Impact of Physical Fitness and Daily Energy Expenditure on Sleep Efficiency in Young and Older Humans


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Key Words
Sleep efficiency · Inactivity · Exercise · Physical activity level · Randomized controlled trial

Abstract
Background: Physical activity is known to influence sleep efficiency. Relatively little is known about the relationship between physical activity and sleep efficiency in young and older humans and the impact of exercise training on sleep efficiency in healthy older individuals. Objectives: To determine the relationship between physical fitness and daily energy expenditure with sleep efficiency in young and older subjects, and assess the effect of 12-month exercise training on sleep efficiency in healthy older participants. Methods: The relationship between physical fitness (maximal cycling test) and daily energy expenditure (accelerometry) with sleep efficiency (accelerometry) was examined cross-sectionally in 12 healthy young adults (27 ± 5 years) and 21 healthy older participants (69 ± 3 years). Subsequently, the effect of 12-month exercise training (n = 11) or control period (n = 10) on sleep efficiency in older participants was examined using a randomized controlled trial. Results: Daily energy expenditure and sleep efficiency did not differ between young and older subjects. A significant correlation was found between energy expenditure and sleep efficiency (r = 0.627, p = 0.029) in young adults, but not in older participants (r = –0.158, p = 0.49). Physical fitness did not correlate with sleep efficiency in either group. Exercise training significantly improved physical fitness (15.0%, p < 0.001), but failed to alter sleep characteristics such as sleep efficiency, sleep onset latency and awakenings. Conclusions: We found that young adults with higher daily energy expenditure have greater sleep efficiency, whilst this relationship is diminished with advanced age. In contrast, we found no correlation between physical fitness and sleep characteristics in healthy young or older participants, which may explain the lack of improvement in sleep characteristics in older participants with 12-month exercise training. Exercise training may be more successful in subjects with existing sleep disturbances to improve sleep characteristics rather than in healthy older subjects.
Introduction

Impaired sleep quality is a frequently reported medical complaint [1], and sleep quality deteriorates with age [2, 3]. For example, 74–88% of the older population report sleep disturbances [3], whilst prevalence rates of insomnia in older subjects range between 12 and 54% [3, 4]. The most common treatment for sleep disturbances is a pharmacological intervention [5, 6]. However, frequent use of sleep medication is associated with several adverse side effects (e.g. sedation, drowsiness, risk of falling and dependence) [7, 8], which are more common in the older population [9, 10]. Therefore, alternative strategies to improve sleep quality in this population are required.

Physical activity is known to influence sleep quality. Previous studies have found that higher energy expenditure during the day is associated with energy conservation and tissue restoration during sleep [11–13], whilst the exercise-induced increase in core body temperature may activate sleep-associated heat-loss mechanisms (see [13] for an overview). In addition, physical exercise has been shown to have a positive influence on longer sleep duration [14–16]. Indeed, epidemiological studies have demonstrated an association between exercise levels and sleep quality [17, 18]. Several studies showed that exercise training can improve subjective and objective measures of sleep in groups with sleep disturbances [19–21], whilst good sleepers might benefit less from exercise training due to a ceiling effect in sleep quality [22, 23]. As most previous studies predominantly focus on groups with (mildly) impaired sleep, relatively little is known about the impact of age per se on the relationship between physical fitness or energy expenditure and sleep efficiency, i.e. an objective measure for sleep quality [24]. Moreover, the potential effects of long-term (12 months) exercise training to improve sleep efficiency in healthy, older humans are not frequently examined.

The purpose of the current study was to (1) investigate the relationship between physical fitness and daily energy expenditure with sleep efficiency in young adults and older participants, and (2) using a randomized controlled trial to examine the effect of a 12-month exercise training program on sleep quality measures, such as sleep onset latency and sleep efficiency, in a group of healthy older participants. We hypothesized that a higher physical fitness and a higher daily activity level are both associated with a better sleep efficiency and that 12 months of exercise training will enhance sleep efficiency in healthy older participants.

Methods

Participants

Twenty-one healthy older participants (11 males and 10 females, age 69 ± 3 years) and 12 healthy young sex-matched controls (6 males and 6 females, age 27 ± 5 years) were recruited from the local community (see fig. 1 for Consort diagram). Older participants, at least 65 years of age, were screened extensively through medical history, physical examination and blood testing. Young adults were screened through medical history and physical examination. Both the older participants and the young adults had a sedentary lifestyle (less than 1 h of physical activity of at least moderate intensity per week examined by self-report questionnaire). All participants were free of self-reported sleep and mood disturbances and did not use sleep medication, anti-depressants or cardiovascular medication. Individuals with cardiovascular disease and diseases that may interfere with sleep quality such as obesity (BMI >30 kg/m²), diabetes mellitus and hypertension (<160/90 mm Hg for older participants, <140/90 mm Hg for young controls) were excluded. The local ethics committee approved the study and conformed to the Declaration of Helsinki, all participants gave their written informed consent before participation.

Experimental Design

Sleep efficiency was examined using accelerometry over a 7-day period. In addition, all participants performed a maximal cycling test to determine physical fitness level. Young participants did not undergo a 12-month intervention, unlike the older participants who were randomly allocated after the baseline measurements to a 12-month intervention of either cycling exercise training or maintaining their current sedentary lifestyle (control).
Participants in the control group were firmly instructed to maintain their normal physical activity level. All measurements were repeated after 6 and 12 months. Efforts were made not to change medication throughout the intervention period, whilst participants who developed health problems that could interfere with sleep quality were excluded from the study.

**Measurements**

Energy Expenditure and Physical Fitness

**Energy Expenditure.** Daily energy expenditure (EE) was assessed using an activity monitor (SenseWear Pro3 Armband, SWA, Body Media) that was worn around the right upper arm. Sampling frequency was 32 Hz and data from the activity monitor were measured in 60-second epochs. The activity monitor measured 24 h per day for 7 consecutive days. Each 24-hour interval was analyzed from 12:00 to 12:00 the following day, and was included when the activity monitor recorded at least 1,296 min per 24-hour cycle (>90% of the total data). Data collected during the time in bed (see later for specific definition) was not included in the analysis for energy expenditure. EE was calculated as total number of kilocalories used per day. The activity monitor has been validated to examine EE in humans against indirect calorimetry, i.e. the gold standard to assess EE in resting and exercise conditions [25].

**Physical Fitness.** Physical fitness was assessed in all participants using a maximal exercise stress test on a bicycle ergometer (Lode, Excalibur Sport, Groningen, the Netherlands) with an incremental protocol (50 W and 10 W·min⁻¹ for older participants; 0 W and 20 W·min⁻¹ for young adults). During the test, participants were verbally encouraged to reach their maximum performance. Continuous measurement of oxygen consumption (VO₂) was performed using an automatic gas analyzer (Oxycon alpha, Jaeger, Breda, the Netherlands). Peak oxygen uptake, in ml O₂/min/kg, was taken as the average oxygen uptake of the last minute of the test and corrected for body weight. Heart rate was measured continuously with a 12-lead ECG. Criteria for the quality of the maximal performance test were: clinical signs of full exhaustion of the participant, respiratory quotient ≥ 1.10, finishing within 10 beats of the maximum predicted heart rate (= 220 – age), and flattening of VO₂ uptake curve (≤ 150 ml increase during the last minute) [26]. Three of 4 criteria had to be met for the test to be successful. Furthermore, blood lactate (mmol/l) was measured before and 2 min after the test and the 10-point Borg scale was used to rate the perceived exertion. When criteria of maximal performance were not reached, the test was repeated after 2 weeks.

Sleep Characteristics

The accelerometer (SenseWear Pro3 Armband, SWA, Body Media) utilizes a combination of sensors (heat flux, galvanic skin response, skin temperature, near body ambient temperature) and a bi-axial accelerometer which allows for assessment of sleep characteristics. The SenseWear data were reduced to binary forms for ‘lying’ (‘0’ = no, ‘1’ = yes) and ‘sleeping’ (‘0’ = no, ‘1’ = yes). These data were used to determine the sleep onset latency, total sleep time, time in bed and the number of awakenings (see below). Each 24-hour interval was analyzed from 12:00 to 12:00 h the following day for a detailed description of one entire sleeping episode. These data were analyzed using a customized analysis software system, which is independent of observer bias. Subsequently, sleep characteristics were averaged across the 7 days and used for further analysis. The activity monitor has been validated to examine sleep against polysomnography [27, 28], i.e. a technique that is considered by many the gold standard to assess sleep physiology in humans.

**Sleep Onset Latency.** The sleep onset was defined as the first encounter of 10 min of which at least 90% of the minutes were scored sleeping after positional change from upright to supine position (i.e. change from ‘0’ to ‘1’ for ‘lying’) [29, 30]. The sleep onset latency was defined as the duration from the positional change to the start of the sleep onset. This definition is in agreement with various other studies that used accelerometry as an objective measure for sleep quality and efficiency [24, 31, 32].

**Total Sleep Time and Sleep Efficiency.** The time in bed was defined as the duration from positional change from upright to supine position (i.e. change from ‘0’ to ‘1’ for ‘lying’) to the first encounter of positional change from supine to upright after awakening (i.e. change from ‘1’ to ‘0’ for ‘lying’). The total sleep time was defined as the total sum of the minutes scored sleeping from sleep onset to the end of the sleeping episode. The sleep efficiency was calculated by: ([total sleep time/time in bed] * 100) [24].

**Awakenings.** The number of awakening is the amount of awake periods of at least 1 min, excluding the final awakening before arising [24].

**Exercise Intervention**

Exercise training was performed 3 times per week for 12 months on a cycling ergometer (Medgraphics, Corival Cycle Ergometer). Each exercise session was supervised and consisted of 10 min warming up at 60% of the individual heart rate reserve (calculated as ([(maximum heart rate – resting heart rate) * 0.60] + resting heart rate)). This was followed by 30 min cycling exercise at 70–85% of the individual heart rate reserve and ended with 5 min cooling down. Heart rate was continuously monitored during exercise using heart rate monitors (Polar RS800; Polar Electro Oy, Kempele, Finland). Workload was individually adjusted throughout the training to correct for improvements in physical fitness.

**Statistical Analysis**

Statistical analysis was performed with the use of Statistical Package for the Social Sciences (SPSS, version 16, Chicago, Ill., USA). Exploration of distribution indicated the data were normally distributed; therefore, baseline differences between the young adults and older participants were analyzed using unpaired t tests for continuous variables and χ² test for categorical data. Correlations between physical fitness, energy expenditure and sleep parameters were determined using Pearson’s correlation coefficient. In the older participants, a two-way repeated measures ANOVA was used to analyze changes in physical fitness, energy expenditure and sleep efficiency outcome variables across the 12-month period (time points: 0, 6 and 12 months), and to analyze differences between training versus control interventions. Data were presented as mean ± SD and the level for significance was set at α ≤ 0.05.
Results

All subjects successfully completed our intervention study. Adherence to the exercise training sessions was 91 ± 8% (range 72–97, median 92). Adherence was defined as completing a training session of at least 30 min cycling at an intensity of 170% of the individual’s heart rate reserve. Subject characteristics of the two study groups are shown in Table 1. Young adults had a lower body mass index and higher physical fitness compared to the older participants. No differences in sleep onset latency, total sleep time and sleep efficiency were observed between young adults and older participants. A significant higher number of awakenings were evident in young adults compared with older participants (Table 1).

Correlation Physical Fitness/Energy Expenditure and Sleep Characteristics

A significant and positive correlation was found between daily energy expenditure and sleep efficiency in young adults (Fig. 2). This correlation was not present in the older cohort (Table 2). Energy expenditure did not correlate with sleep onset latency, total sleep time and awakenings in young adults nor in older participants (Table 2). No correlation was found between physical fitness (V̇O₂max) and sleep characteristics in young adults or older participants (Table 2).

Randomized Controlled Trial in Older Participants

No differences were found in baseline characteristics between both older groups prior to the 12-month intervention (Table 3). Nor were there differences in physical fitness, maximal workload or sleep characteristics between both older groups prior to the 12-month intervention (all p > 0.05; Table 4). A significant increase in physical fitness and maximal workload was found in older participants who performed the exercise training (Table 4). These findings indicate that our exercise training program was successful to improve physical fitness levels in healthy older subjects. A similar change across time was found in energy expenditure in both groups, with higher levels at 6 months (Table 4). However, we found no effect of the 12-month intervention on sleep onset latency, total sleep time, sleep efficiency and the number of awakenings (Table 4).

Discussion

The purpose of this study was to examine the impact of advanced age on the relation between physical fitness and daily energy expenditure with sleep characteristics. We have a number of unique findings in this study. First, a strong relationship between energy expenditure and sleep efficiency was found in young adults and this relationship was absent in the older population. Second,
physical fitness and sleep characteristics were not significantly correlated in young adults or older participants. Finally, despite significantly improved physical fitness in healthy older participants, exercise training had no significant effect on sleep characteristics in this population. Collectively, these findings suggest that the relationship between energy expenditure and sleep efficiency is altered in healthy older participants compared with young peers. The absence of a correlation between physical fitness and sleep efficiency could explain the lack of im-

Table 2. Correlation of physical fitness (VO\textsubscript{2max}) and EE with sleep characteristics (sleep onset latency, total sleep time, sleep efficiency and number of awakenings) in young (n = 12) and older participants (n = 21)

<table>
<thead>
<tr>
<th></th>
<th>Young participants</th>
<th>Older participants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p value</td>
<td>p value</td>
</tr>
<tr>
<td>Physical fitness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep onset latency (min)</td>
<td>0.198</td>
<td>0.54</td>
</tr>
<tr>
<td>Total sleeping time (min)</td>
<td>−0.162</td>
<td>0.62</td>
</tr>
<tr>
<td>Sleep efficiency (%)</td>
<td>0.273</td>
<td>0.39</td>
</tr>
<tr>
<td>Number of awakenings</td>
<td>0.299</td>
<td>0.35</td>
</tr>
<tr>
<td>EE</td>
<td></td>
<td></td>
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<tr>
<td>Sleep onset latency (min)</td>
<td>−0.167</td>
<td>0.60</td>
</tr>
<tr>
<td>Total sleeping time (min)</td>
<td>0.231</td>
<td>0.47</td>
</tr>
<tr>
<td>Sleep efficiency (%)</td>
<td>0.627*</td>
<td>0.029</td>
</tr>
<tr>
<td>Number of awakenings</td>
<td>−0.154</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Table 3. General characteristics of the older population included in the 12-month intervention of either exercise training (n = 11) or control group that maintained their physical activity level (n = 10)

<table>
<thead>
<tr>
<th>Baseline characteristics</th>
<th>Exercise training</th>
<th>Control</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (male:female)</td>
<td>5:6</td>
<td>5:5</td>
<td>0.08</td>
</tr>
<tr>
<td>Age, years</td>
<td>68 ± 2</td>
<td>70 ± 2</td>
<td>0.49</td>
</tr>
<tr>
<td>Height, cm</td>
<td>173 ± 8</td>
<td>170 ± 7</td>
<td>0.31</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>76.5 ± 12.4</td>
<td>71.3 ± 10.4</td>
<td>0.17</td>
</tr>
<tr>
<td>Daily EE, kcal</td>
<td>1,863 ± 364</td>
<td>1,675 ± 207</td>
<td>0.11</td>
</tr>
<tr>
<td>Systolic BP, mm Hg</td>
<td>125 ± 12</td>
<td>137 ± 19</td>
<td>0.11</td>
</tr>
<tr>
<td>Diastolic BP, mm Hg</td>
<td>76 ± 10</td>
<td>82 ± 13</td>
<td>0.31</td>
</tr>
</tbody>
</table>

p value refers to an unpaired t test between both groups. Data are presented as mean ± SD.

Table 4. Physical fitness and sleep characteristics of the exercise group (n = 11) and control group (n = 10)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Group</th>
<th>Time, months</th>
<th>2-way ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>training</td>
<td>25.5±1.1</td>
<td>24.9±2.1</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>24.5±2.8</td>
<td>24.6±2.4</td>
</tr>
<tr>
<td>Energy expenditure, kcal</td>
<td>training</td>
<td>1,863±364</td>
<td>1,954±319*</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>1,675±207</td>
<td>1,721±222</td>
</tr>
<tr>
<td>VO\textsubscript{2max}, ml O₂/kg/min</td>
<td>training</td>
<td>24.7±3.6</td>
<td>28.5±3.3</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>26.0±5.2</td>
<td>25.5±4.9</td>
</tr>
<tr>
<td>Maximal workload, W</td>
<td>training</td>
<td>141±31</td>
<td>169±33</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>144±41</td>
<td>140±35</td>
</tr>
<tr>
<td>Sleep onset latency, min</td>
<td>training</td>
<td>11±7</td>
<td>10±6</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>8±4</td>
<td>10±2</td>
</tr>
<tr>
<td>Total sleeping time, min</td>
<td>training</td>
<td>371±52</td>
<td>366±42</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>386±46</td>
<td>374±44</td>
</tr>
<tr>
<td>Sleep efficiency, %</td>
<td>training</td>
<td>82±11</td>
<td>84±10</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>84±8</td>
<td>81±9</td>
</tr>
<tr>
<td>Number of awakenings</td>
<td>training</td>
<td>9±4</td>
<td>8±4</td>
</tr>
<tr>
<td></td>
<td>control</td>
<td>10±3</td>
<td>9±3</td>
</tr>
</tbody>
</table>

Participants were measured at 0, 6 and 12 months. Data are presented as mean ± SD. A 2-way ANOVA was used to examine changes in parameters across the 12-month period (’intervention’; 0 vs. 6 vs. 12) and whether the change across the intervention differed between both groups (’time*group’). p values for these comparisons are provided in this table. * Posthoc significantly different from 0.
provement in sleep efficiency after a 12-month exercise training program in healthy older participants.

We found no significant differences in sleep time and sleep efficiency between young adults and older participants in our study. This finding is consistent with observations from Jean-Louis et al. [33], but contrasts with others that reported that older age is associated with lower sleep efficiency [4, 34]. A potential explanation for the conflicting results is that some previous studies used sleep questionnaires to assess sleep efficiency [4], which are found to be less reliable than activity monitors to examine sleep efficiency [35]. Another important difference between studies is that we included healthy participants without the presence or history of sleep problems, whilst others included older participants who were institutionalized [34] and who were likely to demonstrate altered sleep patterns [36]. Finally, one previous study did not control for pharmacological interventions [34] that may have interfered with sleep efficiency. An unexpected finding in our study relates to the higher number of awakenings in young adults than in older people, which contrasts with findings of previous studies [34, 37]. However, one previous study also found more awakenings in younger women using an actigraph [33]. Young adults may demonstrate more movement during sleep, which is not necessarily associated with awake episodes. As a result, accelerometry may (incorrectly) identify these periods of higher activity level during sleep as awake periods [31, 32, 38]. Collectively, we found no differences in sleep efficiency between young adults and older participants, which indicates that we have included healthy young adults and older participants without sleep disturbances.

We found a strong positive correlation between daily energy expenditure and sleep efficiency in young people. This finding is in agreement with meta-analyses indicating that sleep may improve following physical exercise of longer durations [14, 16] and that duration, rather than intensity or time of day, might be more predictive of better sleep [14]. Another study examined physical activity levels and found no significant association between day-to-day physical activity and sleep in healthy young and older subjects [23]. However, they also found a small but significantly better self-reported sleep on the most active days compared to the least active days in young subjects. Although speculative, activation of thermoregulatory responses during periods of increased physical activity may relate to the positive correlation between daily energy expenditure and sleep efficiency in young adults [13]. Physical activity, even when performed at moderate intensity such as walking [39, 40] or cycling [41], causes a mild rise in core body temperature, and is followed by activation of heat-loss processes [42]. When performed in the evening, these responses may play a role during the initiation of sleep [43, 44]. However, the exact role of the thermoregulation to explain the link between activity level and sleep should be further examined. Another explanation relates to the ability of sleep for energy conservation and tissue restoration. Increased daily energy expenditure will deplete energy stores, leading to a larger energy restoration during sleep, which consequently is associated with an enhanced sleep efficiency [12, 13]. Finally, high catabolic activity during exercise is associated with a higher energy expenditure, which leads to elevated anabolic activity during sleep. The higher anabolic activity is believed to promote energy use for tissue restoration, but also contributes to improved sleep efficiency [11, 13].

An important and novel finding is that the positive relationship between energy expenditure and sleep efficiency is altered with advanced age, as older participants did not demonstrate a significant correlation. This observation raises questions about the potential mechanisms for the altered relationship between energy expenditure and sleep efficiency with advanced age. One potential explanation relates to the age-related degeneration of the suprachiasmatic nucleus in the hypothalamus [44]. The suprachiasmatic nucleus is the major circadian pacemaker that coordinates behavioral and hormonal circadian rhythms, such as core body temperature, and initiates sleep through thermoregulatory responses [43]. Degeneration of the suprachiasmatic nucleus in older individuals may play a role in their diminished rest-activity circadian rhythm [34]. Another explanation relates to the ability of anabolic processes to regulate sleep. Advanced age is associated with a smaller skeletal muscle mass [45], but also inadequate protein intake [45, 46]. These changes may contribute to impaired anabolic processes in the older group and, therefore, to the impaired relation between energy expenditure and sleep efficiency in older participants. Taken together, our study provides the unique observation that advanced age leads to an attenuated relation between energy expenditure and sleep efficiency.

We found no correlation between physical fitness and sleep characteristics in young adults. This finding is in agreement with some studies [47, 48], which also found that physical fitness does not determine sleep efficiency in young participants. Although others found a correlation between physical fitness and sleep quality [49], this study used subjective measures to assess sleep. We ex-
tend the findings of these previous studies that also healthy older individuals do not demonstrate a relation between physical fitness and sleep characteristics. These findings seem to contrast with the correlation between energy expenditure and sleep characteristics. Nevertheless, higher energy expenditure does not necessarily correlate with a higher physical fitness level [50]. It is demonstrated that higher intensity daily activity levels (METs) rather than energy expenditure, relate to higher physical fitness [51]. Indeed, also in our cohorts of healthy young adults and older participants, we found no significant correlation \( r = 0.086, p = 0.64 \) between energy expenditure and physical fitness. Therefore, our results suggest that a higher physical fitness level per se does not contribute to an improvement of sleep characteristics in healthy individuals.

The lack of a relationship between physical fitness and sleep characteristics is confirmed by the findings of the 12-month exercise training in older individuals. Whilst a marked improvement in physical fitness and maximal workload was found, no changes in sleep characteristics were evident. Although some previous studies provided evidence that exercise training improves sleep quality in adults with (mild) sleep disturbances, these studies typically employ self-reported, subjective measures of sleep quality [19, 21]. When adopting objective measures of sleep, beneficial effects of exercise training on sleep characteristics are rare [52, 53] or mild [20]. Another important methodological difference is that previous studies included participants with moderate sleeping complaints, who are therefore more likely to benefit from an (exercise) intervention to alter sleep characteristics than participants with a normal sleep pattern [13], such as those included in our study. Subjects with normal sleep patterns show a ceiling effect when the effect of an intervention is examined aimed to improve sleep [13, 22]. Therefore, our finding that exercise training does not improve sleep characteristics in healthy older subjects, despite the improved physical fitness, further supports our finding that the relationship between energy expenditure and sleep is blunted with age.

A number of limitations should be considered. First, in this study accelerometry was used to measure sleep characteristics. Accelerometry is a valid and accurate method to assess sleep characteristics [27, 28, 32, 38] and is used previously in sleep-activity studies [31, 34]. Accelerometry provides the advantage of providing an objective assessment of sleep characteristics in a home-based setting with little disruption to normal sleep pattern, whereas the use of polysomnography is impractical in a home-based setting and typically requires a laboratory visit. Nonetheless, the validity of the SenseWear to examine sleep loses some accuracy when sleep becomes more disturbed [28]. Also, estimation of periods of wakefulness by the SenseWear is less accurate than sleep [28], which may impact the total sleep time variable, and therefore the calculation of sleep efficiency. Nevertheless, a previous study found minor discrepancy (14 min) between the SenseWear and polysomnography for the total sleep time [28]. Whilst the use of the SenseWear is associated with some limitations, we have not included subjective measures of sleep quality in our study. Moreover, participants were not informed about the purpose of this study, which excludes the potential for subject bias. Therefore, based on the purpose and methodology of our study, accelerometry is an appropriate and valid tool to examine sleep efficiency.

Another limitation of this study is that we included healthy older subjects without sleep disturbances. Inclusion of such a homogeneous group makes it difficult to extrapolate our results to different groups, whilst the absence of sleep disturbances resulted in low a priori chances to improve sleep characteristics. Also, the relatively small sample size may have contributed to the lack of improvement in sleep characteristics after training. However, it should be taken into consideration that subjects trained for 12 months, i.e. a methodological design that corrected for potential seasonal influences and thereby excluded the potential influence of the daylight cycle on sleep characteristics [13, 54]. Taken together, our results indicate that exercise training in healthy older participants, without (a history of) sleep complaints, does not alter objective measures of sleep efficiency.

**Conclusion**

In conclusion, we found that young adults with higher daily energy expenditure have greater sleep efficiency, whilst this relationship is attenuated with advanced age. In contrast, we found no correlation between physical fitness and sleep characteristics in healthy young adults or older participants, which may explain the lack of improvement in sleep characteristics in healthy older participants with 12 months of exercise training. Exercise training may be more successful in subjects with existing sleep disturbances to improve sleep characteristics rather than in healthy older subjects.
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Disclosure Statement

The authors declare that no competing interests are associated with this study.

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