Passive Measures of Physical Activity and Cadence as Early Indicators of Cognitive Impairment

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Abstract

Background: Emerging research shows regular physical activity reduces cognitive decline risk, but most studies rely on self-reported measures, which are limited by recall bias, subjectivity, and a lack of continuous monitoring capability.

Objective: This study aimed to explore passive physical activity measures as early indicators of cognitive impairment by examining their association with cognitive impairment incidence and neuropsychological (NP) test performance.

Methods: We included participants from the Framingham Heart Study (FHS), a community-based cohort with longitudinal cognitive impairment surveillance. Participants wore an Actical accelerometer for at least 3 days, excluding bathing. Thirty physical activity measures were grouped into intensity-specific durations, step and cadence summaries, and peak cadence. Cox proportional hazard models were applied to assess their associations with incident cognitive impairment, adjusting for age, sex, education, and accelerometer wear time. Predictive performance for incident cognitive impairment was evaluated using time-dependent areas under the receiver operating characteristic curves (AUCs) generated by random survival forest models. Additionally, linear regression models were employed to investigate the relationships between these measures and 18 NP tests.

Results: Among 1212 participants from the FHS Offspring cohort (mean age: 70±8 years; 53.7% women), 10 physical activity measures, including all peak cadence metrics, showed nominal significance with incident cognitive impairment. Models incorporating either peak 1 minute cadence or moderate to vigorous physical activity and total steps/day increased AUC for predicting cognitive impairment by 1.4-4.2%% at 8 years, compared to base models including age, sex, education, and accelerometer wear time. Peak 1 minute cadence and total steps/day also showed significantly positive associations with Trail Making Tests A and B.

Conclusions: Our analysis highlighted significant associations between accelerometer-based physical activity and cognitive performance, emphasizing the role of moderate movement in supporting cognitive health.

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Abstract

Background: Emerging research shows regular physical activity reduces cognitive decline risk, but most studies rely on self-reported measures, which are limited by recall bias, subjectivity, and a lack of continuous monitoring capability.

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Conclusion: Our analysis highlighted significant associations between accelerometer-based physical activity and cognitive performance, emphasizing the role of moderate movement in supporting cognitive health.

Keywords: Passive physical activity; Wearable device; Older adults; Cognitive impairment; Neuropsychological test

Introduction

Physical activity is increasingly recognized as a crucial factor influencing overall health, including cognitive function[1]. It is acknowledged as one of 12 modifiable risk factors for cognitive impairment[2]. Research has shown that engaging in regular physical activity is associated with a lower risk of cognitive decline and better brain function in older adults [3, 4]. Furthermore, meta-analyses have reinforced the link between higher physical activity levels and a lower risk of dementia [5-7]. These findings underscore the importance of assessing and monitoring physical activity in older adults to improve early detection and intervention strategies for cognitive decline.

Most existing studies rely on self-reported physical activity assessments [8-11]. While these methods have been valuable for large-scale epidemiological research due to their practicality and cost-efficiency, they are inherently limited by recall bias and subjectivity [12, 13]. The emergence of digital technologies has revolutionized physical activity assessment, enabling the collection of passive and objective data through wearable devices. These devices, such as accelerometers, provide granular and precise estimates of physical activity, alleviating the limitations of self-report measures[14]. Furthermore, they capture a comprehensive range of lifestyle activities, including household and occupational tasks, offering deeper insights into physical activity patterns beyond structured exercise routines. This advancement significantly enhances our ability to continuously assess and monitor physical activity in diverse and real-world settings.

Emerging research has begun to investigate the relationship between accelerometer-based physical activity and cognitive outcomes in older adults[15, 16]. However, most studies to date have relied on cross-sectional analyses with relatively small sample sizes. Understanding how physical activity is associated with performance on neuropsychological (NP) tests is particularly important, as these tests are critical for evaluating cognitive function across multiple domains, such as memory and executive functions [17-19]. Furthermore, because we know that slower gait speed is also associated with cognitive decline [20, 21], accelerometer-measured cadence, a reflection of walking speed in the free-living environment [22], may be a beneficial domain to investigate. Exploring these relationships offers valuable insights into the mechanisms through which physical activity promotes brain health and helps identify specific activity patterns that are most effective in preserving or improving cognitive function. Such findings can inform

targeted intervention strategies aimed at preventing cognitive decline.

This study aims to investigate passive physical activity and cadence measures as early indicators of cognitive impairment, leveraging the rich data from the Framingham Heart Study (FHS). By utilizing accelerometer-based physical activity and cadence data, we examined their associations with NP test performance across multiple cognitive domains. Additionally, we also studied the relationship of physical activity and cadence measures to incident cognitive impairment, highlighting their potential as biomarkers to enhance early detection and intervention strategies for cognitive decline.

Methods

Study Population

The FHS is a long-term, community-based cohort study that began in 1948 and spans multiple generations. It has conducted ongoing cognitive assessments since 1976[23, 24]. The Offspring cohort, established in 1972, enrolled 5,124 individuals comprising the children of Original cohort members and their spouses[25]. Participants in the Offspring cohort undergo in-person health examinations every 4 to 8 years [26]. During exam cycle 9, participants were instructed to wear an Actical accelerometer on their right hip using a waist-worn belt for monitoring physical activity. Participants were asked to wear the device during waking hours, excluding sleep, and were provided with the option to start immediately or at a later time if personal circumstances (e.g., illness, surgery, or travel) precluded immediate use. Devices were mailed to participants when needed. After the monitoring period, participants returned the devices to FHS staff, who processed the data, checked for anomalies, and prepared the units for future use. A total of 1646 Offspring participants with reprocessed physical activity data were initially included, with 76 participants excluded for not meeting the criterion of at least 3 adherent days (≥10 hours/day). The analysis focused on the 1,212 participants with a time interval of≤5 years between the physical activity measurement date and NP examination date. All participants provided written informed consent. The study received approval from the Institutional Review Board at Boston University Medical Center.

Accelerometry Data Acquisition

Physical activity was monitored using the Actical omnidirectional accelerometer (model #198-0200-00). This device is compact and waterproof (28×27×10 mm,17 grams) designed

to detect accelerations from 0.05 to 2.0 g within a 0.35 to 3.5 Hz frequency range. The device recorded acceleration and deceleration magnitudes in 30-second epochs, categorizing the data into "counts" or "steps". At the FHS, data were processed using Kinesoft software (version 3.3.63) under a standardized protocol to ensure high data quality[27].

Accelerometer Data Reduction

Non-wear periods were excluded using the Choi algorithm[28]. A day was considered adherent if the device was worn for at least 10 hours, across a minimum of 3 days. To normalize differences in wearing time we excluded a 6-hour window from each 24 hour period during which the fewest counts were recorded, representing a potential sleeping period[29]. Activity levels were categorized by intensity: sedentary time (≤100 counts/min), moderate activity (1535-3961 counts/min), and vigorous activity (≥3962 counts/min) [30, 31]. To further account for varying wear times, sedentary minutes were normalized to an 18-hour wear period. Average daily step counts were calculated across adherent days, with values above 20,000 adjusted to mitigate the influence of outliers. A total of 30 physical activity measures were analyzed in this study (**Supplemental Table 1**).

Neuropsychological Assessment

Previous studies have detailed the procedures used for administering the neuropsychological (NP) tests at FHS[32, 33]. This study included the 18 NP tests (**Supplemental Table 2**), assessing various cognitive functions, such as attention and concentration and abstract reasoning[34-39]. Trail Making Test Part B minus Part A (Trails B-A) was calculated as an additional NP measure to provide a clearer measure of executive function. This derived score isolates the executive abilities necessary to complete Trails B by removing the basic sequencing and psychomotor components that are common to both Trails A and Trails B. The distributions of the Hooper Visual Organization Test, Trails A, Trails B, and Trails B-A were normalized by applying a natural log transformation. To ensure consistency in interpretation, these transformed values were adjusted so that higher scores indicate better performance on the tasks[40].

Ascertainment of Cognitive Impairment

In this study, cognitive impairment was categorized as dementia or mild cognitive impairment (MCI). At FHS, diagnoses of cognitive impairment were established by a review committee comprising at least one neurologist and one neuropsychologist [41]. The

diagnosis of dementia followed the criteria established in the fourth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) [42]. MCI was defined as cognitive decline in one or more domains without functional impairment or meeting dementia criteria [43]. Detailed information about the diagnostic process at FHS is available in prior research [44]. Incident cognitive impairment cases were defined as participants who were cognitively intact at baseline but were subsequently diagnosed with cognitive impairment during the follow-up period. For participants diagnosed with incident cognitive impairment, follow-up time was calculated from the date of physical activity measurement to the earliest documented date for dementia or the impairment date for MCI. For participants who did not develop cognitive impairment, follow-up time was censored at the last known contact date or the date of death, whichever came first.

Statistical Analyses

To evaluate the differences in baseline characteristics between groups with incident cognitive impairment and those who remained cognitively intact, continuous variables were analyzed using the Kruskal-Wallis H-test, while categorical variables were assessed with the chi-square test. Standardized values of physical activity measures, with a mean of 0 and a standard deviation of 1, were utilized in the subsequent analysis. Linear regression models were used to assess the association between each of the 30 physical activity measures and NP tests adjusted for age, sex, education, average accelerometer wear time on adherent days, and the time interval between NP and physical activity examination dates. The Cox proportional hazards model was used to evaluate the associations of incident cognitive impairment with each of the 30 physical activity measures, adjusting for age, sex, education, and accelerometer wear time. In this analysis, participants with prevalent cognitive impairment (n=44) or without follow-up information (n=1) were excluded. To account for multiple comparisons, we applied the Bonferroni correction method [45]. The corrected significance threshold was calculated as $P = 0.05/30 \approx 1.67E\text{-}03$. To further investigate the impact of physical activity, Kaplan-Meier survival models were fitted for two participant groups: those with peak 1 minute cadence greater than or equal to 80 steps/minute and those with values less than 80 steps/minute. The cumulative incidence of cognitive impairment was plotted to visualize the differences between the two groups over time.

To evaluate the predictive enhancement of physical activity measures for incident

cognitive impairment over multiple follow-up time points (2, 4, 6, and 8 years), additional analyses were performed using a random survival forest model, a robust machine learning approach for survival data [46, 47]. Model performance was assessed using the mean time-dependent area under the ROC curve (AUC) values from five-fold cross-validation[48]. The baseline model (Model 1) included core predictors such as age, sex, educational level, and average accelerometer wear time. Building upon this, Model 2 incorporated moderate or vigorous physical activity mins/day. Model 3 included total steps/day on Model 1. To explore the impact of peak cadence metrics, Model 4 extended Model 1 by including peak 1 minute cadence. Finally, Model 5 extended Model 1 by incorporating these three physical activity/cadence measures.

Results

Cohort Descriptive

Our study included 1212 participants from the FHS Offspring cohort (mean age: 70± 8 years; 53.7% women) for the association analysis with NP tests. For the association analysis with incident cognitive impairment and the prediction analysis, 1,167 participants were included after excluding those with prevalent cognitive impairment at baseline and those without follow-up information. During a mean follow-up period of 9 years, 131 participants were diagnosed with cognitive impairment. Baseline characteristics revealed significant differences between participants who developed incident cognitive impairment and those who remained cognitively intact. Significant differences were observed between the two groups in variables including age, education, daily time spent in moderate to vigorous physical activity, total steps per day, and whether the peak 1 minute cadence reached or exceeded 80 steps per minute ($P < 0.05$). However, no significant differences were observed in sex, body mass index, diabetes, or prevalent cardiovascular disease. The details of sample characteristics are shown in **Table 1**.

Association Between Physical Activity and Incident Cognitive Impairment

Ten physical activity measures, including all peak cadence metrics, demonstrated nominal significance in their association with incident cognitive impairment, after adjustment for age, sex, educational level, and average accelerometer wear time (**Table 2**). One SD increase in the total steps per minute taken from the highest 10 minutes (not necessarily consecutive) was significantly associated with a 22% (95% CI: 0.65-0.94, $P = 0.0076$) decrease in the

risk of incident cognitive impairment. **Figure 1** illustrates the cumulative incidence of cognitive impairment by comparing participants with the peak 1 minute cadence greater than or equal to 80 steps/minute (Group 1) to those with values less than 80 (Group 2), in unadjusted analysis. The cumulative incidence of cognitive impairment was 23.1% in Group 2 at year 8, significantly higher than the 7.7% observed in Group 1 ($P < 0.0001$).

Figure 2 illustrates the predictive performance for cognitive impairment of five models across 2, 4, 6, and 8 years. Model 4 consistently outperformed Model 1, which only included age, sex, education, and accelerometer wearing time. Model 4, which include peak 1 minute cadence on Model 1, demonstrated the highest performance for 2-year risk prediction (AUC=0.832) and showed stabilization for longer-term predictions (AUC=0.68). All four models that included physical activity or cadence measures outperformed Model 1 in predicting 6- and 8-year risks, with AUC improvements of 2.0-3.9% at 6 years and 1.4-4.2% at 8 years.

Association Between Physical Activity and NP Test Performance

Supplemental Table 2 presents the associations between physical activity and cadence measures with NP tests after Bonferroni correction for multiple tests and adjustment for age, sex, educational level, and average accelerometer wear time. Of the 30 physical activity/cadence measures analyzed, 16 (53.3%) were significantly associated with NP tests, and all of these were associated with at least two NP tests after Bonferroni correction ($P < 1.67E-03$). These measures primarily fall into three categories: durations spent at specific intensity cut-points, step and cadence summaries, and peak cadence. The peak 30 minute cadence exhibited significant associations with 4 NP tests (Trails B, Trails A, Trails B-A, and Controlled Word Association Test), with the most substantial positive association observed with Trails B (beta = 0.07, SE = 0.01, $P = 4.98E-07$). Trails A and B were associated with multiple physical activity measures.

Discussion

This study examined the association of 30 waist-worn accelerometer-based physical activity and cadence measures with incident cognitive impairment, and with ten measures, including all peak cadence metrics, showing nominal significance. Additionally, we evaluated the added predictive power of physical activity and cadence measures for predicting incident cognitive impairment. When either the peak 1-minute cadence or

moderate to vigorous physical activity and total steps/day was added to the models, the AUC for predicting cognitive impairment at 8 years improved by 1.4-4.2% compared to models that only accounted for age, sex, education, and accelerometer wear time.

Our study underscored the significant role of physical activity in cognitive health and its potential as a predictor of cognitive impairment. This aligns with a substantial body of literature indicating that physical activity is a critical factor influencing cognitive health[1-4]. Most existing studies have relied on self-reported physical activity assessment, which can be prone to biases and inaccuracies. By utilizing accelerometer-based measures, our study provided a more objective and precise assessment of daily physical activity. This approach not only validates and extends the findings of previous research but also offers a more comprehensive understanding of how different intensities and patterns of physical activity are associated with cognitive functions. Trails A involves connecting numbered circles in sequence, while Trails B requires alternating between numbers and letters (e.g., 1, A, 2, B) [49]. They were the NP tests most significantly associated with the greatest number of physical activity measures, with Trails B showing the strongest association with all physical activity measures in the steps and cadence summaries and peak cadence categories. This result is consistent with prior research that have demonstrated the sensitivity of trail making tests to variations in physical activity[50-52].

Moreover, our longitudinal analysis revealed that ten physical activity measures, including all peak cadence measures, were significantly associated with incident cognitive impairment with protective effects. Cadence, as a spatiotemporal parameter of gait, reflects walking speed and the intensity of physical activity in free-living environments[22]. Slower gait speed is associated with cognitive decline and increased dementia risk[20, 21]. Importantly, when coupled with memory impairments, gait speed decline shows the strongest link to dementia risk compared to either factor alone, highlighting its potential as an early indicator of cognitive decline[53]. Cognitive performance improvements were observed following a single session of walking at 100 steps per minute for 30 minutes in older adults[54] . Although this finding highlights the utility of cadence as both a marker for cognitive health and a potential intervention target for mitigating cognitive decline, the relationship between cadence and cognition remains limited. The strong performance of Model 4 for 2-year risk prediction (AUC=0.832) suggests that peak 1 minute cadence may be particularly sensitive indicators of early cognitive changes. Furthermore, the stabilization of predictive performance over longer follow-up periods demonstrates the robustness of

these models for extended risk evaluation. Notably, Model 5, which incorporated three physical activity/cadence measures, achieved optimal performance only for 8-year predictions. This finding suggests the need for further research to better understand and optimize the contribution of physical activity measures in predicting cognitive impairment.

Our study presented several strengths. It utilized a large sample from the FHS Offspring cohort with objective accelerometer-based physical activity assessment, covering various measures such as activity duration at different intensity levels, step and cadence summaries, and peak cadence. Additionally, participants have completed a wide range of NP tests, enabling a thorough assessment of cognitive functions across multiple domains. The clinical adjudication of cognitive impairment with longitudinal follow-up further enabled the effect assessment of physical activity on future risk of cognitive impairment. However, we also acknowledged several limitations. First, the majority of FHS offspring participants are of European ancestry, which may restrict the generalizability of our findings to other racial and ethnic groups. Future studies should include more diverse populations to improve the broader applicability of these results. Moreover, the potential influence of social determinants, such as socioeconomic status and social support, on physical activity was not addressed and warrants consideration in future research.

In summary, our study highlighted the importance of utilizing accelerometer-based physical activity and cadence measures to understand their association with cognitive performance. Our findings demonstrated that physical activity, particularly moderate movement and walking speed, can play a crucial role in maintaining cognitive health and reducing the risk of cognitive impairment. These results support the integration of objective physical activity monitoring into routine assessments for older adults, which can aid in the early identification and intervention of cognitive decline. Future research should continue to explore the longitudinal impact of physical activity and cadence on cognitive health and refine predictive models to enhance their clinical utility.

Conflicts of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. Dr. Spartano received funding from Novo Nordisk for an investigator-initiated research grant unrelated to the current project.

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Table 1. Sample characteristics at baseline.

Variable	Study sample 1 (n=1212)	Study sample 2 (n=1167)		
		Incident cognitive impairment (n=131)	Cognitively intact (n=1036)	*P* value*
Age (years), mean (SD)	70 (8)	75 (7)	69 (8)	<0.001
Sex, n (%)				0.95
Women	651 (53.7)	70 (53.4)	481 (53.6)	
Men	561 (46.3)	61 (46.6)	555 (46.4)	
Education, n (%)				0.0039
No high school	27 (2.2)	5 (3.8)	16 (1.5)	
High school	278 (22.9)	39 (29.8)	220 (21.2)	
Some college	334 (27.6)	41 (31.3)	280 (27.0)	
College and higher	573 (47.3)	46 (35.1)	520 (50.2)	
Body mass index, mean (SD)	28.0 (4.9)	27.7 (4.6)	28.1 (4.9)	0.57
Diabetes, n (%)	155 (12.8)	23 (17.6)	124 (12.0)	0.10
Cardiovascular disease, n (%)	151 (12.5)	16 (12.2)	128 (12.4)	0.068
Physical activity, mean (SD)				
Minutes per day spent in sedentary physical activity, min/day	654.8 (81.8)	661.7 (82.6)	652.6 (81.5)	0.30
Minutes per day spent in moderate or vigorous physical activity, min/day	13.5 (22.9)	8.2 (13.5)	14.6 (24.1)	<0.001
Total steps per day, steps/day	5993.9 (3731.2)	4839.1 (3282.1)	6256.1 (3764.4)	<0.001
Peak 1 minute cadence ≥80*, n (%)	991 (81.8)	88 (67.2)	879 (84.8)	<0.001

Note: Study sample 1 was utilized to investigate the associations between physical activity measures and NP test performance. After excluding participants with prevalent cognitive impairments and those without follow-up information, Study sample 2 was used for the analysis of associations between physical activity measures and incident cognitive impairments, as well as for predictive modeling analyses.

*A binary variable indicating whether it is greater than or equal to 80 steps/min.

Table 2. The association between physical activity measures and incident cognitive impairment.

Physical activity measure	HR	95% CI		*P* value
Intensity-specific durations				
Counts per day, counts/day	0.66	0.43	1.02	0.063
Counts per minute, counts/min	0.67	0.44	1.00	0.051
Minutes per day spent in sedentary physical activity, min/day	1.15	0.91	1.46	0.24
Minutes per day spent in light physical activity, min/day	0.94	0.76	1.16	0.55
Minutes per day spent in moderate physical activity, min/day	0.78	0.61	1.01	0.057
Minutes per day spent in vigorous physical activity, min/day	0.77	0.46	1.27	0.31
Minutes per day spent in moderate or vigorous physical activity, min/day	0.72	0.52	1.00	0.053
Total minutes per day accumulated in sedentary intensity activity, min/day	1.16	0.92	1.46	0.22
Total minutes per day accumulated in moderate or vigorous intensity activity, min/day	0.78	0.57	1.07	0.12
Step and cadence summaries				
Steps per day, steps/day	0.80	0.65	1.00	**0.049**
Steps per day with steps per minute below 500 removed, steps/day	0.77	0.59	0.99	**0.039**
Steps per minute, steps/min	0.80	0.65	0.99	**0.039**
Steps per minute with steps per minute below 500 removed, steps/min	0.76	0.59	0.97	**0.029**
Minutes per day spent in cadence of 0 steps per minute, min/day	1.18	0.96	1.46	0.12
Minutes per day spent in the cadence range of 1-39 steps per minute, min/day	0.95	0.79	1.15	0.62
Minutes per day spent in the cadence range of 40-99 steps per minute, min/day	0.81	0.64	1.03	0.091
Minutes per day spent in cadence of at least 40 steps per minute, min/day	0.7	0.62	1.0	**0.045**

	9		0	
Minutes per day spent in cadence of at least 100 steps per minute, min/day	0.85	0.67	1.06	0.15
Minutes per day spent in the cadence range of 1-9 steps per minute, min/day	1.08	0.90	1.30	0.41
Minutes per day spent in the cadence range of 1-19 steps per minute, min/day	1.01	0.84	1.21	0.93
Minutes per day spent in the cadence range of 20-39 steps per minute, min/day	0.89	0.73	1.08	0.23
Minutes per day spent in the cadence range of 40-59 steps per minute, min/day	0.87	0.71	1.08	0.21
Minutes per day spent in the cadence range of 60-79 steps per minute, min/day	0.78	0.58	1.03	0.082
Minutes per day spent in the cadence range of 80-99 steps per minute, min/day	0.75	0.55	1.02	0.062
Minutes per day spent in the cadence range of 100-119 steps per minute, min/day	0.84	0.67	1.06	0.14
Peak cadence				
Peak 1 minute cadence, steps/min	0.82	0.69	0.97	**0.020**
Peak 5 minute cadence, steps/min	0.79	0.67	0.95	**0.0099**
Peak 10 minute cadence, steps/min	0.78	0.65	0.94	**0.0076**
Peak 30 minute cadence, steps/min	0.79	0.65	0.96	**0.015**
Peak 60 minute cadence, steps/min	0.80	0.66	0.97	**0.023**

Regression models adjusted for age, sex, educational level, and average accelerometer wear time

Figure 1. Unadjusted cumulative incidence of cognitive impairment. Group 1: Participants with the peak 1 minute cadence greater than or equal to 80 steps/minute. Group 2: Participants with this measure less than 80.

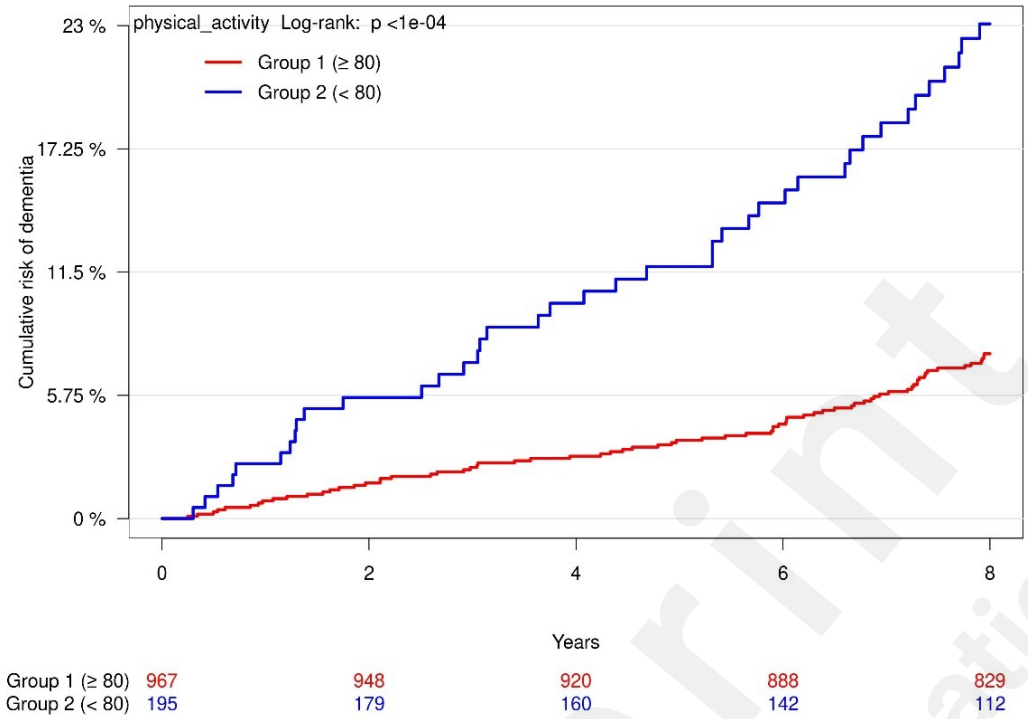
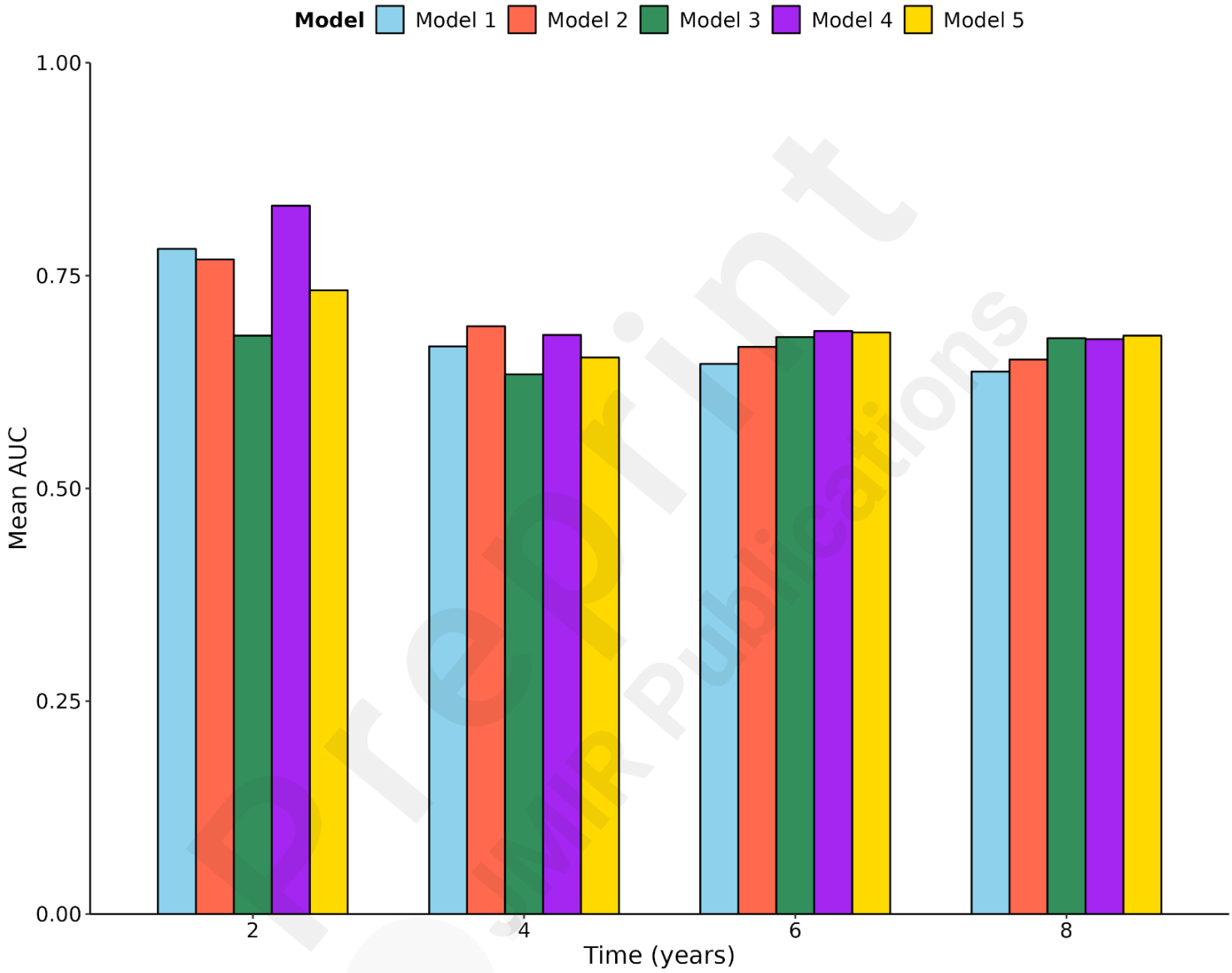


Figure 2. The time-dependent AUC of four models to predict incident cognitive impairment across the next 2, 4, 6, and 8 years. Model 1 used predictors such as age, sex, education, and average accelerometer wear time. Model 2 included these predictors plus moderate or vigorous physical activity mins/day. Model 3 included total steps/day on Model 1. Model 4 added an additional measure on Model 1: peak 1 minute cadence. Model 5 extended Model 1 by incorporating these three physical activity measures.



Supplementary Files

Multimedia Appendixes

Supplemental Tables 1 and 2.
URL: http://asset.jmir.pub/assets/61a94fea993f36f68e779540d14312a2.docx