Compositional Associations of Sleep and Activities within the 24-h Cycle with Cardiometabolic Health Markers in Adults

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EPIDEMIOLOGY

ABSTRACT

FARRAHI, V., M. KANGAS, R. WALMSLEY, M. NIEMELÄ, A. KIVINIEMI, K. PUUKKA, P. J. COLLINGS, R. KORPELAINEN, and T. JÄMSÄ. Compositional Associations of Sleep and Activities within the 24-h Cycle with Cardiometabolic Health Markers in Adults. *Med. Sci. Sports Exerc.*, Vol. 53, No. 2, pp. 324–332, 2021. **Purpose:** This study aimed to examine how compositions of 24-h time use and time reallocations between movement behaviors are associated with cardiometabolic health in a population-based sample of middle-age Finnish adults. **Methods:** Participants were 3443 adults 46 yr of age from the Northern Finland Birth Cohort 1966 study. Participants wore a hip-worn accelerometer for 14 d from which time spent in sedentary behavior (SB), light-intensity physical activity (LPA), and moderate- to vigorous-intensity physical activity (MVPA) were determined. These data were combined with self-reported sleep to obtain the 24-h time-use composition. Cardiometabolic outcomes included adiposity markers, blood lipid levels, and markers of glucose control and insulin sensitivity. Multivariable-adjusted regression analysis, using a compositional data analysis approach based on isometric log-ratio transformation, was used to examine associations between movement behaviors with cardiometabolic outcomes. **Results:** More daily time in MVPA and LPA, relative to other movement behaviors, was consistently favorably associated with all cardiometabolic outcomes. For example, relative to time spent in other behaviors, 30 min·d^{-1} more MVPA and LPA were both associated with lower 2-h post–glucose load insulin level (−11.8% and −2.7%, respectively). Relative to other movement behaviors, more daily time in SB was adversely associated with adiposity measures, lipid levels, and markers of insulin sensitivity, and more daily time asleep was adversely associated with adiposity measures, blood lipid, fasting plasma glucose, and 2-h insulin. For example, 60 min·d^{-1} more SB and sleep relative to the remaining behaviors were both associated with higher 2-h insulin (3.5% and 5.7%, respectively). **Conclusions:** Altering daily movement behavior compositions to incorporate more MVPA at the expense of any other movement behavior, or more LPA at the expense of SB or sleep, could help to improve cardiometabolic health in midadulthood. **Key Words:** ISOTEMPORAL SUBSTITUTION, METABOLIC DISEASES, ADIPOSITY, INSULIN RESISTANCE, DYSLIPIDEMIAS, PHYSICAL ACTIVITY

The full 24-h day is composed of four main movement behaviors, including sleep, sedentary behavior (SB), light-intensity physical activity (LPA), and moderate- to vigorous-intensity physical activity (MVPA) (1,2). There is evidence to suggest that each movement behavior is associated with adult cardiometabolic health (3–6). However, although the evidence base for health benefits arising from recommended amounts of sleep and MVPA is reasonably strong (4,6), less is known about the health implications of sedentary time and LPA (3,5). Time-based recommendations for adults are therefore only currently available for sleep duration (7–9 h per night) and MVPA (30 min·d^{-1}), whereas only general advice to minimize SB and perform more LPA is made (7,8). It remains unclear how time over a full 24-h cycle should be distributed between all movement behaviors for optimal cardiometabolic health in adulthood (2,9).

Historically, movement behaviors have been assumed to be independently associated with health outcomes (9,10). Previous studies have therefore primarily used traditional regression

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methods to examine the health implications of one movement behavior in isolation, or have typically only partially accounted for the other movement behaviors of a daily 24-h cycle (2,11). Because incomplete or improper consideration of other movement behaviors in the 24-h cycle may bias findings (11), it is important to adjust for the full range of 24-h movement behaviors using suitable analytical approaches (2,9).

Movement behaviors can be considered to be codependent and compositional, as they are mutually exclusive time-use components of a fixed period, such as the 24-h day (9–11). A change of time spent in one movement behavior necessitates an exchange of equal time for one or a combination of other movement behaviors. Compositional data analysis methods are able to accommodate codependent data that are constrained to a fixed amount of time and are therefore well suited to analyzing this type of data (10,12,13). To our knowledge, only two studies to date have used compositional data analysis to investigate associations of 24-h time use with cardiometabolic health markers in adulthood. Those studies found that MVPA was beneficially associated with markers of cardiometabolic health, but results for the other movement behaviors were inconsistent (10,14). The objective of this study was to examine how compositions of time use during the 24-h day (that is, the relative amounts of time spent asleep, in SB, LPA, and MVPA), and how time reallocations between movement behaviors, are associated with cardiometabolic health markers, including adiposity levels, blood glucose and insulin, and cholesterol profiles, in a large population-based sample of Finnish adults.

MATERIALS AND METHODS

Study Population and Design

Data for the present study were from the population-based Northern Finland Birth Cohort 1966 study (NFBC1966). NFBC1966 is a life-course study involving participants whose date of birth was expected to be in the year 1966 in northern Finland. Cohort members have been monitored prospectively on a regular basis, and data on their health, lifestyle, and socioeconomic status have been collected by questionnaires. Detailed information about the NFBC1966 study objectives, recruitment, and follow-ups (including the follow-up at age 46 yr on which this investigation is based) is available elsewhere (15–17).

Eligible participants for this cross-sectional study were those members of NFBC1966 who had participated in the latest follow-up performed at age 46 yr, and who agreed to wear an accelerometer for device-based measurement of physical activity. The 46-yr follow-up included completion of postal questionnaires, a clinical examination for the collection of fasting blood samples and anthropometric measurements, and on a separate day an oral glucose tolerance test.

Measurements

Movement behaviors. Participants were asked to wear a hip-worn accelerometer (Hookie AM20; Traxmeet Ltd., Espoo, Finland) during all waking hours except water-based activities for 14 consecutive days. Raw acceleration signals were collected and stored at 100 Hz. The accelerometer data were segmented into 6-s epochs, and mean amplitude deviation (MAD) was computed for each segment. There is excellent agreement between MAD values from Hookie and the commonly used ActiGraph GTX3 accelerometer (18). From the 6-s MAD values, monitor nonwear time was detected and removed using a method that closely resembles a validated and popular approach for count-based accelerometer data (≥90 consecutive minutes of no detected movement, allowing for short movement intervals of up to 30 s, if no other movements were detected in the 30 min either side of the current 30-min interval) (19). We changed the window size (from 2 min to 30 s) that was used for handling the artifactual acceleration as the visual speculation of signals showed that a shorter interval performs better with high-frequency raw acceleration data.

The detected wear-time intervals were then cross-referenced with self-reported sleep times (captured with two questions: "At what time do you normally go to bed?" and "At what time do you normally get out of bed?"), and all accelerometer data that overlapped with a sleep interval were discarded. The remaining 6-s epochs were classified as sedentary (sitting or lying), standing still, LPA, moderate-intensity physical activity, or vigorous-intensity physical activity on the basis of MAD values (20,21), and minutes per day in each activity was obtained by dividing time spent in each activity by the number of valid days. Further differentiation between standing still and sitting or lying was performed using a recently validated approach (20). This approach enables posture estimation from hip-based raw acceleration data on the basis of constant Earth's gravity vector and upright walking posture, and it has shown good to excellent accuracy when compared with thigh-worn posture classification as ground truth under free-living conditions (20). Participants were required to provide four or more valid days of accelerometry, with each valid day defined as ≥10 h of monitor wear time. For the purposes of this study, LPA constituted the sum of all minutes per day spent standing still and in LPA, and MVPA was the sum of minutes per day spent in MVPA. Sleep duration was self-reported in response to the question "How many hours do you sleep on average per day?" Responses were converted to minutes per day asleep.

Cardiometabolic health markers. Participants fasted overnight for 12 h and abstained from smoking and drinking coffee on the day of a clinical examination. Trained nurses measured height, weight, and waist circumference, and body mass index (BMI) was calculated. Body fat, fat mass, and visceral fat area were estimated by bioelectrical impedance analysis (InBody720; InBody, Seoul, Korea) (22). Fasting blood samples were taken and analyzed for plasma glucose, serum insulin, total cholesterol, HDL cholesterol, LDL cholesterol, and triglycerides as previously described (15). The ratios of total to HDL (total/HDL cholesterol ratio) and LDL to HDL (LDL/HDL cholesterol ratio) cholesterol levels were derived

as they provide a better prediction of cardiovascular disease risk than isolated lipid and lipoprotein levels (23). The homeostasis model assessment of insulin resistance (HOMA-IR) was calculated from fasting plasma glucose and insulin levels (24). On a second fasted examination day, participants who were not using medication for diabetes underwent a 75-g oral glucose tolerance test (25), from which 2-h postload plasma glucose and insulin levels were obtained.

Covariates. Sex and birth weight were extracted from medical records. Participants self-reported their education level, employment status, marital status, and household income and further provided information about lifestyles (smoking status and alcohol consumption), health-related quality of life (26), and medication use for high blood pressure, high cholesterol, and diabetes.

Statistical Analysis

All statistical analyses were performed using R version 3.6.2 (R Core Team, Vienna, Austria). R packages "lmtest," "robCompositions," and "Compositions" were used to perform the compositional data analysis. The analyses were performed in accordance with recently published methods for compositional data analysis applicable to movement behaviors (10,12,13). Participant characteristics were described using standard descriptive statistics. The geometric mean is a better representation of central tendency for compositional data (10); hence, the movement behavior composition was described using compositional means, which are geometric means rescaled to collectively sum to 1440 min (24 h). The variation matrix, which provides a proper estimation of dispersion in compositional data (10), was also calculated for the movement behavior composition based on the variances of the logs of all pairwise ratios between behaviors (e.g., variance of ln [SB/LPA]).

All cardiometabolic outcome variables were log-transformed before analyses. Multiple linear regression was used to investigate associations of the 24-h movement behaviors with cardiometabolic health outcomes. The 24-h time-use composition for each participant was created by linearly rescaling the duration of all activities to sum to a total of 1440 min·d^{-1}. Compositional explanatory variables cannot be directly included in linear regression models (27), so the movement behavior composition for each participant was expressed as ratios of its parts using isometric log-ratio (ilr) transformations before the regression analyses (10,13). The same ilr coordinate system was used to back-transform the log-ratio coordinates into proportions for interpretation as minutes per day. Associations between sleep duration and cardiometabolic outcomes may be U-shaped in adults, with both short and long durations exhibiting adverse associations with cardiometabolic outcomes (4,28). Accordingly, we examined U-shaped associations between sleep duration and cardiometabolic outcomes (29). If evidence for a U-shaped association was observed for an outcome, the analysis for that outcome was stratified by sleep duration. On the basis of the existing literature (4,28) and of sleep durations in this study sample, we stratified the analysis by ≤7.5 and >7.5 h·d^{-1} asleep for the outcomes displaying a U-shaped relationship. This cut point, in addition to being within the recommended level of sleep for adults (7 to 9 h per night [4,28]), was the mean sleep duration of all study participants and the approximated "breakpoint" at which associations demonstrated U-shapedness (see Figure, Supplemental Digital Content 1, Results of tests for U-shaped relationship between sleep duration and outcomes, http://links.lww.com/MSS/C98).

To assist meaningful interpretation of results, we estimated how time reallocations between movement behaviors were associated with cardiometabolic health markers (13). Specifically, results from the ilr multiple linear regression models were used to calculate estimated differences in outcomes associated with time reallocations from one movement behavior relative to all other remaining behaviors, and *vice versa* (13). Similarly, differences in outcomes associated with pairwise time reallocations from one movement behavior to another were estimated. Differences in outcomes were estimated for reallocations ranging from 5 to 30 min to/from MVPA and reallocations of 5–90 min to/from the other behaviors in 5-min increments and were plotted to aid interpretation.

RESULTS

Of all 12,058 NFBC1966 cohort members, 10,321 (85.5%) were alive in Finland in 2012 and were invited to the 46-yr follow-up (Fig. 1). A total of 5861 (47% of all cohort members and 57% of those who were invited) participated in the follow-up and wore the accelerometer. Of these, 3443 provided valid acceleration data, in addition to all questionnaire and clinical data that were needed for the present study. The

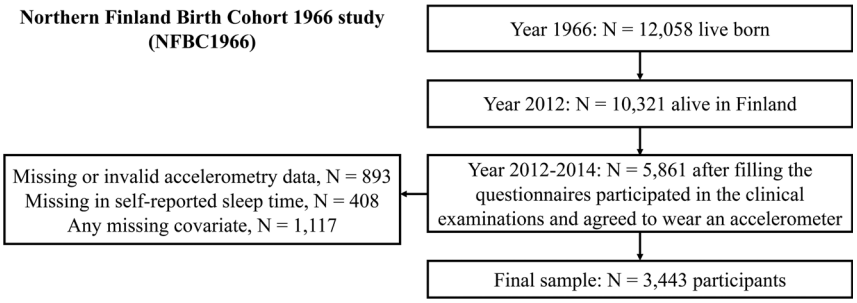

FIGURE 1—The selection of the study population from the NFBC1966.

TABLE 1. Characteristics of the study population overall and by sleep duration categories.

Variable	Mean (SD) or Count (%)		
	Full Sample (N = 3443)	Sleep Duration, ≤7.5 h·d^{-1} (n = 1939)	Sleep Duration, >7.5 h·d^{-1} (n = 1504)
Demographics			
Age, yr	46.6 (0.5)	46.6 (0.5)	46.6 (0.5)
Sex			
Male	1532 (44.5%)	968 (49.9%)	564 (37.5%)
Female	1911 (55.5%)	971 (50.1%)	940 (62.5%)
Education			
Comprehensive school	206 (6%)	135 (7%)	71 (4.7%)
Vocational/college level education	2164 (62.9%)	1248 (64.4%)	916 (60.9%)
Polytechnic/university degree	1073 (31.2%)	556 (28.7%)	517 (34.4%)
Employment status			
Employed	3112 (90.4%)	1792 (92.4%)	1320 (87.8%)
Unemployed	178 (5.2%)	92 (4.7%)	86 (5.7%)
Other (e.g., student, homemaker)	153 (4.4%)	55 (2.9%)	98 (6.5%)
Marital status			
Married/cohabiting	2748 (79.8%)	1544 (79.6%)	1204 (80.1%)
Divorced/widowed	376 (11%)	189 (9.8%)	144 (9.5%)
Unmarried	319 (9.2%)	206 (10.6%)	156 (10.4%)
Household income (€ per year)			
≤50,000	1404 (40.8%)	789 (40.7%)	615 (40.9%)
50,001 to 100,000	1622 (47.1%)	926 (47.8%)	696 (46.3%)
>100,000	417 (12.1%)	224 (11.6%)	193 (12.8%)
Birth weight, kg	3.5 (0.5)	3.4 (0.5)	3.5 (0.5)
Lifestyle factors, medication use, and health-related quality of life			
Alcohol consumption, g·d^{-1}	10.7 (16.4)	11.4 (16.9)	9.6 (4.1)
Health-related quality of life score	0.92 (0.06)	0.92 (0.06)	0.92 (0.06)
Smoking status			
Nonsmoker	1870 (54.3%)	987 (50.9%)	883 (58.7%)
Former smoker	968 (28.1%)	378 (19.5%)	227 (15.1%)
Current smoker	605 (17.8%)	574 (29.6%)	394 (26.2%)
Diabetes, cholesterol, and/or hypertension medication			
Yes	580 (16.8%)	334 (17.2%)	246 (16.4%)
No	2863 (83.2%)	1605 (82.8%)	1258 (83.6%)
Cardiometabolic biomarkers			
Fasting insulin, pmol·L^{-1}	9.4 (8.1)	9.5 (8.7)	9.4 (7.4)
2-h insulin, pmol·L^{-1}	59.2 (57.2)	59.5 (59.9)	58.7 (53.6)
Fasting glucose, mmol·L^{-1}	5.5 (0.8)	5.5 (0.8)	5.5 (0.8)
2-h glucose, mmol·L^{-1}	5.8 (1.6)	5.9 (1.6)	5.7 (1.6)
HOMA-IR	2.4 (3.2)	2.5 (3.8)	2.4 (2.3)
Triglycerides, mmol·L^{-1}	1.2 (0.8)	1.2 (0.8)	1.3 (0.9)
Total/HDL cholesterol ratio	1.6 (0.2)	1.6 (0.3)	1.6 (0.3)
LDL/HDL cholesterol ratio	2.3 (0.9)	2.4 (0.9)	2.4 (0.9)
Adiposity measures			
Body fat, %	28.3 (9)	27.8 (9.1)	29.1 (8.8)
Fat mass, kg	22.5 (10.3)	22.4 (10.6)	22.7 (10)
Visceral fat area, cm^2	97.5 (40.4)	102.1 (41.2)	103.0 (39.2)
BMI, kg·m^{-2}	26.6 (4.7)	26.7 (4.7)	26.5 (4.7)
Waist circumference, cm	91.1 (13.2)	91.8 (13.4)	90.1 (13)

mean (SD) values of accelerometer wear time and self-reported sleep duration for the included participants were 14.3 (1.0) and 7.5 (0.9) h·d^{-1}, respectively. The mean age of participants was 46.6 (0.5) yr, and 55.5% were female. Full descriptive statistics of the participants included in the analysis are shown in Table 1.

The results of tests for U-shaped associations between sleep duration and cardiometabolic outcomes are shown in the Supplementary File 1 (see Figure, Supplemental Digital Content 1, Results of tests for U-shaped relationship between sleep duration and outcomes, http://links.lww.com/MSS/C98). Evidence for U-shaped relationships (slopes with opposite signs with $P < 0.10$) was seen for fasting serum insulin, 2-h glucose, HOMA-IR, triglycerides, visceral fat area, and BMI. The compositional means of movement behaviors, overall and stratified by sleep duration, are shown in Table 2. Compared with the compositional means of participants who slept >7.5 h·d^{-1}, participants who slept ≤7.5 h·d^{-1} had a larger compositional mean for SB, LPA, and MVPA. The variation matrix of the included sample, overall and stratified by sleep duration, is described in Supplementary File 2 [see Table, Supplemental Digital Content 2, Variation matrix of time spent in sleep, sedentary behavior (SB), light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA) by sleep duration categories, http://links.lww.com/MSS/C99]. Overall, the largest log-ratio variances all included MVPA, which indicates that MVPA was least dependent on the other movement behaviors. The lowest log-ratio variance was between sleep and SB (0.063), which indicates more consistent proportionality (codependency) between these behaviors. The same pattern of codependency was observed when the sample was stratified by participants who slept ≤7.5 and >7.5 h·d^{-1}.

The results of ilr compositional data analysis regression models, for cardiometabolic outcomes that were characterized by linear and U-shaped associations with sleep duration, are displayed in Tables 3 and 4, respectively. The composition of movement behaviors across the 24-h day was significantly associated with each of the cardiometabolic outcomes (model P value <0.001 for all). As shown in Tables 3 and 4, regardless of the shape of association with sleep duration, relative to all other behaviors, more daily time in both MVPA and LPA was consistently beneficially associated with cardiometabolic outcomes (e.g., 2-h insulin: MVPA, $\beta = -0.28$; LPA, $\beta = -0.30$). For outcomes with a linear relationship with sleep duration (Table 3), relative to all other behaviors, more time asleep and SB were both detrimentally associated with outcomes (e.g., total/HDL cholesterol ratio: sleep, $\beta = 0.13$; SB, $\beta = 0.05$); the only exceptions were that time in SB was not associated with fasting plasma glucose and time in LPA was not significantly associated with waist circumference (although the association bordered significance, $P = 0.091$). For outcomes that showed a U-shaped relationship with sleep duration (Table 4), generally more daily SB relative to the all other behaviors was detrimentally associated with outcomes. More sleep was detrimentally associated with BMI ($\beta = 0.11$) and triglycerides ($\beta = 0.41$) in individuals with longer sleeping durations. In addition, in longer sleepers, although the associations were not statistically significant, there was some evidence to indicate that more daily time asleep was adversely associated with HOMA-IR and visceral fat area ($P = 0.065$ and $P = 0.094$, respectively).

TABLE 2. Compositional means (percentage of a 24-h day) for sleep, SB, LPA, and MVPA by sleep duration categories, in minutes per day.

Movement Behavior	Compositional Mean (%)		
	Full Sample (N = 3443)	Sleep Duration, ≤7.5 h·d^{-1} (n = 1939)	Sleep Duration, >7.5 h·d^{-1} (n = 1504)
Sleep	515.7 (35.8%)	483.8 (33.6%)	558.2 (38.8%)
SB	496.9 (34.5%)	512.9 (35.6%)	475.6 (33%)
LPA	381.8 (26.5%)	395.9 (27.5%)	363.2 (25.2%)
MVPA	45.6 (3.2%)	47.4 (3.3%)	43 (3%)

TABLE 3. Compositional multiple linear regression estimates for cardiometabolic outcomes that displayed a linear relationship with sleep duration.

				Sleep		SB		LPA		MVPA	
Measures	***n***	**Model R^2**	**Model *P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***
Cardiometabolic biomarkers											
2-h insulin	3006	0.13	<0.001	**0.36 (0.27 to 0.46)**	**<0.001**	**0.22 (0.15 to 0.28)**	**0.001**	**−0.30 (−0.36 to −0.24)**	**<0.001**	**−0.28 (−0.30 to −0.20)**	**<0.001**
Fasting plasma glucose	3380	0.16	<0.001	**0.03 (0.01 to 0.04)**	**0.05**	0.01 (0 to 0.02)	0.178	**−0.03 (−0.04 to −0.02)**	**0.001**	**−0.01 (−0.02 to −0.10)**	**0.002**
Total/HDL cholesterol ratio	3427	0.27	<0.001	**0.13 (0.10 to 0.16)**	**<0.001**	**0.05 (0.03 to 0.07)**	**0.006**	**−0.11 (−0.13 to −0.09)**	**<0.001**	**−0.08 (−0.09 to −0.07)**	**<0.001**
LDL/HDL cholesterol ratio	3429	0.23	<0.001	**0.17 (0.12 to 0.21)**	**<0.001**	**0.09 (0.06 to 0.12)**	**0.003**	**−0.14 (−0.17 to −0.11)**	**<0.001**	**−0.11 (−0.13 to −0.10)**	**<0.001**
Adiposity measures											
Body fat	3381	0.39	<0.001	**0.01 (0.06 to 0.13)**	**0.004**	**0.16 (0.14 to 0.19)**	**<0.001**	**−0.15 (−0.17 to −0.13)**	**<0.001**	**−0.11 (−0.12 to −0.10)**	**<0.001**
Fat mass	3381	0.21	<0.001	**0.13 (0.08 to 0.18)**	**0.009**	**0.26 (0.23 to 0.30)**	**<0.001**	**−0.24 (−0.27 to −0.21)**	**<0.001**	**−0.15 (−0.17 to −0.14)**	**<0.001**
Waist circumference	3424	0.33	<0.001	0.03 (0.01 to 0.04)	0.091	**0.07 (0.06 to 0.08)**	**<0.001**	**−0.05 (−0.06 to −0.04)**	**<0.001**	**−0.04 (−0.05 to −0.03)**	**<0.001**

Only the regression coefficients corresponding to the first ilr coordinate are shown because the first ilr coordinates contain all the information relative to the remaining movement behaviors. All models have been adjusted for age, sex, birth weight, education level, employment status, marital status, household income, health-related quality of life, lifestyle factors (smoking status and alcohol consumption), and medication (for blood pressure, cholesterol, and/or diabetes). Significant associations are shown in bold.

The results for time reallocations between movement behaviors with all cardiometabolic health outcomes are presented in Supplementary File 3 (see Appendix, Supplemental Digital Content 3, Figures of results of time reallocations between movement behaviors with all cardiometabolic health outcomes, http://links.lww.com/MSS/C100). From the estimates (percent change), it was apparent that more time in MVPA at the expense of all other behaviors was associated with favorable changes in outcomes. For instance, as shown in Figure 2 by way of an example, 30 min·d^{-1} more MVPA relative to the remaining behaviors was significantly associated with lower 2-h insulin (−11.8%, 95% confidence interval [CI] = −13.9 to −9.6). Reallocating 30 min·d^{-1} from sleep, SB, and LPA to MVPA was consistently associated with lower 2-h insulin (−13%, 95% CI = −15.3 to −10.7; −12.4%, 95% CI = −14.5 to −10.3; and −9.4%, 95% CI = −11.8 to −7.0, respectively). In general, reallocating time from SB or sleep to LPA was favorably associated with outcomes but to a lesser extent compared with MVPA. Again, using Figure 2 as an example, 60 min·d^{-1} more LPA at the expense of SB and sleep was associated with lower 2-h insulin (−6.1%, 95% CI = −7.7 to −4.4, and −7.4%, 95% CI = −10.3 to −4.5, respectively). Conversely, opposite time reallocations, including adding time to any other behavior from MVPA or generally adding time to sleep or SB from LPA, were associated with unfavorable changes in outcomes. As shown in Figure 2, reallocating 30 min·d^{-1} from MVPA to sleep, SB, and LPA was associated with higher 2-h insulin (31.2%, 95% CI = 24.6–38.1; 30.3%, 95% CI = 24.0–36.9; and 26.3%, 95% CI = 20.0–33.0, respectively). Reallocating 60 min·d^{-1} from LPA to SB and sleep was also associated with higher 2-h insulin (6.9%, 95% CI = 4.8–8.9, and 8.3%, 95% CI = 4.9–11.7, respectively). See Supplementary File 3 for a full description of results for all outcomes (see Appendix, Supplemental Digital Content 3, Figures of results of time reallocations between movement behaviors with all cardiometabolic health outcomes, http://links.lww.com/MSS/C100).

DISCUSSION

In this study, a compositional data analysis approach was used to examine the codependent relationships of movement

TABLE 4. Compositional multiple linear regression estimates for cardiometabolic outcomes that displayed a U-shaped relationship with sleep duration.

				Sleep		SB		LPA		MVPA	
Measures	***n***	**Model R^2**	**Model *P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***
Cardiometabolic biomarkers											
Fasting serum insulin											
Sleep duration ≤7.5 h·d^{-1}	1904	0.17	<0.001	0.17 (0.06 to 0.29)	0.134	**0.25 (0.17 to 0.32)**	**0.001**	**−0.24 (−0.30 to −0.18)**	**<0.001**	**−0.18 (−0.21 to −0.15)**	**<0.001**
Sleep duration >7.5 h·d^{-1}	1476	0.20	<0.001	0.24 (0.08 to 0.40)	0.131	**0.20 (0.11 to 0.30)**	**0.036**	**−0.30 (−0.38 to −0.21)**	**0.001**	**−0.15 (−0.18 to −0.12)**	**<0.001**
2-h glucose											
Sleep duration ≤7.5 h·d^{-1}	1674	0.07	<0.001	−0.02 (−0.08 to 0.04)	0.725	**0.09 (0.06 to 0.13)**	**0.006**	−0.01 (−0.04 to 0.02)	0.695	**−0.06 (−0.08 to −0.05)**	**<0.001**
Sleep duration >7.5 h·d^{-1}	1326	0.10	<0.001	0.12 (0.04 to 0.13)	0.141	−0.02 (−0.06 to 0.03)	0.721	−0.06 (−0.10 to −0.02)	0.151	**−0.04 (−0.06 to −0.03)**	**0.004**
HOMA-IR											
Sleep duration ≤7.5 h·d^{-1}	1885	0.19	<0.001	0.18 (0.06 to 0.31)	0.152	**0.26 (0.18 to 0.34)**	**0.001**	**−0.26 (−0.34 to −0.19)**	**<0.001**	**−0.18 (−0.21 to −0.15)**	**<0.001**
Sleep duration >7.5 h·d^{-1}	1460	0.22	<0.001	0.32 (0.15 to 0.50)	0.065	0.2 (0.10 to 0.31)	0.057	**−0.36 (−0.45 to −0.27)**	**<0.001**	**−0.16 (−0.20 to −0.13)**	**<0.001**
Triglycerides											
Sleep duration ≤7.5 h·d^{-1}	1934	0.20	<0.001	0.13 (0.04 to 0.22)	0.152	**0.19 (0.13 to 0.25)**	**0.001**	**−0.23 (−0.28 to −0.18)**	**<0.001**	**−0.09 (−0.11 to −0.07)**	**<0.001**
Sleep duration >7.5 h·d^{-1}	1495	0.23	<0.001	**0.41 (0.27 to 0.54)**	**0.003**	−0.02 (−0.10 to 0.06)	0.785	**−0.26 (−0.33 to −0.19)**	**<0.001**	**−0.13 (−0.15 to −0.10)**	**<0.001**
Adiposity measures											
Visceral fat area											
Sleep duration ≤7.5 h·d^{-1}	1900	0.19	<0.001	0.12 (0.04 to 0.21)	0.141	**0.23 (0.18 to 0.28)**	**<0.001**	**−0.17 (−0.22 to −0.13)**	**<0.001**	**−0.18 (−0.20 to −0.16)**	**<0.001**
Sleep duration >7.5 h·d^{-1}	1481	0.18	<0.001	0.19 (0.08 to 0.30)	0.094	**0.16 (0.09 to 0.23)**	**0.021**	**−0.11 (−0.25 to −0.14)**	**0.001**	**−0.15 (−0.17 to −0.13)**	**<0.001**
BMI											
Sleep duration ≤7.5 h·d^{-1}	1938	0.17	<0.001	0.04 (0.01 to 0.07)	0.188	**0.07 (0.05 to 0.09)**	**<0.001**	**−0.06 (−0.08 to −0.05)**	**<0.001**	**−0.05 (−0.06 to −0.04)**	**<0.001**
Sleep duration >7.5 h·d^{-1}	1503	0.20	<0.001	**0.11 (0.06 to 0.15)**	**0.022**	0.04 (0.01 to 0.07)	0.13	**−0.10 (−0.13 to −0.08)**	**<0.001**	**−0.05 (−0.06 to −0.04)**	**<0.001**

Only the regression coefficients corresponding to the first ilr coordinate are shown because the first ilr coordinates contain all the information relative to the remaining movement behaviors. All models have been adjusted for age, sex, birth weight, education level, employment status, marital status, household income, health-related quality of life, lifestyle factors (smoking status and alcohol consumption), and medication (for blood pressure, cholesterol and/or diabetes). Significant associations are shown in bold.

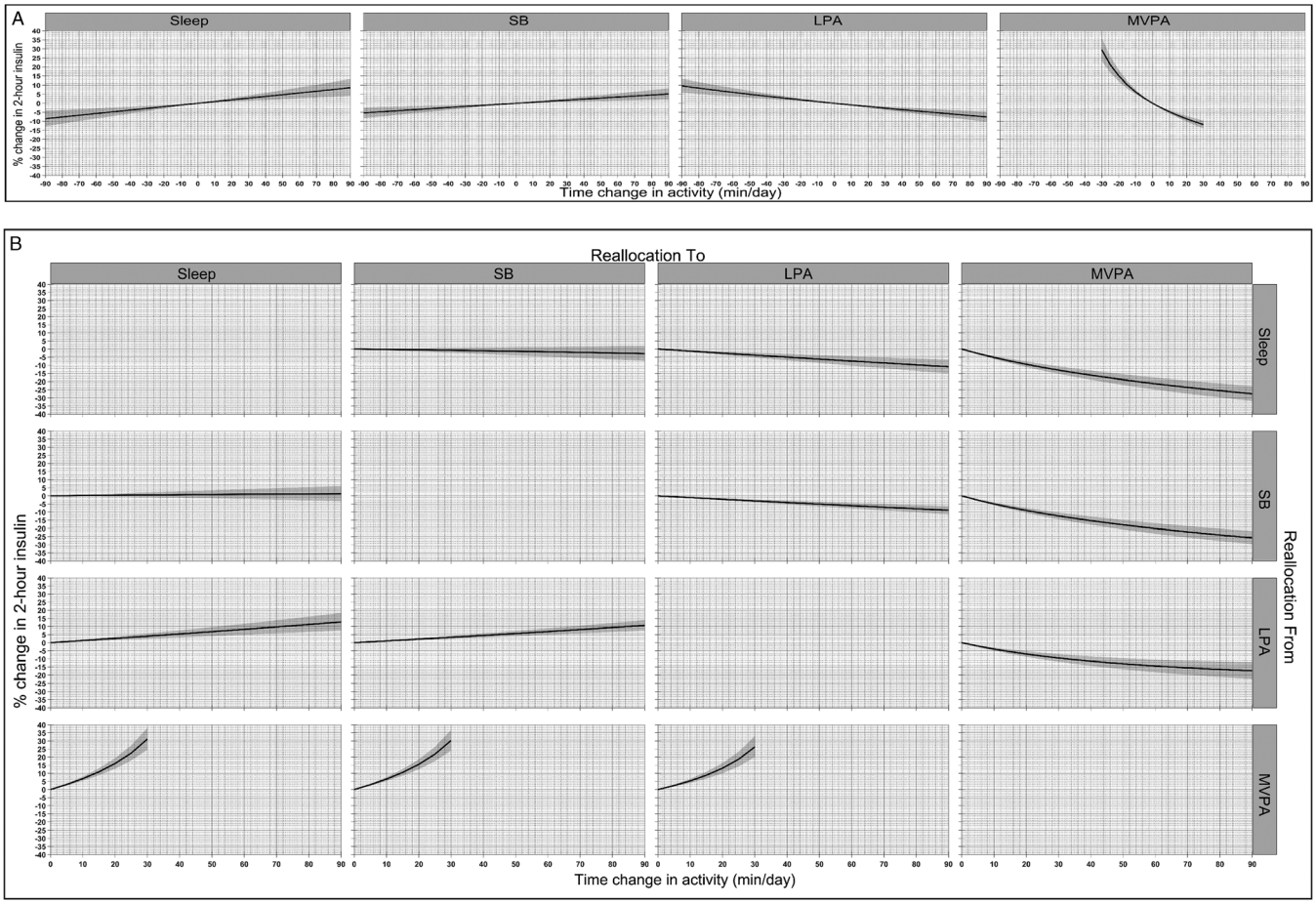

FIGURE 2—Systematically altered movement behavior compositions and percent change in 2-h post–glucose load insulin levels. (A) Percent change for reallocation of time from one movement behavior relative to the remaining movement behaviors (e.g., in the second column [SB], 60 min·d^{-1} more SB is associated with percent change of 3.5, compared with 2-h insulin at the mean composition). (B) Percent change for pairwise reallocation of time from one movement behavior (rows) to another movement behaviors (columns) (e.g., row two, column three indicates the estimated difference in 2-h insulin by reallocating time from SB to LPA, compared with 2-h insulin at the mean composition).

behaviors over the 24-h day with markers of cardiometabolic health, in a large population-based sample of Finnish adults. Relative to time spent in other behaviors, more daily LPA and MVPA were both beneficially associated with cardiometabolic health outcomes. Conversely, more daily SB and sleep were both detrimentally associated with multiple cardiometabolic outcomes. The estimates collectively suggest that more daily time in either MVPA at the expense of any other movement behavior or LPA at the expense of sleep or SB is favorably associated with cardiometabolic health.

This is the first study to use a compositional data analysis approach to model the cardiometabolic health associations of movement behaviors in midadulthood, while simultaneously accounting for possible U-shaped relations between sleep duration and cardiometabolic outcomes. In line with the existing literature (4,30), we identified that the nature of relationships varied by risk markers, with evidence for U-shaped associations with fasting serum insulin, 2-h glucose, HOMA-IR, triglycerides, visceral fat area, and BMI, but no evidence against linearity with all other outcomes. Accommodating U-shaped associations with sleep may explain why, compared with previous compositional studies (10,14,31,32), we found more consistent associations between movement behaviors with cardiometabolic outcomes. Two earlier studies of adults examined associations of 24-h movement behavior compositions with a subset of cardiometabolic outcomes similar to those examined here (10,14). The results of those studies were mixed for all movement behaviors except MVPA, which was consistently associated with lower adiposity measures and beneficially associated with certain cardiometabolic biomarkers (10,14). Our more consistent results might also in part be due to the longer measurement protocol that we used for accelerometer-based measurement of activities (i.e., 14 vs 7 consecutive days). This likely conferred more accurate estimation of habitual physical activity and sedentary time and, in turn, more precise estimates of associations with health outcomes. It is also conceivable that the classification of movement behaviors across the whole continuum was more accurate in this study. Previous studies have used cut point–based methods for assessing physical activities (10,14), which are relatively inaccurate in the estimation of activities of lower intensity under free-living settings compared with activities with higher intensities such as MVPA (33). By contrast, the method used here for the estimation of physical activity has

shown good to excellent performance against thigh-worn accelerometry under free-living settings (20).

The main finding of this study is that relative to all other behaviors, more daily time in both LPA and MVPA was beneficially associated with multiple cardiometabolic health markers. The health benefits of MVPA have been well documented in both compositional (10,14,34–36) and noncompositional studies (2,6), but the health-enhancing potential of LPA has received less research interest (3). Few adults meet the recommended 30 min·d^{-1} of MVPA (37). This highlights the necessity for enhanced understanding of the health implications of LPA, which is a more feasible intensity of movement that is accessible regardless of physical fitness, inclination, and opportunity to be higher physically active. Evidence has started to emerge that more time spent in LPA (3,38), even after accounting for MVPA (39), could improve cardiometabolic outcomes. Furthermore, compositional studies have also reported that more LPA could be beneficial for reduced mortality risk, even after accounting for other activity intensities (40) and sleep (41). Our findings, although supporting the established physical activity recommendations that encourage MVPA for better cardiometabolic health (2), also confirm the findings of recent studies suggesting that LPA may also confer meaningful cardiometabolic health benefits in adults (3).

With regard to the estimates of time reallocations for LPA and MVPA, there are at least two things of note. First, differences in the 24-h time-use budget that were beneficially associated with cardiometabolic health outcomes included more MVPA at the expense of all other behaviors, or to a lesser extent more LPA at the expense of SB or sleep. Second, lower MVPA and LPA (if not reallocated to MVPA) are adversely associated with cardiometabolic outcomes. Although the estimated differences might not be directly comparable with previous studies in terms of effect size due to the differences in study design and measurement of movement behaviors, these results partly agree with the results of previous compositional data analysis studies. Previous studies have also consistently reported that changing time in MVPA is most potently associated with cardiometabolic outcomes, with the association being nonlinear and asymmetrical (10,32,36,42,43). Given that individuals may find adding time to their daily amount of LPA more feasible than performing more MVPA (3), a possible implication of our results is that to achieve favorable changes in cardiometabolic outcomes, practitioners may consider advising middle-age adults to perform more LPA, while also stressing the importance of maintaining daily levels of MVPA.

More daily SB and sleep beyond 7.5 h·d^{-1} (both relative to all other behaviors) were both unfavorably associated with cardiometabolic health markers. Importantly, more sleep in individuals who slept up to but not more than 7.5 h·d^{-1} was not associated with any of the cardiometabolic health outcomes that displayed U-shaped associations with sleep. Our results for SB are in line with previous studies which have reported that more sedentary time is associated with poorer cardiometabolic health, although most of those studies failed to account for sleep (44). Currently, little is known in the literature about the mechanisms by which longer sleep duration is related to cardiometabolic health and even less about the interrelationship between sleep duration and sedentary and the combined effects of these behaviors on cardiometabolic health (2,7,45). However, in accordance with the present results, a recent systematic review concluded that sleeping more than 7 to 8 h per night was associated with a higher degree of cardiovascular disease risk (and also mortality) compared with sleeping less than 7 to 8 h per night (46).

It was apparent from the estimates that generally favorable differences in cardiometabolic outcomes could be achieved by reallocation of time in SB to LPA or MVPA or, to a comparable extent, by reallocation of time spent asleep to LPA or MVPA. Of note is that, for the outcomes that displayed U-shaped relationships with sleep duration, more daily time in SB was detrimentally associated with outcomes irrespective of whether participants slept more or less than 7.5 h·d^{-1}. This suggests that reduced sedentary time may be beneficial for cardiometabolic health regardless of sleep duration, which is in line with the findings of a previous study using an isotemporal substitution approach (47).

The strengths of this study include the relatively large population-based sample of Finnish adults and the wide range of cardiometabolic health markers that were investigated. In addition, device-based measurement of daily activities was captured over a relatively long timeframe and with raw accelerometry, from which movement behaviors were estimated using a robust analytical approach (20). Testing for possible U-shaped relationships between sleep duration and outcomes, and when necessary stratifying analyses by short and long sleep, is another strength. Limitations include that, because of its observational and cross-sectional design, inference about the temporality of associations is limited and causality cannot be determined. For instance, it is conceivable that poorer cardiometabolic health might lead to longer sleep duration, rather than *vice versa*. Furthermore, our results are based on theoretical time reallocations. Future studies, perhaps a series of experimental and longitudinal cohort studies, are needed to more realistically understand the true effects of different time substitutions on cardiometabolic outcomes (43). The study sample was homogenous in terms of age and ethnicity. Although beneficial with respect to reducing the potential for confounding of the observed associations, this limits the generalizability of the results to more diverse populations. Sleep duration was self-reported and therefore was probably measured with less accuracy than the other movement behaviors, including sedentary time and physical activity, which were estimated by accelerometry. However, although self-reported sleep durations are often higher than accelerometer-estimated sleep durations in middle-age adults, the differences between them are small (48). It is therefore unlikely that the result of associations would have been different or changed with accelerometer-estimated sleep durations compared with the results that were found here with self-reported sleep durations. Hence, the point at which the U-shaped relationships were found (7.5 h·d^{-1}) could be slightly different with accelerometer-estimated sleep durations. Studies with device-based estimates of sleep duration are needed

to verify the optimal amount of sleep for better cardiometabolic health in adults.

CONCLUSIONS

More daily time in MVPA at the expense of any other behavior could be the most time-efficient change in the movement behavior composition for improving cardiometabolic health in midadulthood. Alternatively, more daily time in LPA at the expense of sleep or SB could also be beneficial for cardiometabolic health, but to a lesser extent compared with more time in MVPA. Conversely, reduced daily time in MVPA or LPA seemed to be detrimental for cardiometabolic health, which suggests that daily levels of MVPA and LPA, if not increased, should at least be maintained to prevent deterioration of cardiometabolic health.

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