Development and Testing of an Integrated Score for Physical Behaviors

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[1]*Department of Kinesiology and Public Health, California Polytechnic State University, San Luis Obispo, CA;* [2]*Department of Statistics, Texas A&M University, College Station, TX;* [3]*Metabolic Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, MD; and* [4]*School of Mathematical and Physical Sciences, University of Technology Sydney, Sydney, AUSTRALIA*

ABSTRACT

KEADLE, S. K., E. S. KRAVITZ, C. E. MATTHEWS, M. TSENG, and R. J. CARROLL. Development and Testing of an Integrated Score for Physical Behaviors. *Med. Sci. Sports Exerc.*, Vol. 51, No. 8, pp. 1759–1766, 2019. **Purpose:** Interest in a variety of physical behaviors (e.g., exercise, sitting time, sleep) in relation to health outcomes creates a need for new statistical approaches to analyze the joint effects of these distinct but inter-related physical behaviors. We developed and tested an integrated physical behavior score (PBS). **Methods:** National Institutes of Health-American Association of Retired Persons Diet and Health Study participants (N = 163,016) completed a questionnaire (2004–2006) asking about time spent in five exercise and nonexercise physical activities, two sedentary behaviors (television and nontelevision), and sleep. In half of the sample, we used shape-constrained additive regression to model the relationship between each behavior and survival. Maximum logit scores from each of the eight behavior-survival functions were summed to produce a PBS that was proportionally rescaled to range from 0 to 100. We examined predictive validity of the PBS in the other half-sample using Cox Proportional Hazards models after adjustment for covariates for all-cause and cause-specific mortality. **Results:** In the testing sample, over an average of 6.6 yr of follow-up, 8732 deaths occurred. We found a strong graded decline in risk of all-cause mortality across quintiles of PBS (Q5 vs Q1 hazard ratio [95% CI] = 0.53 [0.49, 0.57]). Risk estimates for the PBS were higher than any of the components in isolation. Results were similar but stronger for cardiovascular disease (Q5 vs Q1 = 0.42 [0.39, 0.48]) and other mortality (Q5 vs Q1 = 0.42 [0.36, 0.48]). The relationship between PBS and mortality was observed in stratified analyses by median age, sex, body mass index, and health status. **Conclusions:** We developed a novel statistical method generated a composite physical behavior that is predictive of mortality outcomes. Future research is needed to test this approach in an independent sample.
Key Words: PHYSICAL ACTIVITY; SEDENTARY BEHAVIOR, EXERCISE, SLEEP, PROSPECTIVE COHORT, MORTALITY

Accumulating evidence indicates that a variety of physical behaviors affect health in positive and negative ways. A physically active lifestyle, including time spent in moderate and vigorous physical activities and strength training, improves longevity and quality of life and decreases risk of many chronic diseases (1). Mortality risk is also inversely associated with light-intensity activity (2), positively associated with time spent in sedentary behaviors (3,4), and with both too little and too much sleep (5,6).

Analyzing the independent versus combined effects of several different physical behaviors on health outcomes is challenging. Studies have historically focused on isolating an independent behavior while adjusting for other behaviors—for example, does the association between sedentary time and mortality risk persist when adjusting for time spent in moderate-vigorous intensity physical activity (7)? More recently, recognizing time trade-offs among sleep, sedentary behavior, and physical activity, researchers have examined the effect of substituting time spent in one behavior with another using isotemporal substitution or compositional analyses (8,9)—for example, does replacing 1 h of sitting with 1 h of light-intensity activity result in mortality benefits (8,10–13)? Both of these approaches provide insight into the behavior–disease relationship, but neither quantifies the

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joint impact of different physical behaviors on health and longevity.

Studies in nutritional epidemiology demonstrate the utility of indices to characterize overall patterns of behavior (14–17), but to date, there have been few attempts to integrate multiple physical behaviors into a single index. Investigators for the European Investigation into Cancer and Nutrition study developed an index that included physical activity at work, sport, cycling, television viewing, and computer use by selecting the self-reported activity variables that were the most strongly associated with accelerometer counts (18). Another study used National Health and Nutrition Examination Survey data to examine the cross-sectional relationship of a physical index that included combined moderate-vigorous physical activity, sitting time, grip strength and estimated fitness with various health outcomes (19). Both approaches relied on simple scoring systems that do not account for established nonlinear relationships of health with aerobic activity and sedentary time (13,20), and neither method considered sleep duration despite its established association with health (21). Moreover, to our knowledge, no previous studies have examined the prospective association of such an index with mortality.

There is a need for new approaches to analyze the joint effects of distinct but inter-related physical behaviors with health outcomes. We developed a physical behavior score (PBS) (ranging from 0 to 100) that integrated different types and intensities of physical activity, sitting and sleep behaviors. To demonstrate the predictive validity of the new score, we estimated the relationship between it and mortality from any cause and subtypes including cardiovascular disease, cancer, and other mortality in a large prospective cohort of American adults.

METHODS

The National Institutes of Health (NIH)-American Association of Retired Persons (AARP) Diet and Health Study cohort was established in 1995 to 1996, when 566,398 AARP members (50–71 yr) in six states and two metropolitan areas responded to a questionnaire about their medical history, diet, and demographics (22). Between 2004 and 2006, 313,835 participants completed a follow-up questionnaire that asked detailed questions about active and sedentary behaviors, medical history, and risk factors. Those eligible for this analysis (N = 163,016) personally responded to both questionnaires, were free of major diseases at the start of follow-up (2004–2006), and had sufficiently complete exposure data. Specific reasons for exclusions are as follows: questionnaire was completed by proxy respondents (n = 18,600), and at the time of follow-up questionnaire, self-rated poor health (n = 38,550), preexisting degenerative or chronic diseases (e.g., Parkinson's, end-stage renal disease) (n = 22,475), or missing primary exposure data (i.e., physical activity, sleep duration or sedentary time) (n = 71,194). Questionnaire completion was considered to imply informed consent and the US National Cancer Institute's Special Studies institutional review board approved the study.

The physical activity questionnaire asked how much time per week was spent in 16 activities during the past 12 months (Supplemental Digital Content 1: Physical Behavior questionnaire, http://links.lww.com/MSS/B550). Activities were classified as exercise and sports (eight questions) or as nonexercise activities (eight questions), which included household chores and lawn and garden activities. For each of the physical activity questions, response options were: none, 5, 15, 30 min, 1 h, 1.5, 2 to 3, 4 to 6, 7 to 10, >10 $h \cdot wk^{-1}$. The energy cost of each activity was assigned using standard methods, and physical activity energy expenditure was calculated ($MET \cdot h \cdot d^{-1}$). Three sitting questions asked about the number of hours spent "in a typical 24-h period during the past 12 months," with eight possible response options: none, <3, 3 to 4, 5 to 6, 7 to 8, 9 to 10, 11 to 12, or ≥12 $h \cdot d^{-1}$ (see Table, Supplemental Digital Content 1, Physical Behavior Questionnaire and Scoring, http://links.lww.com/MSS/B550). The exercise items have been validated against physical activity diaries, (r = 0.62 and 0.65) (23,24). Estimates of physical activity from the survey have been correlated with total energy expenditure as assessed by doubly labeled water (r = 0.33) and estimates of sitting time were significantly, although weakly, correlated with activPAL accelerometer (r = 0.16) (25).

For this analysis, survey responses were classified into one of eight physical behaviors (including five types of physical activity, two types of sedentary behavior, and sleep duration) as follows:

1. Light household activity ($MET \cdot h \cdot wk^{-1}$; 1 question): cooking, cleaning, laundry, dusting.
2. Moderate-vigorous household activity ($MET \cdot h \cdot wk^{-1}$; 6 questions): household chores (e.g., vacuuming), moderate outdoor chores (e.g., weeding), vigorous outdoor chores (e.g., carrying lumber), home repairs (e.g., painting), caring for children, caring for another adult.
3. Moderate exercise ($MET \cdot h \cdot wk^{-1}$; 3 questions): walking for exercise, walking for other daily activities, playing golf.
4. Vigorous exercise ($MET \cdot h \cdot wk^{-1}$; 5 questions): tennis, swimming laps, bicycling, jogging, other aerobic exercise.
5. Weight training ($MET \cdot h \cdot wk^{-1}$; 1 question): weight training using free weights and machines.
6. Sitting watching television, video or DVD ($h \cdot d^{-1}$; 1 question).
7. Other sitting ($h \cdot d^{-1}$; 1 question): reading, knitting, using a computer.
8. Sleeping at night or napping during the day ($h \cdot d^{-1}$; 1 question).

For each category, extreme values (>95th percentile) were truncated to the 95th percentile, plus random error.

End Point Ascertainment and Covariate Assessment

Vital status was determined through linkage with the Social Security Administration Death Master File and the National Death Index. The primary end points for our analysis were mortality from all causes, and cause-specific mortality. Cause-specific mortality was assigned using International Classification of Diseases, 10th revisions (ICD-10) codes. We categorized cancer mortality (C00-C44, C45.0, C45.1, C45.7, C45.9, C48-C97, and D12-D48). Cardiovascular disease mortality included

ICD-10 coded I00-I09, I10-I13, I20-I51, I60-I69, and I70-I78. Remaining causes of death were categorized as other causes. Mortality follow-up was through December 31, 2011. Demographic characteristics (sex, race/ethnicity, education) were assessed on the baseline questionnaire and other covariates (age, smoking, body mass index [BMI] based on self-reported height and weight, health status, and disease history) were based on values reported on the follow-up questionnaire.

Statistical Analyses

Overall approach to development and testing. First, we analyzed descriptive statistics for each of the eight physical behaviors and determined Spearman correlations among them (see Table, Supplemental Digital Content 2, Description and pairwise correlations for each of the PBS components, http://links.lww.com/MSS/B551). Overall, the correlations between components were weak, but statistically significant, with the exception of vigorous exercise and weight training ($R = 0.43$). The next highest correlations were for moderate-vigorous household activity and moderate exercise ($R = 0.28$) and light-intensity household activity ($R = 0.28$). To develop the PBS, we took a data-driven approach by using generalized additive models (26), adjusting for covariates, to quantify the relationship between each physical behavior and survival. We then rescaled the fitted probabilities to produce an overall score ranging from 0 to 100. Finally, we examined predictive validity of the composite PBS. Specific details of the analyses are described below.

Covariates. Covariates were selected to be consistent with previous analyses of mortality and physical activity and sedentary time in this data set (12). The fully adjusted models for both the score development and predictive validity were adjusted for the following covariates: age (yr), sex, education (<12 yr, high school graduate, some college, college graduate, unknown), smoking history (never, stopped 10+ yr, stopped 5–9 yr, stopped 1–4 yr, stopped <1 yr, current smoker, unknown), race/ethnicity (non-Hispanic white, non-Hispanic black, other, unknown), overall health (excellent, very good, good, fair, unknown), BMI (<25, 25–29.9, 30+ $kg \cdot m^{-2}$, unknown), physician-diagnosed depression (yes, no, or missing), physician-diagnosed heart disease (yes, no, missing).

Development of the PBS. A technical description of the score development is available in Supplemental Digital Content 3 (see Table, Supplemental Digital Content 3, Technical Description of Score Development, http://links.lww.com/MSS/B552). We randomly selected half of the sample to develop the PBS. To obtain the scores for each of the eight physical behavior variables, we fit a logistic regression with survival (nonmortality) as the outcome, using a nonparametric Generalized Additive Model using a randomly selected half of the sample (26). Based on previous research, the shape of the relationship between each physical behavior and mortality was incorporated into the model using the Shape Constrained Additive Regression (SCAR) method of Chen and Samworth (2015) (SCAR package; https://cran.r-project.org/web/packages/scar/index.html). Specifically, the dose–response relationship between aerobic activity and survival is concave and increasing (20), sedentary time is concave and decreasing, and hours of sleep is concave (4,21,27). Models were adjusted for the covariates described above.

Maximum logit scores from each of the eight behavior-survival functions were summed to produce a maximum total score, such that components more strongly associated with survival contributed more toward the total score (see Figure, Supplemental Digital Content 4, score development, http://links.lww.com/MSS/B553). This total was rescaled to range from 0 to 100, with 0 being highest risk and 100 being lowest risk, to be consistent with composite scores from other fields, such as the Healthy Eating Index (15). Sedentary behavior values were reverse coded because more sedentary time decreases survival probability. Because of its inverted U-shaped relationship with survival, scores for sleep duration were scaled such that long sleepers (>10 $h \cdot d^{-1}$) and those whose reported no hours of sleep received a 0 score. Figure 1 shows plots for the rescaled values for each of the eight components, with *y*-axes indicating the relative importance of each physical behavior to the overall PBS. Table 1 shows the final scoring system, and Supplemental Digital Content 4 shows the histogram of the total score across the data set, http://links.lww.com/MSS/B553.

Example PBS. In Table 1, we show a breakdown of how much each behavior contributes to the overall score. Moderate exercise, vigorous exercise, and moderate-vigorous household activity accounted for the majority of the score (57/100 points) (Table 1). We also provide the PBS for a hypothetical person who is at the median for all reported behaviors, resulting in a score of 75.14 (Q3) (13.7 $MET \cdot h \cdot wk^{-1}$ of moderate activity, 0 $MET \cdot h \cdot wk^{-1}$ of vigorous activity per week, 7 $MET \cdot h \cdot wk^{-1}$ of light household activity, 13.25 $MET \cdot h \cdot wk^{-1}$ of MVPA household activity, 0 $MET \cdot h \cdot wk^{-1}$ of weight training, 3.0 $h \cdot d^{-1}$ sitting nonwatching television, 3.5 $h \cdot d^{-1}$ of television sitting, and 7.5 h of sleep). Table 1 also shows two hypothetical people who achieve physical activity recommendations (14 $MET \cdot h \cdot wk^{-1}$: 8 $MET \cdot h \cdot wk^{-1}$ moderate exercise and 3 $MET \cdot h \cdot wk^{-1}$ of MVPA household activity and 3 $MET \cdot h \cdot wk^{-1}$ of vigorous exercise) but vary by levels of sitting time and sleep, which results in different PBS scores and classifies them in different quintiles (Q3 vs Q2, respectively). In terms of minutes of physical activity, the 14 $MET \cdot h \cdot wk^{-1}$ for this hypothetical person approximately translate to 5 $d \cdot wk^{-1}$ of a brisk walk (3.5 METs) for 30 min, one 30-min exercise class (6 METs) each week and <15 $min \cdot d^{-1}$ of moderate household chores (3 METs). The provided R-code (see https://github.com/kravitzel/Physical-Behavior-Score and Document, Supplemental Digital Content 5, R-code to calculate PBS for individual or group, http://links.lww.com/MSS/B554) includes a function to calculate the PBS either for an individual or for a data set with information on the same eight physical behaviors.

Predictive validity of PBS. To model the relationship between the PBS and mortality risk, we used Cox Proportional Hazards Regression to examine mortality risk across PBS quintiles in the second half of the sample. We tested the proportional hazards assumption using Schoenfeld residuals and

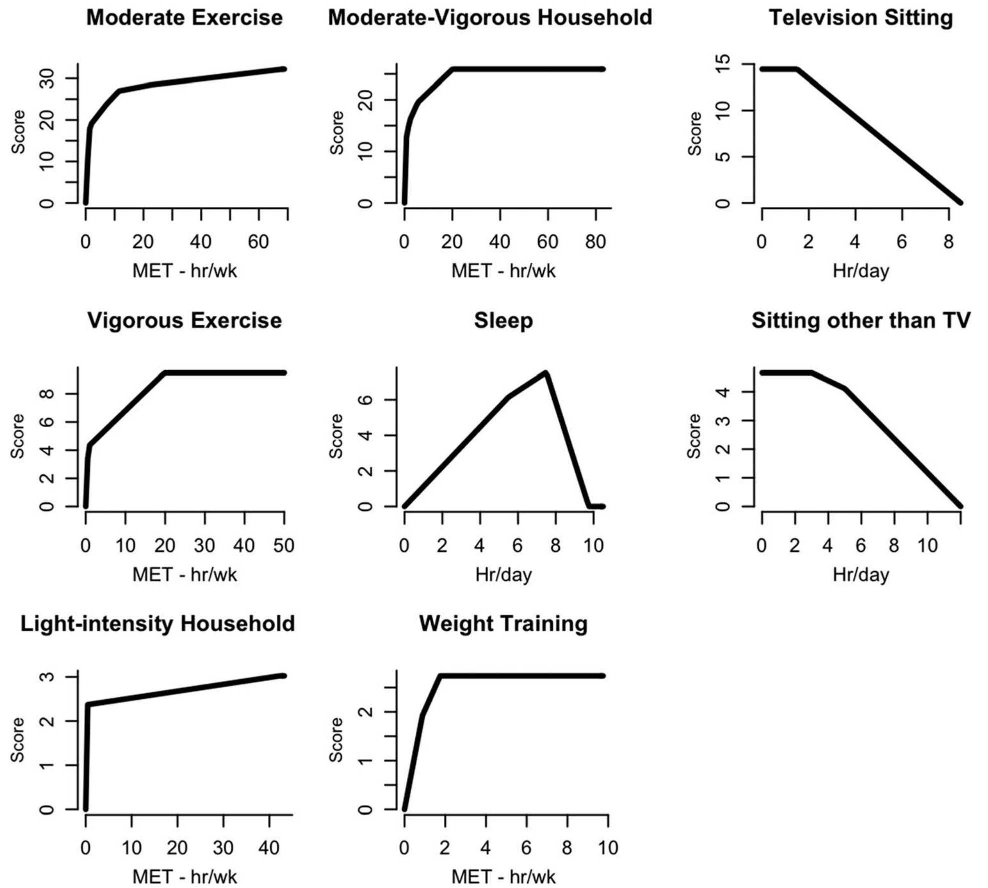

FIGURE 1—Relationship between different physical behaviors and survival, rescaled to sum to 100. Shape-constrained additive regression models returned eight sets of predicted values, one for each function that is fit to describe the relationship between physical behavior and survival. The values on the *x*-axis are weekly MET-hours expended during a particular physical activity or daily hours spent in a particular sedentary time or sleep. The values on the *y*-axis show the additive effect of each physical behavior on the logits (log-odds) of survival, rescaled to range from 0 to 100. These are the fitted values described in Supplemental Digital Content 3: Technical Description of Score Development, http://links.lww.com/MSS/B552. All models were adjusted for age (yr), sex, education (<12 yr, high school graduate, some college, college graduate, unknown), smoking history (never, stopped 10+ yr, stopped 5–9 yr, stopped 1–4 yr, stopped <1 yr, current smoker, unknown), race/ethnicity (non-Hispanic white, non-Hispanic black, other, unknown), overall health (excellent, very good, good, fair, unknown), BMI (<25, 25–29.9, 30+ kg·m^{-2}, unknown), physician-diagnosed depression (yes, no, or missing), physician-diagnosed heart disease (yes, no, missing). Shading indicates 95% CI.

found this assumption was not violated (see Document, Supplemental Digital Content 6, Testing Proportional Hazards Assumption, http://links.lww.com/MSS/B555) (28). We also determined the mortality risk by quintiles of aerobic activity and sedentary time, and sleep quartiles (Q1: <5 h·d^{-1}; Q2 is 5–7 h·d^{-1}; Q3: 7–8 h·d^{-1} [referent], Q4 is >9 h·d^{-1}) in multivariate adjusted models as a comparator for the PBS. Separate models were fit for all-cause and cause-specific mortality (cardiovascular disease, cancer, and other causes). We repeated the categorical (quintile or quartile) analysis separately for men and women and also conducted a sex-stratified Cox proportional hazards regression analysis using PBS as a continuous variable. For the continuous analysis, the referent point was set at the 5th percentile (PBS of 53.5). We also conducted stratified analyses by sex, age group (median split), BMI categories (normal weight BMI, <25 kg·m^{-2}; overweight BMI, 25–29.9 kg·m^{-2}; obese, ≥30 kg·m^{-2}) and self-reported health status (fair, good, very good, and excellent). All subgroup analyses were adjusted for covariates. All models adjusted for the same confounders, and all analyses were done in R (version 3.4.3), with an alpha level of 0.05.

RESULTS

Table 2 shows the baseline participant characteristics by PBS quintile. There tended to be more variation in physical activity compared with sedentary time and sleep across quintiles. The quintile cutoffs were Q1 (0 to 66.47); Q2 (>66.47 to 73.63); Q3 (>73.63 to 79.03); Q4 (>79.03 to 84.85); Q5 (>85.85). Participants in the first quintile (Q1) tended to be more obese, have lower education levels, were less likely to report health status as excellent compared to those in Q5. Over an average of 6.6 yr of follow-up, there were 8732 deaths (3503 cancer, 2732 cardiovascular disease, 2497 other cause). There was a strong graded decline in risk of all-cause mortality across quintiles of PBS (Table 3). Compared with the first

TABLE 1. Reported physical behaviors and corresponding PBS for maximum, median, and two hypothetical people in the NIH-AARP diet and health study cohort, 2004–2011.

	Maximum Score		Median Values	
	Criteria for Maximum	Maximum PBS	Reported Physical Behavior	Assigned PBS
Physical behavior				
Moderate exercise	>50 MET·h·wk^{-1}	32	13.7 MET·h^{-1}	27.25
Vigorous exercise	>20 MET·h·wk^{-1}	10	0 MET·h^{-1}	0
Light household activity	>3 MET·h·wk^{-1}	3	7 MET·h^{-1}	2.47
MVPA household activity	>20 MET·h·wk^{-1}	25	13.25 MET·h^{-1}	22.9
Weight training	>2 MET·h·wk^{-1}	3	0 MET·h^{-1}	0
Sitting other than TV	0 h·d^{-1}	5	3 h·d^{-1}	4.66
Hours of TV sitting	0 h·d^{-1}	14	3.5 h·d^{-1}	10.32
Hours of sleep	7.5 h·d^{-1}	8	7.5 h·d^{-1}	7.54
Total score (quintile)		100 (Q5)[a]		75.14 (Q3)
	Hypothetical Person A: Meets Guidelines/Average Sit		**Hypothetical Person B: Meets Guidelines/High Sit**	
	Reported Physical Behavior	**Maximum PBS**	**Reported Physical Behavior**	**Assigned PBS**
Physical behavior	8 MET·h^{-1}	24.36	8 MET·h^{-1}	24.36
Moderate exercise	3 MET·h^{-1}	4.9	3 MET·h^{-1}	4.9
Vigorous exercise	3.5 MET·h^{-1}	2.42	3.5 MET·h^{-1}	2.42
Light household activity	3 MET·h^{-1}	16.86	3 MET·h^{-1}	16.86
MVPA household activity	1 MET·h^{-1}	2.04	1 MET·h^{-1}	2.04
Weight training	3 h·d^{-1}	4.66	5 h·d^{-1}	4.11
Sitting other than TV	3 h·d^{-1}	10.32	5 h·d^{-1}	7.23
Hours of TV sitting	7.5 h·d^{-1}	7.54	6 h·d^{-1}	6.5
Hours of sleep		74.13 (Q3)		68.14 (Q2)
Total score (quintile)				

MET-hours per week is the MET value for each activity multiplied by the reported hours per week; MVPA is moderate-vigorous intensity physical activity. Moderate, ≥3 METs; vigorous ≥6 METs. PBS score for quintiles are Q1 (0 to 66.47); Q2 (>66.47 to 73.63); Q3 (>73.63 to 79.03); Q4 (>79.03 to 84.85); Q5 (>85.85).
[a]Overall summary scores were rounded to nearest whole number for this illustration.

quintile of PBS, hazard ratio (HR) (95% confidence interval [CI]) were 0.72 (0.68, 0.77), 0.64 (0.60, 0.69), 0.58 (0.555, 0.62), and 0.53 (0.49, 0.57) for quintiles 2 to 5, respectively. Results were similar but stronger for cardiovascular disease mortality (Q5 vs Q1 = 0.42 [0.37, 0.48]) and other mortality (Q5 vs Q1 = 0.42 [0.36, 0.48]). The PBS was also associated with graded decreased risk of cancer mortality (Q5 vs Q1 = 0.75 [0.68, 0.85]).

We then compared the magnitude of the mortality associations using the combined PBS to the individual behavioral components in isolation. For all-cause mortality, when comparing Q5 to Q1, the HR for PBS 0.53 (0.49, 0.57) was a stronger association than those observed for the individual score components (i.e., aerobic activity 0.63 (0.57, 0.69), sedentary time 0.74 (0.67, 0.82) and sleep duration 1.24 (1.17, 1.30), (7–8 h vs 9 + h·d^{-1})). Aerobic activity consistently had stronger associations than

TABLE 2. Baseline participant characteristics and physical behavior components by quintile of PBS in the NIH-AARP diet and health study cohort, 2004–2006.

		Q1	Q2	Q3	Q4	Q5
Age (yr, mean [SD])		71.2 (5.4)	70.7 (5.4)	70.4 (5.4)	70.1 (5.3)	69.7 (5.2)
Sex (% female)		54.7	57.2	59.6	60.7	60.6
White (%)		90.8	92.6	93.4	93.8	93.9
BMI category (%)	Normal weight	24.9	29.7	34.2	37.5	42.7
	Overweight	36.2	40.6	40.7	40.9	40.3
	Obese	33.1	24.5	20.5	16.9	12.6
Smoking status (%)	Never	35.4	37.8	38.9	40.4	41.2
	Current	7.4	6.0	5.2	4.3	2.8
Education	Some high school or high school graduate	36.5	34.6	31.8	28.5	23.3
	College graduate	37.3	39.9	43.1	46.8	52.5
Depression (%)		16.6	12.8	11.0	9.8	8.8
Heart disease (%)		26.0	21.1	19.7	18.8	17.4
Health status (%)	Excellent	7.7	10.7	13.6	16.9	23.3
	Very good	28.0	36.7	40.4	43.7	46.0
	Good	42.2	40.4	37.1	32.9	26.6
	Fair	22.2	12.2	8.8	6.4	4.1
Physical behavior components (median [25th, 75th])						
Moderate exercise (MET·h·wk^{-1})		4.4 (2.5, 9.4)	9.4 (5.1, 18.0)	13.7 (7.3, 25.9)	20.7 (11.6, 36.0)	28.8 (15.1, 51.1)
Vigorous exercise (MET·h·wk^{-1})		0.0 (0.0, 0.0)	0.0 (0.0, 1.9)	0.0 (0.0, 7.3)	3.8 (0.0, 17.5)	18.3 (8.8, 36.5)
Light household activity (MET·h·wk^{-1})		5.3 (1.5, 12.5)	6.3 (2.5, 21.3)	7.8 (3.8, 21.3)	12.5 (3.8, 22.8)	12.5 (6.3, 30.0)
Moderate-vigorous household activity (MET·h·wk^{-1})		3.5 (0.9, 8.4)	9.1 (4.5, 18.1)	14.4 (7.5, 28.3)	19.3 (10.4, 36.0)	26.4 (16.0, 47.0)
Weight training (h·wk^{-1})		0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.0 (0.0, 0.9)	0.9 (0.0, 5.3)
TV sitting (h·d^{-1})		3.5 (3.5, 5.5)	3.5 (1.5, 5.5)	3.5 (1.5, 3.5)	1.5 (1.5, 3.5)	1.5 (1.5, 3.5)
Non-TV sitting(h·d^{-1})		5.0 (3.0, 7.0)	5.0 (3.0, 7.0)	3.0 (3.0, 5.0)	3.0 (3.0, 5.0)	3.0 (3.0, 5.0)
Sleep (h·d^{-1})		7.5 (5.5, 7.5)	7.5 (5.5, 7.5)	7.5 (5.5, 7.5)	7.5 (7.5, 7.5)	7.5 (7.5, 7.5)

Demographic characteristics (education, sex, race/ethnicity) were assessed on the baseline questionnaire (1995) and other variables were assessed on follow-up questionnaires (2004–2006) (i.e., age, physical behaviors smoking, BMI) based on self-reported height and weight, health status and disease history) were based on values reported on the follow-up questionnaire. MET-hours per week is the MET value for each activity multiplied by the reported hours per week moderate, ≥3 METs; vigorous, ≥6 METs.

TABLE 3. Comparison of PBS to groups components for all-cause and cause-specific mortality.

		Q1	Q2	Q3	Q4	Q5
All-cause	PBS	Reference	0.72 (0.68, 0.77)	0.64 (0.60, 0.69)	0.58 (0.55, 0.62)	0.53 (0.49, 0.57)
	Aerobic activity	Reference	0.74 (0.68, 0.80)	0.63 (0.57, 0.69)	0.65 (0.58, 0.72)	0.63 (0.57, 0.69)
	Sedentary time	Reference	0.88 (0.80, 0.96)	0.84 (0.78, 0.91)	0.77 (0.71, 0.84)	0.74 (0.67, 0.82)
	Sleep	—	1.15 (1.07, 1.23)	1.02 (0.98, 1.09)	Reference	1.24 (1.17, 1.30)
Cardiovascular disease	PBS	Reference	0.63 (0.56, 0.71)	0.58 (0.52, 0.65)	0.52 (0.47, 0.58)	0.42 (0.37, 0.48)
	Aerobic activity	Reference	0.69 (0.58, 0.79)	0.53 (0.41, 0.64)	0.54 (0.42, 0.66)	0.55 (0.43, 0.67)
	Sedentary time	Reference	0.88 (0.74, 1.01)	0.78 (0.65, 0.89)	0.68 (0.56, 0.80)	0.65 (0.52, 0.78)
	Sleep	—	1.20 (1.07, 1.34)	1.01 (0.92, 1.11)	Reference	1.24 (1.14, 1.36)
Cancer	PBS	Reference	0.91 (0.83, 1.01)	0.81 (0.73, 0.90)	0.79 (0.72, 0.88)	0.75 (0.68, 0.85)
	Aerobic activity	Reference	0.92 (0.82, 1.01)	0.84 (0.73, 0.94)	0.83 (0.73, 0.94)	0.82 (0.72, 0.87)
	Sedentary time	Reference	0.91 (0.79, 1.02)	0.91 (0.79, 1.01)	0.92 (0.81, 1.02)	0.88 (0.80, 0.96)
	Sleep	—	1.12 (1.02, 1.21)	0.97 (0.88, 1.05)	Reference	1.11 (1.02, 1.21)
Other	PBS	Reference	0.64 (0.57, 0.72)	0.53 (0.47, 0.60)	0.44 (0.38, 0.50)	0.42 (0.36, 0.48)
	Aerobic activity	Reference	0.63 (0.52, 0.75)	0.58 (0.46, 0.70)	0.55 (0.43, 0.67)	0.51 (0.38, 0.64)
	Sedentary time	Reference	0.87 (0.74, 1.01)	0.77 (0.65, 0.90)	0.68 (0.56, 0.80)	0.65 (0.52, 0.78)
	Sleep	—	1.24 (1.09, 1.39)	1.15 (1.06, 1.26)	Reference	1.40 (1.29, 1.51)

Multivariate models adjusted for age (yr), sex, education (<12 yr, high school graduate, some college, college graduate, unknown), smoking history (never, stopped 10+ yr, stopped 5–9 yr, stopped 1–4 yr, stopped <1 yr, current smoker, unknown), race/ethnicity (non-Hispanic white, non-Hispanic black, other, unknown), overall health (excellent, very good, good, fair, unknown), BMI (<25, 25–29.9, 30+ $kg \cdot m^{-2}$, unknown), physician-diagnosed depression (yes, no, or missing), physician-diagnosed heart disease (yes, no, missing). For aerobic activity Q1 is low physical activity (0–27.8 $MET \cdot h \cdot wk^{-1}$), for sedentary time Q1 is high sitting (10.5+ $h \cdot d^{-1}$) and for sleep referent (Q3) is 7–8 $h \cdot d^{-1}$, Q1 is <5 $h \cdot d^{-1}$, Q2 is 5–7 $h \cdot d^{-1}$ and Q4 is >9 $h \cdot d^{-1}$. Aerobic activity, sedentary time and sleep were mutually adjusted in the same models.

sedentary time or sleep for all-cause and cause-specific mortality. For cause-specific mortality, the relationship with PBS was consistently stronger (7%–13% lower HR) than for that of aerobic activity alone (Table 3).

The relationship between physical behaviors and mortality was stronger for women than for men, although there was still a strong, dose–response relationship between PBS score for both men and women (see Document, Supplemental Digital Content 7, Results from sex stratification, http://links.lww.com/MSS/B556). In sex-specific quintiles for all-cause mortality, women in the highest quintile had 54% reduction in all-cause mortality (Q5 vs Q1 = 0.46 [0.41, 0.52]), while men in the highest quintile had a 45% reduction in mortality risk (Q5 vs Q1 = 0.55 [0.50, 0.60]). This observed sex-difference was consistent across cause-specific mortality (Supplemental Digital Content 7, http://links.lww.com/MSS/B556). To investigate potential confounding and reverse causation, stratified analyses were conducted for all-cause mortality by subgroups. We found the relationship between PBS and mortality was associated with decreased mortality risk in both younger and older groups, across category of self-reported health status and BMI categories (Fig. 2).

DISCUSSION

This article presents a new method to combine a number of distinct physical activities, sedentary behaviors and sleep into an integrated score. In a large sample of US adults, we showed this score has strong predictive validity for both men and women. It also showed a strong dose–response relationship with mortality risk in both men and women, and it was more strongly associated with mortality risk than its individual components, indicated by non-overlapping CI (Table 3). In addition to being novel from a statistical perspective, the PBS has important practical applications that may advance the field of physical behavior epidemiology.

A primary application of the PBS is in its potential to estimate the overall association between a comprehensive range of physical behaviors, morbidity and mortality. In 2012, Lee and colleagues (29) estimated the global mortality burden due to lack of leisure time physical activity was 5.3 million deaths annually, but this estimate was based on inactivity alone. Given that the observed risk estimates using the PBS were stronger than that for aerobic activity alone, our study suggests that the burden due to the combination of low activity, high sitting time, and sleep duration may even higher. Moreover, physical behaviors are inherently interrelated and synergistic, and this type of indexed score accounts for this relationship. An

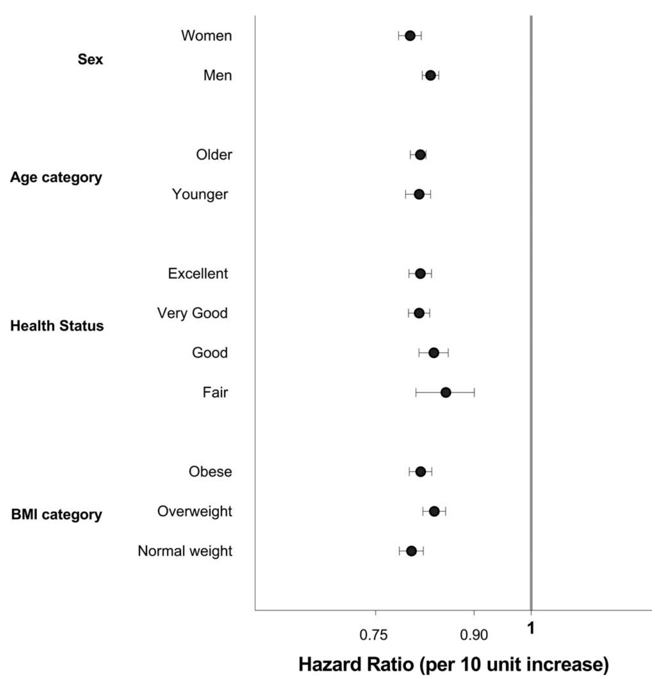

FIGURE 2—Stratified analysis of PBS in relation to All-Cause Mortality. Values are HR and CI per 10 unit increase in PBS. All models were adjusted for age (yr), sex, education (<12 yr, high school graduate, some college, college graduate, unknown), smoking history (never, stopped 10+ yr, stopped 5–9 yr, stopped 1–4 yr, stopped <1 yr, current smoker, unknown), race/ethnicity (non-Hispanic white, non-Hispanic black, other, unknown), overall health (excellent, very good, good, fair, unknown), BMI (<25, 25–29.9, 30+ $kg \cdot m^{-2}$, unknown), physician-diagnosed depression (yes, no, or missing), physician-diagnosed heart disease (yes, no, missing).

important next step will be to translate the scoring system that we empirically developed in this cohort to other studies that assess physical behaviors in similar questionnaires (8,23,24,30). To facilitate this, we have provided R-code to calculate the PBS in Supplemental Digital Content 5, http://links.lww.com/MSS/B554.

A second application of this approach is in epidemiologic analyses using the composite score reflecting multiple physical behaviors as a single covariate. Given the growing list of physical behaviors that have been linked with health-related outcomes, it may be advantageous to use an overall index that represents multiple domains and types of physical behavior. The UK Biobank has elected a similar approach for accelerometer-measured activity, by including a single summary variable representing overall movement as the primary covariate for activity, rather than categorizing sedentary, light and moderate-vigorous physical activity (31). Our approach may require additional questions to ensure the range of physical behaviors are covered, but it allows researchers to adjust for multiple dimensions of physical behavior without having to enter separate variables for each behavior into their model. This application of the PBS will have particular importance in studies where physical behavior is a covariate rather than the primary exposure of interest, when investigating the link between physical behaviors and rare disease outcomes or in small samples where statistical efficiency is a primary concern.

The statistical approach we used is innovative. Although shape-constrained regression has been used in a variety of fields (see (32)), this is, to our knowledge, the first time it has been applied in the analysis of physical activity, sedentary behavior, and sleep. This approach is a unique way of letting previous knowledge guide the choice of statistical model. Additionally, when the relationship between two variables is known to satisfy a predefined relationship, shape-constrained regression has been shown to give results that are, on average, closer to the truth than comparable methods without shape constraints (32,33). This may help to explain the strong, statistically significant results we obtained.

There is a large body of evidence in nutritional epidemiology that has demonstrated the conceptual and etiologic value in assessing dietary patterns (i.e., combinations of foods and nutrients) in relationship to health. (15–17,34) Dietary pattern analyses recognize that, in contrast to isolating a single component of food (e.g., carbohydrates), the foods people eat are likely to be correlated and synergistic. Dietary pattern indices have been developed a posteriori (using a data-driven approach like principal component analyses) or *a priori*, using score-based approaches (e.g., the Healthy Eating Indices derived from federal dietary guidelines). Our approach borrows strengths from each of these, *a priori*, we identified key physical behaviors to be included in the PBS, and then used a data-driven approach to weight each of the individual components of the total score in relation to the outcome of interest—in this case, survival.

The PBS recognizes that individuals can achieve health benefits through different combinations of behavior, for example, engaging in high volume of moderate exercise, or engaging in a lot of household activity, limiting sedentary time and adequate sleep. The strongest contributors to the PBS score were moderate exercise and television viewing, which is consistent with previous research and the 2018 Physical Activity Guidelines, which state that adults who sit less and do any amount of moderate-to-vigorous physical activity gain health benefits (1,7). This may have implications for developing and evaluating interventions that target multiple behaviors, which is an important area for future research.

There are important limitations to note. Our sample is fairly well educated, predominantly white older adults (59–80 yr). Although this is an important demographic given the aging US population, we do not know if these results generalize to younger samples or those with different racial/ethnic compositions. Physical behaviors were self-reported, which is subject to recall and measurement error. However, the use of a questionnaire enables details about activity domain that are not differentiated well using an accelerometer (e.g., household vs leisure) and activity types (e.g., biking and weight lifting) that are not accurately captured by activity monitors. In contrast to a previous day recall or activity monitoring, the survey was not designed to capture a complete 24-h cycle of daily activity, sitting and sleep. Activities were reported as duration per week and then converted to MET-hours per week to account for differing energy cost of different activities. Future research is needed to determine the utility of this approach using instruments like previous day recalls or activity monitors that are designed to assess a complete 24-h period (25). Sleep duration is strongly associated with health (21), but there are other aspects of sleep quality that are associated with health outcomes that we did not assess (35).

This study has important strengths including a large sample with considerable statistical power. The questionnaire included a wide range of activities, which enabled the multidimensional evaluation of physical behaviors. The statistical approach is a novel application that incorporates both the strength and shape of associations into an easily interpretable overall score (0–100). The method for developing a PBS score presented in this article would generalize to a different sample and/or a different instrument to assess physical behavior, but may result in different weighting of the components. An additional strength is the dissemination of R-code for individuals to calculate their PBS score based on these data, and for researchers to apply to full data sets to estimate PBS in independent samples.

CONCLUSIONS

This article presents a statistical method to generate a composite physical behavior that has high predictive validity for mortality outcomes. Although widespread in other areas of epidemiology (14–17), this is one of the first attempts to characterize integrate multiple distinct physical behaviors into a single physical composite score. This score can be applied to quantify the overall disease burden of physical behaviors rather than looking at different types of physical activity in isolation, and it can be used as a parsimonious covariate to adjust for physical behaviors. Future research is needed to test this approach in an independent sample and with different health outcomes.

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