the same foot (sec)
Cadence	The number of footfalls minus one, divided by the ambulation time (steps/min)
Double Support %	The sum of all periods of time when both feet are in contact with the ground during the stance phase, presented as a percentage of the Gait Cycle Time
Single Support %	The period of time when only the current foot is in contact with the ground, presented as a percentage of the Gait Cycle Time
Swing %	The period of time when the foot is not in contact with the ground, presented as a percentage of the Gait Cycle Time
Stance %	The period of time when the foot is in contact with the ground, presented as a percentage of the Gait Cycle Time
Standing Balance	
COP (Center of Pressure) Path Length	COP Path Length from start to end time for entire path travelled (cm/sec)
COP X Range	The range of the COP X position, from start time to end time (cm)
COP Y Range	The range of the COP Y position, from start time to end time (cm)

Table 3. Descriptive statistics of the gait and balance parameters examined. EO=Eyes open; EC=Eyes closed; [a] Indicates median values - as data were not normally distributed, non-parametric statistics were run on the median values

Parameters	Room-level Light Pre-Sleep Mean (SD)	Room-level Light Pre-Sleep %CoV	Room-level Light Awakening Mean (SD)	Room-level Light Awakening %CoV
Gait				
Stride Velocity	98.00 (15.98)	4.59	92.10 (12.73)	5.71
Stride Length	112.29 (13.87)	3.51	107.40 (12.34)	4.06
Step Length	55.96 (6.84)	4.99	53.68 (6.23)	5.78
Stride Width	8.88 (2.89)	24.98[a]	10.14 (3.35)	28.22[a]
Step Time	0.58 (0.06)	4.25	0.59 (0.06)	5.18
Gait Cycle Time	1.16 (0.12)	3.52	1.17 (0.11)	3.86
Cadence	103.81	-	101.63	-
Double Support %	26.87 (3.03)	4.85	27.25 (3.18)	6.45
Single Support %	36.66 (1.50)	4.19	36.28 (1.58)	5.25
Swing %	36.33 (1.64)	4.12	36.25 (1.58)	5.38
Stance %	63.67 (1.64)	2.01[a]	63.75 (1.00)	2.79[a]
Standing Balance				
COP (Center of Pressure) Path Length	EO: 0.62[a]	-	0.79[a]	-
	EC: 0.71[a]	-	0.76[a]	-
COP X Range	EO: 1.38[a]	-	1.61[a]	-
	EC: 1.53[a]	-	1.84[a]	-
COP Y Range	EO: 1.04[a]	-	1.13[a]	-
	EC: 1.40	-	1.55	-

Table 4. Results of the Model of Variation in Stride Velocity due to Time and Condition

Fixed Effect	**Coefficient**	**Standard Error**	***t* value**
Intercept, γ_{00}	4.523	0.275	16.429
Time, γ_{10}	1.210	0.276	4.068
Condition, γ_{11}	-	-	-

Random Effect	**Variance Component**
Participant mean, ζ_{0j}	0.791
Level-1 effect, ε_{ij}	3.039

Table 5. Results of the Model of Center of Pressure Path Length (Eyes Open) due to Time and Condition

Fixed Effect	**Coefficient**	**Standard Error**	***t* value**
Intercept, γ_{00}	0.845	0.096	8.79
Time, γ_{10}	0.169	0.060	2.81
Condition, γ_{11}	-	-	-

Random Effect	**Variance Component**
Participant mean, ζ_{0j}	0.156
Level-1 effect, ε_{ij}	0.146

Table 6. Results of the Model of Center of Pressure Path Length (Eyes Closed) due to Time and Condition

Fixed Effect	**Coefficient**	**Standard Error**	***t* value**
Intercept, γ_{00}	1.008	0.211	4.78
Time, γ_{10}	0.124	0.053	2.31
Condition, γ_{11}	-	-	-

Random Effect	**Variance Component**
Participant mean, ζ_{0j}	0.904
Level-1 effect, ε_{ij}	0.114

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