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Research Report

Dose–Response Association Between Physical Activity (Daily MIMS, Peak 30-Minute MIMS) and Cognitive Function Among Older Adults: NHANES 2011–2014

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Abstract

Background: The purpose of this study was to determine the dose–response association between habitual physical activity (PA) and cognitive function using a nationally representative data set of U.S. older adults aged ≥60 years.

Methods: We used data from the 2011–2014 National Health and Nutrition Examination Survey (n = 2 441, mean [*SE*] age: 69.1 [0.2] years, 54.7% females). Cognitive function was assessed using the digit symbol substitution test (DSST) and animal fluency test (AFT). Habitual PA was collected using a triaxial accelerometer worn on participants' nondominant wrist. PA was expressed as 2 metrics using monitor-independent movement summary (MIMS) units: the average of Daily MIMS (MIMS/day) and peak 30-minute MIMS (Peak-30_{MIMS}; the average of the highest 30 MIMS min/d). Sample weight-adjusted multivariable linear regression was performed to determine the relationship between each cognitive score and MIMS metric while adjusting for covariates.

Results: After controlling for covariates, for each 1 000-unit increase in Daily MIMS, DSST score increased (β-coefficient [95% CIs]) by 0.67 (0.40, 0.93), whereas AFT score increased by 0.13 (0.04, 0.22); for each 1-unit increase in Peak-30_{MIMS}, DSST score increased by 0.56 (0.42, 0.70), whereas AFT score increased by 0.10 (0.05, 0.15), all $p < .001$. When including both MIMS metrics in a single model, the association between Peak-30_{MIMS} and cognitive scores remained significant ($p < .01$), whereas Daily MIMS did not.

Conclusions: Our findings suggest that higher PA (both daily accumulated and peak effort) is associated with better cognitive function in the U.S. older adult population.

Keywords: Accelerometer, Aging, Cognition, Exercise, MIMS

Regular physical activity (PA) is recognized as an effective approach for improving and maintaining cognitive function among older adults (1). Previous research indicates that both acute exercise and long-term PA interventions contribute to better cognitive performance (eg, executive function, processing speed, and memory) (1,2). However, there is a lack of evidence concerning the potential dose–response relationship between *habitual* PA (volume and intensity) and cognitive outcomes, and whether this relationship is modified by demographic or other health-related factors (1,2).

The U.S. National Health and Nutrition Examination Survey (NHANES) recently released accelerometer-determined PA monitor (PAM) data for the 2011–2012 and 2013–2014 cycles. Notably, different from the waist-worn PAM protocol in earlier cycles, the 2011–2014 PAM data were collected using a wrist-worn triaxial accelerometer to improve wear time compliance. In response to this change, the data were processed using a novel algorithm developed by John et al. (3), with participant-level data summarized in monitor-independent movement summary (MIMS) units by minute, hour, and day. A key advantage of the MIMS metric is that it is generated by a device-independent universal algorithm that allows comparisons across various studies and designs (3). Analogous to other established PA metrics (eg, daily steps or activity counts), PA volume can be expressed as "Daily MIMS" (ie, total MIMS units accumulated per day) across valid days of assessment (4). However, an analogous intensity-based expression of MIMS units is lacking.

Traditionally, accelerometer-determined intensity has been quantified as minutes per day or week spent in moderate-to-vigorous PA (MVPA) using manufacturer-specific cut-point systems (eg, activity counts from ActiGraph) corresponding with ≥3 metabolic equivalents (5). To date, no studies have established such cut-points for the novel MIMS metric. Borrowing from the step-based metrics literature (6–8), a viable alternative is an index of peak values that reflects minute-level epochs with higher rates of movement (accelerations) across the monitoring period. Tudor-Locke et al. (6) first introduced the concept of peak 30-minute cadence (ie, the average of the 30 highest cadence [steps/min] values within a day) to represent an individual's "best effort." Peak-30 minute cadence is shaped by both intensity and persistence of ambulatory behavior within a day as well as its consistency (regularity) across valid days (7), and it has been included in previous cross-sectional studies as a proxy for PA intensity (8–10) based on the underlying association between cadence and intensity (11). Similar to cadence (steps/min), MIMS values per minute (MIMS/min) were shown to increase at higher PA intensities such as treadmill locomotion at increasingly faster speeds (3). Thus, analogous to peak 30-minute cadence, minute-level (ie, 1-minute epoch) NHANES PAM data can be used to compute peak 30-minute MIMS (Peak-30_{MIMS}; ie, the average of the highest 30 [not necessarily consecutive] MIMS-minute per day, averaged across valid wear days) as an index of higher intensity epochs over the monitoring period. The examination of Daily MIMS and Peak-30_{MIMS} allows a more comprehensive evaluation of PA (both volume and intensity) and its relationship with cognitive function.

Therefore, the purpose of this study was to investigate the dose–response association between PA (expressed as Daily MIMS and Peak-30_{MIMS}) and cognitive function among U.S. older adults (aged ≥ 60 years) from the 2011–2014 NHANES dataset. Importantly, the current study will help guide our understanding of MIMS metric thresholds aligned with cognitive function using free-living wrist-worn accelerometry data from a nationally representative sample (NHANES).

Methods

Study Design and Sample

NHANES is a cross-sectional health survey that uses a complex, multistage probability design to achieve a representative sample of the noninstitutionalized U.S. population. Participants from the NHANES 2011–2012 and 2013–2014 cycles were included in this analysis. The study population was delimited to older adults aged ≥ 60 years because cognitive tests were administered only to this specific age group. Descriptions of the data collection procedures can be found on the CDC website (https://www.cdc.gov/nchs/nhanes/about_nhanes.htm).

Measurements

PA was measured using a triaxial accelerometer (ActiGraph GT3X+, ActiGraph Corp., Pensacola, FL; 80 Hz sampling frequency). Participants were asked to wear the accelerometer on their nondominant wrist for 7 consecutive days to capture 24-hour movement during awake and sleep hours. Consistent with previous reports (12), we removed the data from the first and last day of wear, and included data from individuals with ≥4 days of valid PAM wear, whereby a valid day was defined as ≥10 hours of wear time and the recorded sleep-wear time was <17 hours (4). Participant-level minute-by-minute MIMS data were downloaded from the NHANES website and processed using custom R scripts to generate volume (Daily MIMS) and intensity (Peak-30_{MIMS}). Specifically, Daily MIMS (MIMS/day) was calculated as the sum of all MIMS/min data accumulated within a day and averaged across all valid days. Peak-30_{MIMS} (MIMS/min) was obtained by (i) first rank ordering an individual's MIMS/min values within each valid day of observation, (ii) calculating the mean of the highest 30 values within each day, and (iii) Finally, taking the average of the resulting MIMS/min values across all valid wear days. Supplementary Figure 1 illustrates the data processing steps performed to calculate Peak-30_{MIMS}.

Cognitive function was assessed using the Digit Symbol Substitution Test (DSST) and the Animal Fluency Test (AFT). The DSST is a performance module from the Wechsler Adult Intelligence Scale III (WAIS-III) that evaluates processing speed, sustained attention, and working memory (13), whereas the AFT test examines categorical verbal fluency (a component of executive function) (14). Complete details on measurement and scoring protocol can be found in the Cognitive Functioning Questionnaire data file documentation (https://wwwn.cdc.gov/Nchs/Nhanes/2013-2014/CFQ_H.htm).

In addition, we included covariates that might confound the association between PA and cognitive function, including demographics (age, sex, race–ethnicity, and education level), body mass index (BMI) categories (underweight: <18.5 kg/m^2, normal weight: 18.5–24.9 kg/m^2, overweight: 25.0–29.9 kg/m^2, obese: 30 kg/m^2), and hypertension (yes: systolic ≥ 130 mmHg or diastolic ≥ 85 mmHg; No: systolic < 130 mmHg and diastolic < 85 mmHg). We also considered controlling for cognitive status and physical function; however, there were insufficient data collected for these variables (ie, approximately 80% and 50% of the participants data were missing, respectively) in the NHANES data set.

Statistical Analysis

Statistical analyses were conducted using the "*survey*" package in R and accounted for sample weights according to the NHANES analytical guidelines. Descriptive statistics were computed based on sample characteristics and reported using sample weighted mean (*SE*) for continuous variables, and number with weighted percentage for categorical variables. Pearson correlations (*r*) were calculated to assess the unadjusted associations between MIMS metrics and cognitive scores. Univariate analyses were performed to examine the statistical differences in cognitive scores and MIMS metrics among the population characteristic subgroups by using *t*-tests, ANOVA, and the Kruskal–Wallis test (for non-normally distributed variables). Since there are no established thresholds for MIMS metrics associated with health outcomes or cut-points for MVPA, we computed quartiles of MIMS metrics with their corresponding cognitive test scores.

To address the primary aim, multiple linear regressions were performed to determine dose–response associations between each MIMS metric (ie, Daily MIMS, Peak-30_{MIMS}) and the 2 cognitive test scores (ie, DSST and AFT) separately, while adjusting for covariates. Furthermore, because individuals who accrue a greater amount of daily PA (Daily MIMS) are also likely to achieve a higher Peak-30_{MIMS} (ie, collinearity), we constructed a model including both Daily MIMS and Peak-30_{MIMS} for each cognitive test to examine independent effect(s) on cognitive function. The adjusted regression coefficients (β's) with 95% confidence intervals (CIs), p-values, and R^2 values were estimated and presented for all regression models, and the significance level was set at $p < .05$.

Results

Of the 2 949 older adults who had the 2 cognitive test scores, we excluded individuals without complete PAM data ($n = 433$), and then removed those with missing values for covariates included in this analysis ($n = 75$). The final analytic sample consisted of 2 441 older adults with full data sets for cognitive tests and valid PAM data. Sample weight-adjusted characteristics, and results of the univariate analyses are presented in Table 1. Both Daily MIMS and Peak-30_{MIMS} were positively correlated with DSST score ($r = .27$ and .41, respectively) and AFT score ($r = .16$ and .25, respectively). Finally, the correlation between Daily MIMS and Peak-30_{MIMS} was 0.79.

Figure 1 displays the dose–response relationship between the 2 cognitive scores with Daily MIMS and Peak-30_{MIMS} separated by quartiles (Q1–Q4, values are provided in Figure 1). A clear trend of increasing mean DSST and AFT scores with higher quartile levels of Daily MIMS or Peak-30_{MIMS} was observed. Statistical testing using ANOVA or the Kruskal–Wallis test indicated significant differences in mean cognitive scores across quartiles of MIMS metrics ($p < .001$).

Table 2 summarizes the multivariable-adjusted associations between daily MIMS and Peak-30_{MIMS} with cognitive function scores in linear regression models. Overall, in models that only included a single MIMS metric separately (either Daily MIMS or Peak-30_{MIMS}) with covariates (Models 1, 2, 4, and 5), both Daily MIMS and Peak-30_{MIMS} were significantly associated with the 2 cognitive test scores ($p < .01$). After controlling for covariates, for each 1 000-unit increase in Daily MIMS (Model 1 and Model 4), DSST score (β-coefficient [95% CIs]) increased by 0.67 (0.40, 0.93), whereas AFT score increased by 0.13 (0.04, 0.22), all $p < .01$. For each 1-unit increase in Peak-30_{MIMS} (Models 2 and 5), DSST score increased by 0.56 (0.42, 0.70), whereas AFT score increased by 0.10 (0.05, 0.15), all $p < .001$.

Table 1. Cognitive Test Scores and Physical Activity (MIMS Metrics) by Population Characteristics (Weighted Mean [*SE*] and *p*-Values from Univariate Analyses[a])

		DSST Score		AFT Score		Daily MIMS (MIMS/d)		Peak-30_{MIMS} (MIMS/min)	
	N (weighted %)	Mean (*SE*)	*p*-Values	Mean (*SE*)	*p*-Values	Mean (*SE*)	*p*-Values	Mean (*SE*)	*p*-Values
Whole sample	2 441 (100%)	52.3 (0.6)	—	18.2 (0.2)	—	11 298.0 (98.9)	—	36.5 (0.2)	—
Sex			<.001		<.001		<.001		<.001
Female	1247 (54.4%)	53.8 (0.7)		17.9 (0.2)		11 813.9 (133.8)		37.3 (0.3)	
Male	1194 (45.6%)	49.8 (0.6)		18.4 (0.2)		10 603.1 (118.8)		35.4 (0.3)	
Race			<.001		<.001		<.001		<.001
Non-Hispanic White	1185 (80.1%)	54.4 (0.7)		18.8 (0.2)		11 098.0 (122.6)		36.2 (0.3)	
Non-Hispanic Black	584 (8.3%)	40.3 (1.1)		14.9 (0.2)		11 275.3 (133.9)		34.9 (0.3)	
Other Hispanic	253 (3.7%)	36.3 (1.3)		15.2 (0.3)		12 631.5 (267.8)		38.0 (0.5)	
Mexican American	207 (3.2%)	41.4 (1.4)		17.1 (0.5)		12 797.1 (193.7)		40.1 (0.5)	
Non-Hispanic Asian	178 (2.9%)	50.5 (1.2)		14.6 (0.3)		12 493.3 (335.9)		40.7 (0.9)	
Other race	34 (1.7%)	51.5 (2.0)		18.5 (1.1)		11 124.0 (1078.9)		36.0 (2.2)	
Education			<.001		<.001		.156		.0002
Less than high school	594 (15.7%)	36.6 (0.3)		14.7 (0.3)		10 962.2 (177.4)		34.8 (0.4)	
High school	589 (22.3%)	48.4 (1.1)		16.4 (0.2)		11 316.8 (245.3)		35.9 (0.4)	
Above high school	1258 (62.0%)	57.2 (0.2)		19.7 (0.2)		11 323.2 (113.4)		37.0 (0.3)	
BMI category			.793		.203		<.001		.0002
Underweight	35 (1.5%)	52.8 (1.2)		16.4 (1.2)		11 540.3 (799.0)		36.0 (1.3)	
Normal	622 (24.4%)	51.6 (1.3)		18.1 (0.4)		12 268.1 (285.9)		38.0 (0.6)	
Overweight	843 (35.5%)	52.4 (1.0)		18.1 (0.3)		11 419.4 (142.2)		36.8 (0.3)	
Obese	941 (38.6%)	52.4 (0.7)		18.3 (0.3)		10 572.3 (116.5)		35.3 (0.2)	
Hypertension			<.001		.0026		.0858		.0037
Yes	1365 (52.6%)	50.6 (0.8)		17.7 (0.3)		11 121.8 (116.8)		35.8 (0.2)	
No	1076 (47.4%)	53.8 (0.6)		18.7 (0.2)		11 427.4 (141.1)		37.1 (0.3)	

Notes: AFT = animal fluency test; BMI = body mass index; DSST = digit symbol substitution test; MIMS = monitor-independent movement summary. Peak-30_{MIMS} = peak 30-minute MIMS. BMI category: underweight = BMI < 18.5 kg/m², normal weight = 18.5-24.9 kg/m², overweight = 25.0-29.9 kg/m², obese ≥ 30 kg/m². Hypertension: yes = systolic ≥ 130 mmHg or diastolic ≥ 85 mmHg; no = systolic < 130 mmHg and diastolic < 85 mmHg.

[a]*p*-Values for sex and hypertension were calculated by *t*-tests; *p*-values for Peak-30_{MIMS} were calculated using Kruskal–Wallis tests; *p*-values for other variables were calculated by ANOVA.

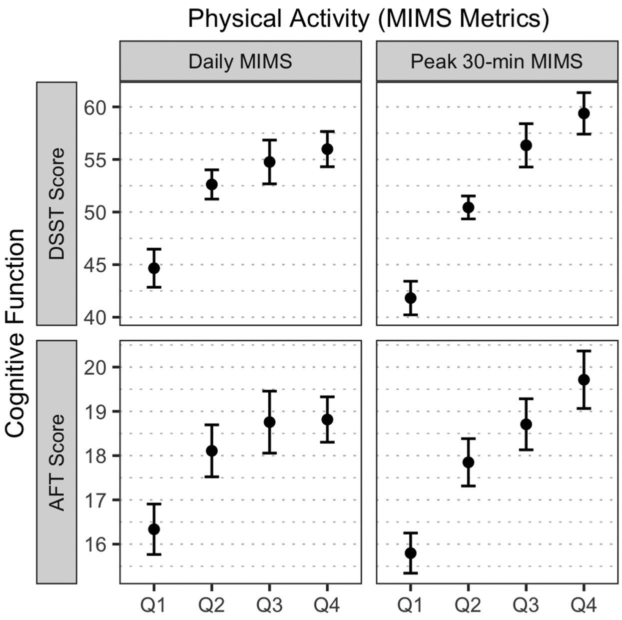

Figure 1. Relationship between cognitive function and physical activity (Daily MIMS and Peak-30_{MIMS}) separated by quartiles among U.S. older adults ≥60 years old (n = 2 441), NHANES 2011–2014. Points and error bars represent mean values and 95% CIs of DSST and AFT scores in each quartile level of Daily MIMS or Peak 30-minute MIMS (Peak-30_{MIMS}). Q1–Q4 represents quartiles of MIMS metrics. Specifically, Daily MIMS was separated by Q1: 2 419–8 909, Q2: 8 909–11 039, Q3: 11 039–13 386, and Q4: 13 386–28 883; corresponding DSST scores for Q1–Q4 Daily MIMS were 44.7 [42.9, 46.5], 52.7 [51.3, 54.1], and 56.1 [54.4, 57.7], and corresponding AFT scores for Q1–Q4 Daily MIMS were 16.3 [15.8, 16.9], 18.1 [17.5, 18.7], 18.8 [18.1, 19.5], and 18.8 [18.3, 19.3]. Peak-30_{MIMS} was separated by Q1: 15.2–31.8, Q2: 31.8–36.5, Q3: 36.5–40.7, and Q4: 40.7–122.2; corresponding DSST score for Q1–Q4 Peak-30_{MIMS} were 41.8 [40.2, 43.4], 50.5 [49.4, 51.5], 56.3 [54.2, 58.4], and 59.4 [57.4, 61.4], and corresponding AFT scores for Q1–Q4 Peak-30_{MIMS} were 15.8 [15.3, 16.2], 17.9 [17.3, 18.4], 18.7 [18.1, 19.3], and 19.7 [19.1, 20.4]. AFT = Animal Fluency Test; DSST = Digit Symbol Substitution Test; MIMS = monitor independent movement summary; Peak-30_{MIMS} = Peak 30-minute MIMS (ie, the average of the 30 highest MIMS within a day, averaged across valid wear days).

Interestingly, in Model 3 (DSST score) and Model 6 (AFT score) that included both MIMS metrics with adjustment for covariates, the association between Peak-30_{MIMS} and both cognitive test scores remained significant (p < .001 and p = .003 for DSST and AFT scores, respectively), whereas Daily MIMS was no longer significantly associated with cognitive test scores (p = .058 and 0.452, respectively). Models 3 and 6 did not include an interaction term for Daily MIMS and Peak-30_{MIMS} as there was no significant interaction when including them in a single model (p > .05). The β-coefficients and p-values of covariates for all models are provided in the supplementary material (Supplementary Tables S1 and S2).

Discussion

To the best of our knowledge, this is the first study to examine the dose–response association between habitual PA and cognitive function using NHANES 2011–2014 wrist-worn PAM data. Overall, our results demonstrated that both PA volume (Daily MIMS) and peak effort (Peak-30_{MIMS}) were significantly positively associated with cognitive function. Interestingly, the current analysis revealed an independent association between Peak-30_{MIMS} and cognitive function after controlling for Daily MIMS and covariates (age, sex, race/ethnicity, education level, BMI, and hypertension). In other words, when maintaining a similar level of daily PA, individuals who performed PA at a higher peak effort or intensity across a day had a better cognitive performance. This finding indicates that there might be a stronger association between peak effort (intensity and persistence) and cognitive function compared to daily PA volume when expressed in MIMS units. In addition, the data we report herein may serve as benchmark values related to PA (MIMS volume and intensity metrics) and cognitive function in older adults.

Our findings are in alignment with previous research demonstrating a positive relationship between PA and multiple cognitive domains, including executive function, processing speed, and verbal fluency (1,15). However, the majority of existing cross-sectional studies on this topic have utilized self-reported PA measures and focused on leisure-time MVPA (16,17), with few studies examining

Table 2. Sample Weight-Adjusted Multivariable Regression of the Association Between Physical Activity (MIMS Metrics) and Cognitive Test Scores Adjusting for Age, Gender, Race, Education Level, BMI Category, and Presence of Hypertension (n = 2 441), NHANES 2011–2014[a]

	Intercept		Daily MIMS (per 1 000 MIMS /d)		Peak-30_{MIMS} (MIMS/min)		
	Adjusted β (95% CIs)	p-Value	Adjusted β (95% CIs)	p-Value	Adjusted β (95% CIs)	p-Value	R^2
DSST Score							
Model 1	93.94 (82.22, 105.65)	<.001	0.67 (0.40, 0.93)	<.001	—	—	.433
Model 2	71.89 (58.42, 85.36)	<.001	—	—	0.56 (0.42, 0.70)	<.001	.459
Model 3[b]	72. 03 (58.57, 85.49)	<.001	-0.35 (-0.71, 0.01)	.058	0.69 (0.49, 0.89)	<.001	.461
AFT Score							
Model 4	29.63 (25.67, 33.60)	<.001	0.13 (0.04, 0.22)	.006	—	—	.243
Model 5	25.84 (20.88, 30.81)	<.001	—	—	0.10 (0.05, 0.15)	<.001	.250
Model 6[b]	25.86 (20.89, 30.83)	<.001	-0.05 (-0.17, 0.08)	.452	0.12 (0.05, 0.19)	.003	.252

Notes: BMI = body mass index; MIMS = Monitor independent movement summary; Peak-30_{MIMS} = peak 30-minute MIMS (ie, the average of the 30 highest MIMS within a day, averaged across valid wear days); 95% CI = 95% confidence interval; DSST = digit symbol substitution test; AFT = animal fluency test. Models 1–3: MIMS metric and DSST score (dependent variable) with adjustment for covariates. Model 4–6: MIMS metric and AFT score (dependent variable) with adjustment for covariates. Models 1, 2, 4, and 5 only included one of the MIMS metrics and covariates, that is, either Daily MIMS or Peak-30_{MIMS}; Models 3 and 6 included both Daily MIMS and Peak-30_{MIMS}, and covariates.

[a]Table 2 only reports the adjusted β coefficients (95% CIs) and p-values for main outcomes (ie, cognitive test scores and MIMS metrics) in all models, results of other covariates for all models are provided in Supplementary Material.

[b]Model 3 and Model 6 did not account for the interaction between Daily MIMS and Peak-30_{MIMS} (nonsignificant, p > .05).

the overall association of accelerometer-determined PA volume and/or intensity (18). Notably, despite the potential positive effects of higher levels of MVPA on multiple domains of cognitive function (eg, working memory) reported previously (15), our findings might not be comparable to prior studies that have utilized self-reported or accelerometer-determined MVPA. First, each MIMS metric describes a specific aspect of habitual PA. Daily MIMS represents PA volume regardless of intensity, which is distinct from self-reported MVPA or accumulation of activity counts or minutes above an a priori defined MVPA cut-point system. Second, in contrast to MVPA cut-points that ignore lower but still important PA intensities, Peak-30_{MIMS} considers acceleration magnitudes ranging from lower to higher peak efforts within a day and across all valid days, allowing for the comparison across a full range of PA intensity levels (eg, light vs vigorous). This is especially important for older adults, as this population tends to spend relatively little time (0.0–16.3 min/d) above MVPA cut-points (5). Thus, compared to the aforementioned studies, the present study reports a more comprehensive PA assessment and therefore provides additional insights into the relationship between PA (volume and intensity) and cognition.

The present study provides a unique contribution to the literature because there is limited evidence regarding the association between PA and cognitive function using accelerometer-determined free-living PA measures from a large representative sample, with much of the prior work relying on self-reported PA measures. Moreover, this study is the first to introduce a novel peak PA index (Peak-30_{MIMS}), which assesses activity performed at an individual's highest intensity or effort, and its independent association with cognitive performance. However, the current study has several limitations. First, the cross-sectional study design precludes causal inferences regarding the association between PA and cognition, and there remains the possibility of reverse and/or bidirectional causality. For example, Sabia et al. (19) demonstrated that declines in PA were observed during the preclinical phase of dementia. Second, although our analyses attempted to control for several demographic and health-related factors, there remains potential for additional residual confounding (eg, physical function and cognitive profile). Finally, based on the population sampling procedures used to obtain a representative sample, the generalizability of our results might be restricted to the U.S. older adult population. Notably, the majority of the sample were classified as overweight or obese (74.1%); therefore, these results should be interpreted with caution when applied to other populations.

In conclusion, the current findings suggest that higher habitual PA (both daily accumulated [Daily MIMS] and peak effort [Peak-30_{MIMS}]) associates with better cognitive function in this representative U.S. older adult population. When controlling for daily MIMS and covariates, the association between Peak-30_{MIMS} and cognitive test scores remained significant, indicating that when maintaining a similar level of daily PA, individuals who perform PA at higher peak efforts across a day may have better cognitive performance. Results from this study improve our understanding of the dose–response relationship between PA and cognitive function based on accelerometer-determined PA metrics. Furthermore, researchers are encouraged to analyze wrist-worn PAM data from large data sets using the universal MIMS algorithm and to report PA levels using the daily and peak metrics described herein to facilitate cross-study comparison. Considering the widespread use of wearable technologies by researchers, clinicians, and the general public, there is considerable potential for the application of a universal algorithm to enhance the understanding of the relationship between PA and cognitive function or other health outcomes under varying experimental and real-world conditions.

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Conflict of Interest

None declared.

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