

American Journal of Preventive Medicine

RESEARCH ARTICLE

Associations of Activity and Sleep With Quality of Life: A Compositional Data Analysis



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Introduction: Associations between time spent on physical activity, sedentary behavior, and sleep and quality of life are usually studied without considering that their combined time is fixed. This study investigates the reallocation of time spent on physical activity, sedentary behavior, and sleep during the 24-hour day and their associations with quality of life.

Methods: Data from the 2011–2016 Rotterdam Study were used to perform this cross-sectional analysis among 1,934 participants aged 51–94 years. Time spent in activity levels (sedentary, light-intensity physical activity, moderate-to-vigorous physical activity, and sleep) were objectively measured with a wrist-worn accelerometer combined with a sleep diary. Quality of life was measured using the EuroQoL 5D-3L questionnaire. The compositional isotemporal substitution method was used in 2018 to examine the association between the distribution of time spent in different activity behaviors and quality of life.

Results: Reallocation of 30 minutes from sedentary behavior, light-intensity physical activity, or sleep to moderate-to-vigorous physical activity was associated with a higher quality of life, whereas reallocation from moderate-to-vigorous physical activity to sedentary behavior, light-intensity physical activity, or sleep was associated with lower quality of life. To illustrate this, a reallocation of 30 minutes from sedentary behavior to moderate-to-vigorous physical activity was associated with a 3% (95% CI=2, 4) higher quality of life score. By contrast, a reallocation of 30 minutes from moderate-to-vigorous physical activity to sedentary behavior was associated with a 4% (95% CI=2, 6) lower quality of life score.

Conclusions: Moderate-to-vigorous physical activity is important with regard to the quality of life of middle-aged and elderly individuals. The benefits of preventing less time spent in moderate-to-vigorous physical activity were greater than the benefits of more time spent in moderate-to-vigorous physical activity. These results could shift the attention to interventions focused on preventing reductions in moderate-to-vigorous physical activity levels. Further longitudinal studies are needed to confirm these findings and explore causality.

Am J Prev Med 2020;59(3):412–419. © 2020 American Journal of Preventive Medicine. Published by Elsevier Inc. All rights reserved.

INTRODUCTION

The aging process is related to an increased risk of morbidity and disability, which could result in a lower quality of life (QoL).¹ Recent studies have shown that higher levels of physical activity (PA) and lower levels of sedentary time are associated with better QoL.^{2,3} In addition, both short and long sleep durations (≤ 6 and ≥ 9 hours, respectively) have been linked to

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0749-3797/\$36.00

<https://doi.org/10.1016/j.amepre.2020.03.029>

poorer QoL.^{4,5} However, most previous studies on activity and QoL have important limitations.

First, the association of PA and sleep with QoL has been studied previously either in isolation or with only partial adjustment for time spent in other behaviors.⁶ Traditional regression and isotemporal substitution models use time-dependent activity data as absolute continuous values. However, daily time is constrained at 24 hours, and all activity combined contributes to a composite whole. Time spent in one level of activity necessarily replaces time spent in at least one other level, and little is known about the effect of replacing one level of activity with another in this finite space of time. Although some studies attempted to take this into account by expressing activity behaviors in proportions or percentages with respect to the given total, this still gives the problem of collinearity when assessing multiple behaviors. An alternative analytic approach is the compositional isotemporal substitution model, which addresses the codependency of activity behaviors to account for the time spent in each behavior by treating each behavior as a composite of a finite whole.⁷ Because the compositional analysis uses time-dependent activity data as relative values, this also allows for asymmetrical results for the reallocation of behaviors.

Second, measures of daytime activity and sleep in these studies have mostly been assessed with self-reported questionnaires.^{1,3–5} These subjective measurements are prone to reporting errors and recall bias, especially in older populations, in whom cognitive impairment is more likely.⁸ The Rotterdam Study is a large population-based study with objectively assessed measures of daytime activity and sleep in a middle-aged and elderly population by using a wrist-worn triaxial accelerometer.⁹ Wrist-worn devices can be worn day and night, thereby allowing for collection of 24 hours of activity data. These 24-hour activity data and the compositional isotemporal substitution model can be used to assess the difference in QoL estimated for any reallocation between daily activity behaviors.

The aim of this study is to investigate the allocation of PA, sedentary behavior (SB), and sleep during the 24-hour day and its association with QoL in a middle-aged and elderly population of the Rotterdam Study.

METHODS

Study Population

A cross-sectional analysis was performed in 2018, embedded in the Rotterdam Study, an ongoing prospective population-based cohort study in the Netherlands. Detailed information on the Rotterdam Study can be found elsewhere.⁹

Between June 2011 and June 2014 (Wave 1) and between July 2014 and May 2016 (Wave 2), 3,507 participants were invited to wear an accelerometer for 7 days. Of this total, 2,102 participants

had complete information on QoL and data on activity for ≥ 4 days with $>1,200$ minutes per day (Figure 1). From this group, an additional 79 participants without sleep diary data were excluded and 89 observations were excluded for participants who participated in both waves. The remaining 1,934 participants were considered eligible for analysis. There were no major differences between the included and excluded participants (Appendix Table 1, available online).

Measures

To measure activity, all participants were asked to wear a triaxial accelerometer (GeneActiv) on the nondominant wrist for 7 consecutive days and nights and to additionally complete a 7-day sleep diary in which overnight sleep periods were reported. Because the GeneActiv device is waterproof, it can also be worn while bathing and swimming. As in previous studies, the accelerometer was sampled at 50 Hz and acceleration was expressed in milligal (mg) relative to gravity ($1\text{ g}=9.81\text{ m/s}^2$).^{10–13} Nonwear time was estimated as time periods where the SD of acceleration in all 3 axes fell below 13 mg for >1 hour and was excluded from analyses. Accelerometer data were processed in Python, version 2.6.6, using the open-access PAMPRO software, version 0.3 (T. White [2016]; <https://zenodo.org/badge/latestdoi/18706328>).

Activity was categorized into SB (<48 mg), light-intensity PA (LIPA; 48–154 mg), and moderate-to-vigorous PA (MVPA; >154 mg).¹⁴ Sleep duration was quantified with a validated algorithm¹⁵ using information on overnight sleep periods from the sleep diary and subtracted from total SB. All the 4 activity levels were expressed in minutes per day and added up to 24 hours when combined.

Health-related QoL (hereafter referred to as QoL) was measured using the Dutch version of the EuroQoL 5D-3L (EQ-5D-3L). The EQ-5D-3L consists of 5 dimensions (5D; i.e., mobility, self-care, daily activities, pain/discomfort, and mood) assessed with a single question.¹⁶ These 5 questions can be scored according to 3 response levels (3L; i.e., no problems, some or moderate problems, and extreme problems) coded from 1 to 3. Placing the answers of all the 5 questions in a series results in a 5-digit QoL profile (e.g., 12,323), where 11,111 represents the best possible QoL and 33,333 the worst. This profile was converted with weighted utility scores to an overall index score ranging from 0 (poor QoL) to 1 (perfect QoL) as described in more detail elsewhere.¹⁷ As an additional indicator of QoL, the EQ-5D-3L includes a standard vertical 20 cm visual analog scale (VAS), where individuals can indicate their current health on a scale from 0 to 100.

Information on covariates was collected through home interviews or questionnaires or at the study center. Height and weight were measured, and BMI was calculated (kg/m^2). A food frequency questionnaire was used to compute a diet quality score,¹⁸ and alcohol consumption (g/day) was obtained. In a home interview, the authors obtained information on smoking (former/current/never), education (4 categories¹⁹), marital status (partner yes/no), job status (employed/unemployed), and living situation (completely independent/partially independent). Information on chronic diseases was obtained from the interview, measurements in the center, and medical records. A comorbidity score was created as the number of current chronic conditions (i.e., presence of cancer, diabetes, or cardiovascular disease). Information on the use of sleep medication (yes/no) in the past 7 days was obtained from the sleep diary.

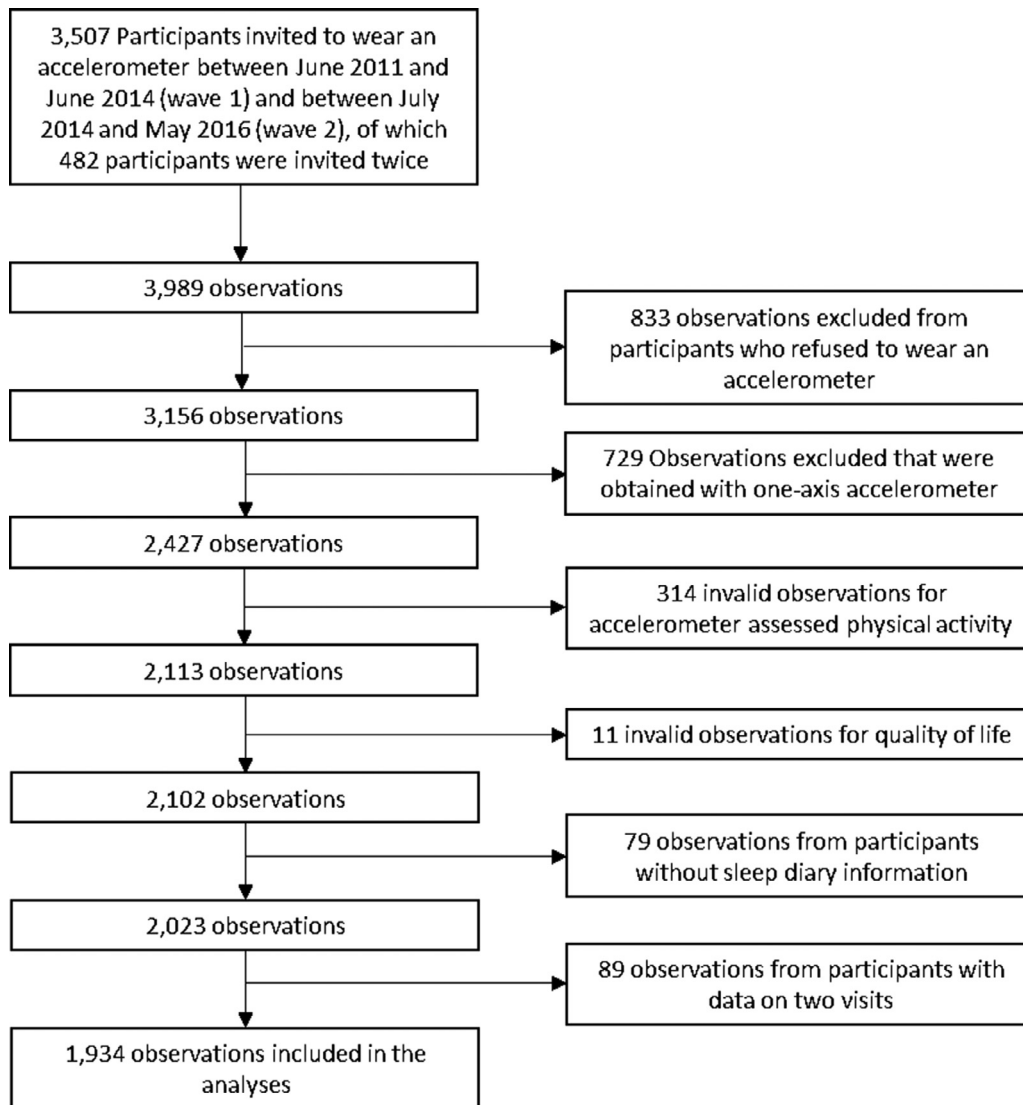


Figure 1. Flow chart of participant inclusion.

Statistical Analysis

Descriptive statistics were used to characterize the sample. For the compositional analysis, activity compositions were created by expressing the time spent in each activity (i.e., LIPA, MVPA, SB, and sleep) as a proportion of the 24-hour day. The activity compositions were then expressed as isometric log-ratio coordinates to account for the interdependency of the activity domains.⁷ These coordinates were used to express the activity composition in linear regression models, with the QoL score as the dependent variable and the activity composition as the independent variable. The linear models were then used in a prediction function in R to estimate the QoL score for a specific activity composition. In this scenario, the QoL score was first obtained for the mean activity composition of the study population and then for a composition in which time spent in 1 activity domain was substituted for time spent in another (e.g., 30 minutes of sleep reallocating 30 minutes of SB) relative to the mean activity composition. Then, the difference in QoL scores along with the 95% CI was computed.

Two models were created. The first model was adjusted for sex and age. The second model was additionally adjusted for education, marital status, living situation, job status, smoking, alcohol, diet score, BMI, comorbidity score, and the use of sleep medication.^{20,21} Within each model, 2 different analyses were performed. In the first analysis, the differences in the EQ-5D-3L index score were estimated. The second analysis estimated the differences in the VAS score.

The data contained 43.7% missing data for dietary variables and 6.6% for job status. All other covariates had <2% missing data. Multiple imputation ($n=10$ imputations) was used by the expectation maximization method. Analyses were performed on all imputed data sets separately, and the results were pooled. Stratified analyses by sex, age, and MVPA level were conducted, in which age and MVPA were stratified at the median level (i.e., 72 years and 79 minutes, respectively).^{20,21} All analyses were conducted using SPSS, version 24, and R, version 3.1.3.

RESULTS

The characteristics of the study population are shown in [Table 1](#). The mean age of the participants was 70.9 (SD=9.27) years, and 51.5% were women. Mean hours of sleep and SB per day were 6.43 (SD=1.04) hours and 13.54 (SD=1.31) hours, respectively. Mean minutes of LIPA and MVPA per day were 148.11 (SD=31.54) minutes and 82.72 (SD=28.74) minutes, respectively. The mean QoL EQ-5D-3L index score was 0.87 (SD=0.16).

In the multivariable-adjusted models, a reallocation of 30 minutes from MVPA to SB, LIPA, or sleep was associated with a lower EQ-5D-3L index score ([Table 2](#)). Similarly, reallocation of 30 minutes to MVPA from SB, LIPA, or sleep was associated with a higher EQ-5D-3L index score. The largest estimated difference in EQ-5D-3L index score was -0.05 (95% CI= $-0.08, -0.02$) on a score ranging from 0 to 1 when reallocating 30 minutes

of MVPA to LIPA, meaning that this reallocation was associated with a 5% decrease in EQ-5D-3L index score. The estimated differences in the EQ-5D-3L index score were not exactly symmetrical. For example, a reallocation of 30 minutes from MVPA to SB was associated with a slightly larger difference in the EQ-5D-3L index score (-0.04 , 95% CI= $-0.06, -0.02$) than the reallocation of 30 minutes from SB to MVPA (0.03, 95% CI=0.02, 0.04).

For the VAS score, the results were similar to those of the EQ-5D-3L index score ([Table 2](#)). Reallocating time from MVPA was associated with a lower VAS score, whereas reallocating time to MVPA was associated with a higher VAS score. For the VAS score, the largest estimated difference was -3.84 (95% CI= $-6.35, -1.32$) on a score ranging from 0 to 100 for reallocation of 30 minutes from MVPA to LIPA.

When 30 minutes of SB or sleep were replaced with 30 minutes of LIPA, or vice versa, the association was not significant with both indicators of QoL ([Table 2](#)). Results of the sex–age-adjusted model were similar for the EQ-5D-3L index score and VAS score ([Appendix Table 2](#), available online).

In the stratified analyses, associations for MVPA were slightly stronger for men among participants aged ≥ 72 years and those with lower MVPA levels but remained statistically significant in all subgroups for the EQ-5D-3L index ([Appendix Tables 3–5](#), available online). In the male category, among younger participants, and among those with high MVPA levels, a higher LIPA tended to be associated with a lower QoL but only for the EQ-5D-3L index score and estimates were small. For QoL measured with the VAS score, results for MVPA were in a similar direction but no longer statistically significant for women, participants aged < 72 years, and those with higher MVPA levels ([Appendix Tables 6–8](#), available online).

DISCUSSION

In this middle-aged and elderly population, reallocating 30 minutes to MVPA from any other activity behavior is associated with a higher QoL score, whereas reallocating 30 minutes from MVPA to any other activity behavior is associated with a lower QoL score. In addition, the association between MVPA and QoL is not exactly symmetrical; a decrease in MVPA has a slightly larger association than an increase in MVPA.

To the authors' knowledge, this is the first study using compositional data analysis to investigate the association between the distribution of time spent in 4 different activity behaviors and QoL in middle-aged and elderly adults. Recently, a similar study using compositional

Table 1. Characteristics of the Study Population (N=1,934)

Characteristics	Mean (SD)
Age, years	70.9 (9.27)
Women, n (%)	996 (51.5)
Educational level, n (%)	
Primary education	118 (6.1)
Lower education	719 (37.2)
Intermediate education	597 (30.9)
Higher education	500 (25.9)
Living independent, n (%)	1,842 (95.2)
Employed, n (%)	426 (22.0)
Living with someone, n (%)	1,397 (72.2)
Smoking, n (%)	
Never	627 (32.4)
Former	1,137 (58.8)
Current	170 (8.8)
Alcohol, g/day	12.9 (15.7)
BMI	25.1 (4.6)
Diet quality score (0–14)	6.8 (1.9)
Comorbidities, n (%)	
0	1,138 (58.8)
1	623 (32.2)
2	153 (7.9)
3	20 (1.0)
Use of sleep medication, n (%)	283 (14.6)
Sleep (hours/day)	6.4 (1.0)
Sedentary behavior (hours/day)	13.5 (1.3)
LIPA (minutes/day)	148.1 (31.5)
MVPA (minutes/day)	82.7 (28.7)
EQ-5D-3L index score	0.87 (0.16)
VAS score	78.9 (14.1)

Note: Numbers are mean (SD) unless otherwise stated. EQ-5D-3L, EuroQoL 5D-3L; LIPA, light-intensity physical activity; MVPA, moderate-to-vigorous physical activity; VAS, visual analog scale.

Table 2. Associations of 30 Minutes Reallocations Between Activity Behaviors With the EQ-5D-3L Index Score and VAS Score (N=1,934)

Variable	LIPA, Delta (95% CI)	MVPA, Delta (95% CI)	SB, Delta (95% CI)	Sleep, Delta (95% CI)
EQ-5D-3L index score				
LIPA	—	-0.05 (-0.08, -0.02)	-0.01 (-0.02, 0.001)	-0.01 (-0.02, 0.002)
MVPA	0.04 (0.02, 0.06)	—	0.03 (0.02, 0.04)	0.03 (0.02, 0.04)
SB	0.01 (-0.001, 0.03)	-0.04 (-0.06, -0.02)	—	0.002 (-0.002, 0.005)
Sleep	0.01 (-0.002, 0.02)	-0.04 (-0.06, -0.02)	-0.001 (-0.005, 0.002)	—
VAS score				
LIPA	—	-3.84 (-6.35, -1.32)	-0.86 (-1.84, 0.12)	-0.66 (-1.63, 0.31)
MVPA	3.05 (0.87, 5.24)	—	2.00 (0.89, 3.11)	2.20 (1.05, 3.36)
SB	1.05 (-0.13, 2.24)	-2.97 (-4.63, -1.32)	—	0.20 (-0.09, 0.50)
Sleep	0.86 (-0.31, 2.04)	-3.16 (-4.86, -1.47)	-0.19 (-0.47, 0.09)	—

Note: Boldface indicates statistical significance ($p < 0.05$).

Estimates are obtained from compositional data analysis and reflect the difference in EQ-5D-3L index score and VAS score for the reallocation of time from the behavior in the column to the behavior in the row, while keeping the time spent in other activities constant (i.e., the first value of -0.05 in Row 1 is the estimated difference in EQ-5D-3L index score for the reallocation of 30 minutes from MVPA to LIPA). Reallocations of behaviors are relative to the mean activity composition of the study population. Higher EQ-5D-3L index score and VAS score indicate higher QoL. The effect was computed for time reallocation around the average composition. Models were adjusted for age, sex, educational status, marital status, living situation, job status, smoking, alcohol intake, dietary guidelines score, BMI, comorbidity score, and the use of sleep medication.

EQ-5D-3L, EuroQoL 5D-3L; LIPA, light intensity physical activity; MVPA, moderate-to-vigorous physical activity; QoL, quality of life; SB, sedentary behavior; VAS, visual analog scale.

data analysis of activities in relation to QoL was conducted among children.²² This study also found that increasing time spent in MVPA was associated with a higher QoL and decreasing time spent in MVPA was associated with a lower QoL. Another study examined the association of SB and PA with self-rated health and found that substituting sedentary time with an equal amount of LIPA or MVPA was associated with better physical health.²³

A systematic review reported a consistently positive association between PA and QoL.²⁴ Individuals who spend more time in MVPA may report a better QoL because of the effects on physical health (e.g., reduced disease risk and improved fitness) and psychologic benefits of PA (e.g., improved self-esteem and socialization).^{25,26} Although no conclusions on the temporal direction or causality of the association can be drawn from this study, a recent meta-analysis of exercise interventions on QoL showed that over a period of 3–6 months, a small but meaningful improvement in QoL can be achieved by exercise interventions in a healthy population, which suggest a causal effect.²⁷ Still, the reverse might also be true as a better QoL may be expected to affect activity levels. A study investigating the factors associated with PA in older adults reported QoL as one of the most important factors associated with engagement in PA.²⁸

Findings from this study suggest that the association of replacing MVPA with another behavior and vice versa with QoL is not exactly symmetrical. For example, 30 minutes less of MVPA and more of SB was associated

with a 4% decrease in EQ-5D-3L index score, whereas 30 minutes more of MVPA and less of SB was associated with a 3% increase in EQ-5D-3L index score. This asymmetry was also found in other studies using the compositional data analysis method.^{22,29} This asymmetry seems plausible because removing 30 minutes from MVPA is a large amount of daily time spent in MVPA, whereas decreasing SB by 30 minutes only accounts for 2%–5% change in total SB time.

These findings did not show a significant association when SB or sleep was replaced with LIPA and vice versa. A similar study examined the effects of replacing SB with PA on QoL and found that LIPA was unrelated to QoL.³⁰ However, a recent systematic review reported that LIPA is beneficially associated with several health outcomes, including well-being, after adjustment for MVPA.³¹ An explanation for this contradicting findings could be that LIPA includes more household chores (e.g., cooking, cleaning, ironing) than MVPA, which includes activities that typically take place in leisure settings.³² Further research exploring whether and to what extent LIPA contributes to QoL may provide insights into this issue.

In this study, associations were somewhat stronger among men, among participants at a higher age, and among participants with lower overall MVPA levels, but directions were the same in all subgroups. Other cross-sectional studies also found that higher levels of PA were positively associated with QoL for both men and women.^{21,33} A literature review on PA and QoL reported

that there was no evidence across studies that age was a moderator of QoL, which is in line with these findings.³⁴ These findings support that increasing MVPA may have a slightly greater benefit among those who are less physically active, although the difference with those who were more physically active in the study population was small. A difference in associations between MVPA and QoL measured with the EQ-5D-3L index score or the VAS score was not found. This suggests that the combined index score of QoL based on 5 different domains reflects an individual's current health at the moment of filling in the questionnaire indicated on a VAS, which has been reported in previous literature.³⁵

This study may have implications for public health, suggesting that the associated harm of less MVPA is greater than the benefit of more MVPA relative to the mean activity composition of this study population. The mean time spent in MVPA in this study was 82.7 minutes per day, which far exceeds the 150 minutes per week recommendation from WHO.³⁶ For individuals who already have high levels of PA, interventions focused on preventing a decline rather than increasing PA could therefore already be effective. This could highlight the need for interventions focused around events or occasions when time spent in MVPA typically tends to decline (e.g., during the colder months of the year, in certain life stages, or after specific life events).³⁷ Most current interventions or public health campaigns are aimed at increasing PA levels, but very few specifically aim to support individuals to remain active through the life course.

One of the major strengths of this study is the use of the compositional data analysis methods, which accounts for the constraint nature of time. Another strength is the large sample size of 1,934 participants from a well-characterized population-based cohort. Furthermore, data on activities were measured objectively with waterproof accelerometers worn over the 24 hours of a day, which ensured high compliance. Participants were requested to wear the accelerometer for 7 consecutive days, which exceeds the 3–5 days required to assess a daily estimate of the individual's habitual activity.³⁸ Moreover, it has been reported that activity at middle and elderly age tends to be relatively constant with time.³⁹

Limitations

The findings of this study must be considered in the context of some limitations. First, the cross-sectional analyses preclude any assessment of directionality of the association. Second, this study used the 3L version of the EQ-5D questionnaire. A 5L version is also available comprising 5 levels of answering options, which could

therefore be a more comprehensive measurement of QoL with a smaller ceiling effect.⁴⁰ Furthermore, the EQ-5D-3L instrument only assesses QoL. However, the findings from the index score and VAS score were similar, suggesting that the measurement of QoL was robust. Accelerometers do not allow differentiation between the postural allocations of sitting, standing, and lying down and can therefore not distinguish different types of activities. Furthermore, only overnight sleep periods were included from the sleep diary. Therefore, naps during the day were not taken into account and were included as SB. Finally, the categorization of activity levels with accelerometry is dependent on the algorithm and cut points used and should therefore be interpreted with caution.

CONCLUSIONS

In summary, MVPA is an important activity with regard to the QoL of middle-aged and elderly individuals. The associated benefits of preventing 30 minutes less of MVPA are greater than the benefits of 30 minutes more of MVPA. These results could shift the attention of interventions to not only focusing on increasing MVPA but also preventing a decline in a middle-aged and elderly population. However, further longitudinal studies are needed to confirm these findings and the availability of repeated measurements would contribute to elucidate the directionality of the observed associations.

ACKNOWLEDGMENTS

The authors are grateful to the study participants, the staff from the Rotterdam Study, and the participating general practitioners and pharmacists. The authors thank Amy Hofman for her help with additional data analysis.

The Rotterdam Study is funded by Erasmus MC and Erasmus University, Rotterdam, The Netherlands; the Netherlands Organization for Scientific Research; the Netherlands Organization for Health Research and Development; the Research Institute for Diseases in the Elderly; the Ministry of Education, Culture and Science; the Ministry of Health, Welfare and Sports; the European Commission; and the Municipality of Rotterdam.

All procedures were performed in accordance with the 1964 Helsinki declaration and its later amendments, and the Rotterdam Study was approved by the IRB (Medical Ethics Committee) of Erasmus Medical Center (Registration Number MEC 02.1015) and by the Dutch Ministry of Health, Welfare and Sport (Population Screening Act [WBO], license number 1071272-159521-PG). All participants provided written informed consent to participate in the study and to have their information obtained from treating physicians. The Rotterdam Study is registered in the Netherlands National Trial Register (www.trialregister.nl) and into WHO International Clinical Trials Registry Platform (www.who.int/ictrp/network/primary/en/) under shared Catalogue Number NTR6831.

Data can be obtained on request. Requests should be directed toward the management team of the Rotterdam Study (secretariat.epi@erasmusmc.nl), which has a protocol for approving data requests. Because of restrictions based on privacy regulations and informed consent of the participants, data cannot be made freely available in a public repository.

OHF and CMK had the original idea for the study. SV and CMK performed the statistical analyses and interpreted the data. SV drafted the article. All authors revised the manuscript critically for important intellectual content and approved the final article.

No financial disclosures were reported by the authors of this paper.

SUPPLEMENTAL MATERIAL

Supplemental materials associated with this article can be found in the online version at <https://doi.org/10.1016/j.amepre.2020.03.029>.

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