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Smartwatch-monitored physical activity and myopia in children: a 2-year prospective cohort study

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Abstract

Background While outdoor time's protective role against myopia is established, the relationship between physical activity (PA) and myopia development remains unclear. This study aimed to determine the impact of PA on myopia in children.

Methods In this prospective, school-based cohort study conducted in Shanghai from 2016–2018, children aged 6–9 years from 24 primary schools wore smartwatches for 1 year to record activity intensity and environmental status (indoor/outdoor). Activity load was calculated as a weighted sum of time spent in light (1 ×), moderate (2 ×), and vigorous (3 ×) activities. Myopia shift was measured by 2-year changes in spherical equivalent (SE) and axial length (AL). Limited myopia progression was defined as myopic shift ≤ -0.50 D over 2 years.

Results Among 4306 participants (mean age 7.3 ± 0.6 years; 47.1% girls), mean daily activity times indoors were 134.26 ± 31.99, 9.05 ± 3.34, and 2.63 ± 2.71 min for light, moderate, and vigorous activities respectively, with corresponding outdoor times of 59.10 ± 17.71, 12.64 ± 4.79, and 2.21 ± 1.11 min. Activity load showed protective associations in both environments, stronger outdoors (β = 0.18; 95% CI, 0.10–0.27; $p < 0.001$) than indoors (β = 0.06; 95% CI, 0.003–0.12; $p = 0.037$). Children in the highest quartile of indoor activity (≥ 3.02 weighted hours/day) showed 22% higher odds of limited myopia progression (adjusted OR = 1.22; 95% CI, 1.00–1.50; p for trend = 0.048), while those with outdoor activity ≥ 1.47 weighted hours/day demonstrated 34–77% higher odds (adjusted OR: Q3 = 1.34, 95% CI 1.01–1.80; Q4 = 1.77, 95% CI 1.32–2.36; p for trend < 0.001). Outdoor activity load was particularly protective in non-myopic children (β = 0.15; 95% CI, 0.07–0.23; $p < 0.001$) and those with daily outdoor time < 120 min (β = 0.22; 95% CI, 0.11–0.33; $p < 0.001$), while indoor activity load was protective in Grade 2 students (β = 0.11; 95% CI, 0.03–0.20; $p = 0.009$) and children with ≥ 120 min of outdoor time (β = 0.23; 95% CI, 0.07–0.39; $p = 0.006$).

Conclusions Activity load, integrating both time and intensity of PA, shows significant protective associations with myopic shift in both indoor and outdoor environments. This protective effect exists independent of light exposure, suggesting that PA might offer additional benefits for myopia prevention beyond the known effects of outdoor time.

Keywords Myopia, Physical activity, Activity load, School children

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Background

Myopia has emerged as a major global public health concern, with its prevalence rising dramatically over recent decades, particularly in East Asian countries [1–4]. Among school-age children in China, the prevalence of myopia has reached alarming levels, with rates exceeding 80% in urban areas by the end of high school [2, 5], while global projections suggest that approximately 50% of the world's population will be affected by 2050 [6]. More concerning is the trend toward earlier onset and faster progression of myopia [1, 7, 8], leading to an increased prevalence of high myopia, which can result in severe complications including retinal detachment, myopic macular degeneration, cataract, and glaucoma [9, 10]. Moreover, the economic burden associated with myopia correction and management poses significant challenges to healthcare systems worldwide [11].

While extensive research has established the protective role of outdoor time in myopia prevention [12–16], the relationship between physical activity (PA) and myopia onset and development remains unclear. Biologically, PA may offer protection against myopia through multiple pathways. It enhances choroidal blood flow and ocular circulation [17, 18], elevates dopamine levels [19], and potentially modulates axial elongation and myopia progression [20]. However, current research findings remain controversial. Some studies have suggested that PA may protect against myopia development and progression [21–25], while others have failed to demonstrate such effects [12, 23, 26, 27]. This discrepancy primarily stems from methodological limitations in existing studies. First, most investigations have relied on subjective questionnaires [22, 28] or short-term accelerometer measurements [23–25], which may not accurately capture long-term patterns of PA. Second, previous studies have struggled to effectively differentiate between indoor and outdoor PA [21, 26], making it difficult to isolate the independent effects of PA from the known benefits of outdoor light exposure.

This study employed self-developed smartwatch to monitor children's PA intensity and time in both indoor and outdoor environments [15, 29]. This approach not only overcomes the recall bias inherent in traditional questionnaire surveys but also enables precise quantification of daily activity load. While previous studies have established the protective effect of outdoor time against myopia, this study aimed to investigate whether PA intensity provides additional protective effects independent of outdoor time, potentially offering new evidence for myopia prevention and control.

Methods

Study design and participants

The study was conducted as part of the Shanghai Time Outside to Reduce Myopia (STORM) trial [15, 30]. The STORM was a prospective, cluster-randomized, school-based, intervention trial conducted from October 2016 to December 2018 in Shanghai, China. The detail study design and methodology were described in detail in previous studies [15, 30]. In brief, children aged 6 to 9 years from 24 primary schools in Shanghai, China, were randomized to either a control group, a test group I (40-min outdoor time/day) or test group II (80-min outdoor time/day).

The implementation of outdoor time was supervised at multiple levels, including school administrators, municipal education departments, district-level eye disease prevention centers, and other relevant authorities. It is important to note that the STORM intervention trial mandated an increase in outdoor time but did not prescribe the type or intensity of activities performed during this period. Participants had full autonomy in selecting their activities during outdoor time, which to some extent reflected their natural behavior patterns.

The trial excluded participants with ocular disorders (e.g., strabismus, amblyopia), prior myopia control treatments (e.g., atropine, orthokeratology), ocular surgery history, or refusal of cycloplegia.

This trial was conducted in accordance with the Helsinki Declaration for experimentation on humans. All participating children and their parents at the school were provided with detailed information on the trial and informed consent was provided by the legal guardians of all the students. The STORM trial was approved by the Ethics Committee of Shanghai General Hospital (No. 2016KY138). This trial is registered with ClinicalTrials.gov, identifier: NCT02980445.

Ophthalmological examination and questionnaire

In the trial, children were evaluated at schools and data collected by a trained team of physicians and included visual acuity (retro-illuminated Early Treatment Diabetic Retinopathy chart, Guangzhou Xieyi Weishikang), axial length (AL) measurements (IOL Master, Carl Zeiss Meditec), intraocular pressure check (NT-1000; Nidek), and cycloplegic autorefraction (KR-8900, Topcon). AL measurements were conducted 3 times, and if the difference between any 2 measurements exceeded 0.05 mm, the measurement was repeated. The average AL was used as the final AL value. Ocular abnormalities were assessed using slit-lamp examination and direct ophthalmoscopy. Cycloplegia was induced with 2 drops (if insufficient, 3 drops) of 1% cyclopentolate (Cyclogyl; Alcon) instilled in both eyes with a 5-min interval in between the 2 drops. Cycloplegia was considered sufficient when the pupil dilated beyond 6 mm and exhibited no response to light. Spherical equivalent (SE) refractive error was calculated as the sum of the spherical refractive power and half of the cylindrical refractive power. Children were examined at yearly intervals with the same equipment and protocol utilized for baseline and each follow-up examination. Myopia was defined as cycloplegic SE ≤ -0.50 diopters (D).

Near work time was assessed using a standardized electronic questionnaire at each follow-up visit. Parents reported the time (in minutes) their children spent on reading, academic activities, and the use of electronic devices (television, computer, or mobile games). Total daily near work time was calculated by summing the time spent on these activities, and the mean daily near work time (in hours) was obtained by averaging measurements from baseline, 1-year, and 2-year follow-up assessments. Demographic and physical characteristics were documented through questionnaires and examinations, including age, sex, parental myopia status, and anthropometric measurements. Body mass index (BMI) was calculated based on measured height and weight using standard formula (kg/m^2).

PA and outdoor time measurements using smartwatches

During the second year of the trial, smartwatches were distributed to the participants. They were instructed to wear the smartwatches continuously from 7:00 AM to 7:00 PM every day. The smartwatches were equipped with a 3-axis accelerometer, a light sensor, and a GPS receiver. Data were sampled once per minute, with each data point consisting of the following: time (year/month/day/00:00:00), 3 luminance (lux) readings, 3 ultraviolet light intensity readings, step count, and wearing status. The wearing status was determined by a dual-parameter algorithm that integrates both skin contact and movement detection. Specifically, a minute was classified as 'wearing' when two conditions were met: (1) either the infrared sensor (Model EM30718, Epticore Microelectronics) reading exceeded 187 or the tilt angle was greater than 60 degrees, and (2) movement was detected within the preceding 10 min. This detection method has been validated through internal laboratory testing at Epticore Microelectronics under various conditions, including different skin types, ambient lighting, and wearing positions, achieving over 90% accuracy in wear detection. Data points recorded as 'not wearing' were excluded from the smartwatch data processing. Only data from participants who wore the smartwatch for more than 6 h per day and had at least 90 valid wearing days throughout the year were included in the analysis.

We have developed a model in previous study that utilizes luminance, ultraviolet light intensity and GPS recorded by the smartwatch to distinguish between indoor and outdoor environments, achieving an accuracy of 92.4% [29]. PA was classified into indoor and outdoor activities based on the environmental status. Activity intensity was quantified using steps per minute (SPM). Following previous studies, we categorized activity intensity into 3 levels: light (1–99 SPM), moderate (100–130 SPM), and vigorous (> 130 SPM) [31–33]. While the smartwatches primarily recorded movement intensity rather than specific activity types, observational data from school visits suggested that indoor activities typically included classroom movement, indoor recess activities, physical education classes, and casual movement during leisure time. Outdoor activities primarily consisted of walking to and from school, structured recess activities, outdoor physical education, free play in schoolyards, and casual walking in community settings. The light activity category (1–99 SPM) was generally associated with walking and light movement, moderate activity (100–130 SPM) corresponded to brisk walking and light recreational play, while vigorous activity (> 130 SPM) was linked to running and more intense play or sports activities.

For each participant, we calculated the following indexes: 1) Daily activity time: average time spent in different intensity levels for both indoor and outdoor activities over the 1-year period (minutes or hours/day). 2) Activity intensity: mean steps per minute for both indoor and outdoor activities over the 1-year period. 3) We defined "activity load" that was a composite index integrating both time and intensity of PA, calculated as (1 × light activity time) + (2 × moderate activity time) + (3 × vigorous activity time). The concept of activity load was developed based on the weighted metabolic equivalent (METs) system used in PA and exercise science [34, 35]. Similar to how METs reflect the energy cost of activities as multiples of resting metabolic rate, our activity load calculation assigns progressive weights (1×, 2×, and 3×) to activities of increasing intensity. This weighting approach aligns with previous research showing that higher-intensity activities have proportionally greater physiological effects [36, 37].

Additionally, the average daily outdoor time over the 1-year period was calculated based on the indoor/outdoor status recorded by the smartwatch. The mean light intensity (in lux per minute) was computed throughout the year.

Statistical analysis

All analyses were performed using R version 4.4.2 (R Foundation for Statistical Computing, Vienna, Austria).

The primary outcomes were 2-year changes in SE and AL. Changes in SE (D) and AL (mm) were calculated as the difference between the final and baseline measurements over the 2-year follow-up period. Only participants who completed baseline, 1-year, and 2-year SE and AL measurements were included in the final analysis. Those who missed either the 1-year or 2-year follow-up examinations were excluded to ensure a consistent follow-up duration across all participants. Multiple linear regression models were used to assess associations between activity measures and myopic shift. For activity time and intensity analyses, models were adjusted for baseline age, sex, parental myopia, BMI, near work time, and grade, with outdoor activity additionally adjusted for light intensity. For activity load analyses, we employed 3 models with increasing levels of adjustment: Model 1 (unadjusted), Model 2 (adjusted for age, sex, parental myopia, BMI, near work time, and grade), and Model 3 (additionally adjusted for light intensity for outdoor activity).

For trend analysis, activity loads were categorized into quartiles, and differences between quartiles were examined using analysis of variance with post-hoc tests. For analysis of progression rates, we categorized participants based on their 2-year myopic shift. Limited myopia progression was defined as a myopic shift ≤ -0.50 D over 2 years (average annual progression ≤ -0.25 D), a threshold that has been considered clinically meaningful in previous myopia intervention trials [38, 39]. Subgroup analyses were conducted to examine the associations of activity loads with myopic shift across different demographic and clinical characteristics, including sex, grade, parental myopia, baseline myopic status, and daily outdoor time (< 120 vs ≥ 120 min). Results are presented as beta coefficients (β) with 95% confidence intervals (CIs). Statistical significance was set at $p < 0.05$.

This study was reported following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement for cohort studies. The completed STROBE checklist is provided in Additional File 1.

Results

Participants characteristics

Of 4306 participants included in the analysis, 2027 (47.1%) were girls and 2279 (52.9%) were boys, with a mean age of 7.3 ± 0.6 years (Table 1). At baseline, 271 participants (6.3%) were myopic. All participants had complete demographic data and ophthalmological measurements (SE, AL), while parental myopia data were available for 4100 out of 4306 participants (95.2%). At baseline, the mean SE was 1.02 ± 0.99 D and AL was 22.87 ± 0.95 mm. During the 1-year study period, the average SE change in the total population was −0.40 ± 0.43 D, and the average AL change was 0.26 ± 0.18 mm. Over 2 years, the SE change was −0.88 ± 0.73 D, while the AL change was 0.57 ± 0.32 mm.

Compared to non-myopic children, myopic participants were significantly older (7.6 ± 0.5 vs. 7.2 ± 0.6 years, $p < 0.001$) and had longer AL at baseline (23.91 ± 0.72 mm vs. 22.81 ± 0.70 mm, $p < 0.001$). Over the 2-year study period, they exhibited greater SE and AL changes (−1.78 ± 0.78D vs. −0.82 ± 0.69D, $p < 0.001$; and 0.96 ± 0.31 mm vs. 0.54 ± 0.30 mm, $p < 0.001$, respectively).

Smartwatch compliance and physical activity patterns

To assess smartwatch compliance, we conducted a detailed analysis of wearing patterns. Figure 1 presents the hourly wearing patterns of all 4306 participants before data processing, showing the highest compliance rates during school hours (8:00 AM to 4:00 PM). Moreover, of the total participants, 3330 (77.3%) met the inclusion criteria of wearing the smartwatch for ≥ 6 h per day for ≥ 90 days throughout the year. Figure 2 illustrates the hourly smartwatch wearing compliance after data processing, showing consistently high compliance during school hours (8:00 AM to 3:00 PM), with rates exceeding 90% (ranging from 90.7% to 93.8%). Compliance was lower in the early morning (6:00–7:00 AM, 28.5–73.2%) and after-school hours (5:00–9:00 PM, decreasing from 78.8% to 1.7%), suggesting that some participants removed the devices after returning home. As participants were not required to wear the devices during sleep, no data were available for 10:00 PM to 5:00 AM in both Figs. 1 and 2. Overall, participants exhibited high compliance with the wearing protocol.

For PA patterns, participants spent a mean of 134.3 ± 32.0, 9.1 ± 3.3, and 2.6 ± 2.7 min per day in light, moderate, and vigorous indoor activities, respectively (Table 1). The corresponding outdoor activity times were 59.1 ± 17.7, 12.6 ± 4.8, and 2.2 ± 1.1 min per day. The mean activity load was 160.3 ± 35.5 weighted minutes per day for indoor activities and 91.0 ± 25.3 weighted minutes per day for outdoor activities. Additionally, outdoor light activity time was significantly lower in the myopic group (54.84 ± 16.40 min/day) compared to the non-myopic group (59.40 ± 17.76 min/day, $p < 0.001$), suggesting potential lifestyle differences between the two groups. However, no statistically significant differences were observed in other PA patterns, including indoor activity duration and intensity, as well as moderate-to-vigorous outdoor activity time (all $p > 0.05$).

Association of PA time and intensity with myopic shift

Table S1 in Additional file 2 showed that outdoor light activity time was significantly associated with reduced myopic shift (β = 0.27; 95% CI, 0.13–0.42; $p < 0.001$)

Table 1 Demographic characteristics and physical activity patterns in the study

Characteristic[a]	Total ($n = 4306$)	Non-myopia ($n = 4035$)	Myopia ($n = 271$)	*p* value
Age at baseline, years	7.3 ± 0.6	7.2 ± 0.6	7.6 ± 0.5	< 0.001
Sex				0.008
Girls	2027 (47.1)	1923 (47.7)	104 (38.4)	
Boys	2279 (52.9)	2112 (52.3)	167 (61.6)	
Grade				< 0.001
Grade 1	2076 (48.2)	2032 (50.4)	44 (16.2)	
Grade 2	2230 (51.8)	2003 (49.6)	227 (83.8)	
BMI, kg/m^2	16.8 ± 2.6	16.8 ± 2.5	17.1 ± 2.8	0.042
Parental myopia ($n = 4100$)	4100			< 0.001
Neither	1888 (46.0)	1816 (47.3)	72 (27.7)	
One parent only	1453 (35.4)	1343 (35.0)	110 (42.3)	
Both parents	759 (18.5)	681 (17.7)	78 (30.0)	
SE at baseline, D	1.02 ± 0.99	1.19 ± 0.75	−1.40 ± 0.91	< 0.001
1-year SE change, D	−0.40 ± 0.43	−0.38 ± 0.42	−0.87 ± 0.49	< 0.001
2-year SE change, D	−0.88 ± 0.73	−0.82 ± 0.69	−1.78 ± 0.78	< 0.001
AL at baseline, mm	22.87 ± 0.95	22.81 ± 0.70	23.91 ± 0.72	< 0.001
1-year AL change, mm	0.26 ± 0.18	0.25 ± 0.18	0.49 ± 0.18	< 0.001
2-year SE change, mm	0.57 ± 0.32	0.54 ± 0.30	0.96 ± 0.31	< 0.001
Near work time, h/day	4.23 ± 1.55	4.23 ± 1.55	4.34 ± 1.64	0.698
Physical activity ($n = 3330$)[b]				
Indoor activity				
Light activity time, min/day	134.26 ± 31.99	134.27 ± 31.99	134.20 ± 32.18	0.977
Moderate activity time, min/day	9.05 ± 3.34	9.03 ± 3.35	9.37 ± 3.16	0.132
Vigorous activity time, min/day	2.63 ± 2.71	2.64 ± 2.74	2.58 ± 2.26	0.720
Activity intensity, steps/min	39.16 ± 3.64	39.14 ± 3.64	39.51 ± 3.74	0.148
Activity load, weighted min/day[c]	160.26 ± 35.50	160.23 ± 35.47	160.67 ± 36.13	0.856
Outdoor activity				
Light activity time, min/day	59.10 ± 17.71	59.40 ± 17.76	54.84 ± 16.40	< 0.001
Moderate activity time, min/day	12.64 ± 4.79	12.67 ± 4.80	12.20 ± 4.56	0.152
Vigorous activity time, min/day	2.21 ± 1.11	2.21 ± 1.11	2.22 ± 1.19	0.921
Activity intensity, steps/min	61.09 ± 6.02	61.07 ± 6.02	61.29 ± 6.06	0.609
Activity load, weighted min/day[c]	91.01 ± 25.31	91.36 ± 25.33	85.90 ± 24.41	0.009

Abbreviation: *BMI* Body Mass Index, *SE* spherical equivalent, *D* diopter, *AL* axial length

[a] Data are presented as mean ± SD or number (percentage)

[b] Physical activity measurements were available for 3330 children who completed activity monitoring

[c] The activity load was defined as (1 × light activity time) + (2 × moderate activity time) + (3 × vigorous activity time)

and AL progression ($\beta = -0.15$; 95% CI, −0.21 to −0.09; $p < 0.001$) over 2 years. In contrast, indoor activity parameters and activity intensity showed no significant associations with myopic shift or AL progression.

Association of activity load with myopic shift

After adjustment for demographic and lifestyle factors, both indoor and outdoor activity loads were associated with reduced myopic shift and AL progression during the 2-year follow-up (Table 2). Indoor activity load showed modest associations (myopic shift: $\beta = 0.06$; 95% CI, 0.003–0.12; $p = 0.037$; AL progression: $\beta = -0.03$; 95% CI, −0.06 to −0.005; $p = 0.021$). Outdoor activity load demonstrated stronger protective effects (myopic shift: $\beta = 0.18$; 95% CI, 0.10–0.27; $p < 0.001$; AL progression: $\beta = -0.10$; 95% CI, −0.13 to −0.06; $p < 0.001$), which persisted after additional adjustment for light intensity.

Dose–response relationships between activity loads and myopic shift

For dose–response analysis, we categorized activity loads into quartiles (Fig. 3). Higher indoor activity load (≥ 3.02 vs < 2.26 weighted hours/day) was associated with reduced myopic shift ($p < 0.001$) and axial length

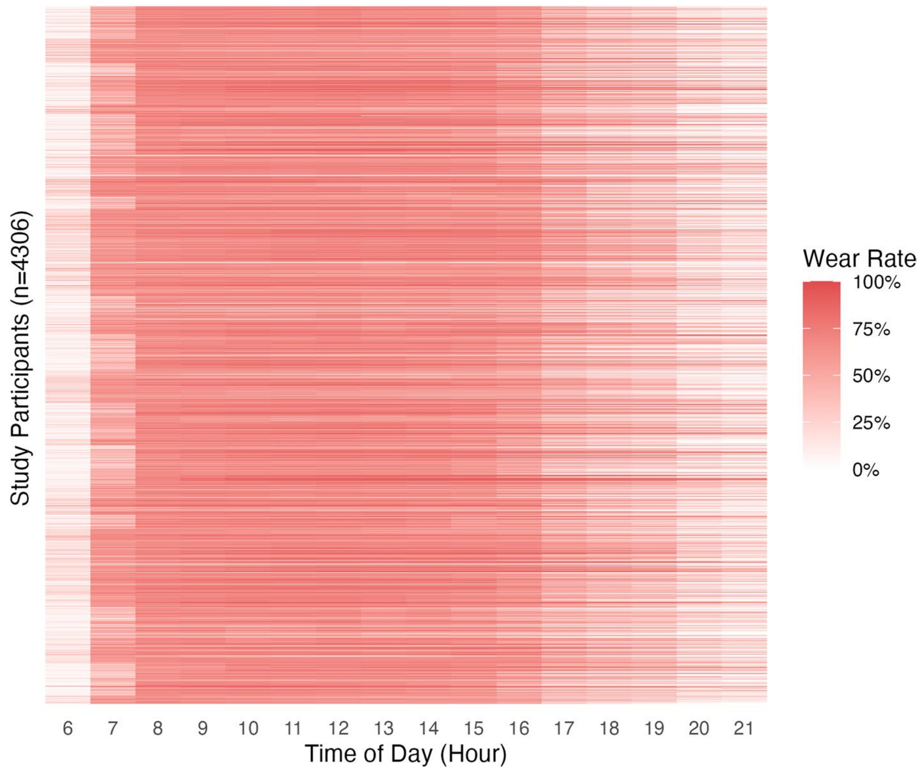

Fig. 1 Hourly smartwatch wearing patterns of all study participants before data processing. Heatmap depicting the smartwatch wearing compliance of all 4306 participants across different hours of the day (6:00 AM to 9:00 PM) before data processing. Each horizontal row represents an individual participant, and color intensity reflects the wear rate percentage, with darker red indicating higher compliance. The highest compliance rates were observed during school hours (8:00 AM to 4:00 PM). No data were collected between 10:00 PM and 5:00 AM, as participants were not instructed to wear the devices during these hours

progression ($p = 0.005$). The protective effects were stronger for outdoor activity load (≥ 1.78 vs < 1.21 weighted hours/day), with higher quartiles showing significantly less myopic shift and axial length progression ($p < 0.0001$).

To further quantify these protective effects, we analyzed the associations between activity load quartiles and limited myopia progression (defined as myopic shift ≤ -0.50 D over 2 years; Table 3). The estimated annual progression rate was −0.40 D/year in the first year and −0.44 D/year based on the 2-year cumulative change (−0.88 D over 2 years). Given this, setting the threshold for limited progression at ≤ -0.25 D/year effectively identifies children with significantly lower myopia progression than the population average. For indoor activity load, Q4 was associated with 22% higher odds of limited progression compared to Q1 (adjusted OR = 1.22; 95% CI, 1.00–1.50), with a statistically significant trend across quartiles (p for trend = 0.048 after adjustment). The protective effect was stronger for outdoor activity load, where Q4 had 77% higher odds of limited progression compared to Q1 (adjusted OR = 1.77; 95% CI, 1.32–2.36). Notably, a significant protective effect emerged from Q3 (adjusted OR = 1.34; 95% CI, 1.01–1.80), suggesting this level (1.47–1.77 weighted hours/day) might represent a threshold for effective myopia protection. This dose–response relationship remained significant after adjustment for potential confounders (p for trend < 0.001).

Subgroup analyses between activity loads and myopic shift

Subgroup analyses revealed differential associations of indoor and outdoor activity loads with myopic shift across various demographic and clinical characteristics (Fig. 4). Indoor activity load showed an overall modest association with less myopic shift (β = 0.06; 95% CI, 0.003–0.12; $p = 0.040$), with the strongest association observed in grade 2 students (β = 0.11; 95% CI, 0.03–0.20; $p = 0.009$). When stratified by daily outdoor time, indoor activity load exhibited a significant protective effect against myopic shift in children who spent ≥ 120 min outdoors per day (β = 0.23; 95% CI, 0.07–0.39; $p = 0.006$), whereas no significant protective effect was observed in

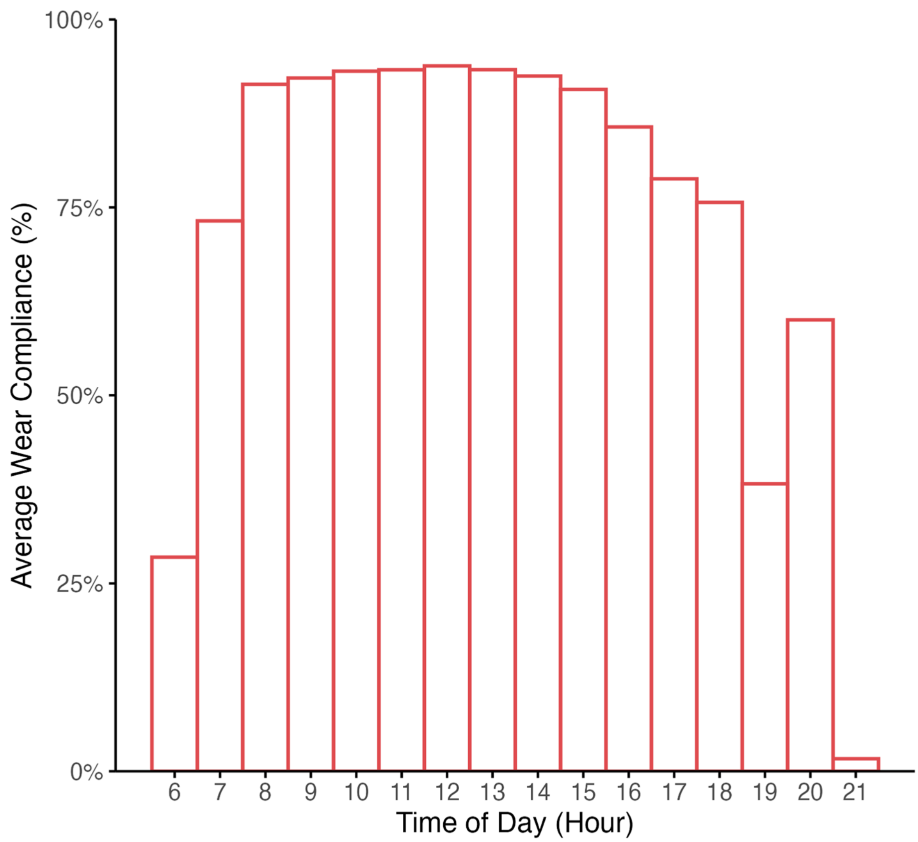

Fig. 2 Average hourly smartwatch wearing compliance after data processing. Histogram depicting the average smartwatch wearing compliance percentage across different hours of the day (6:00 AM to 9:00 PM) after applying the inclusion criteria (≥ 6 h per day for ≥ 90 days). No data were recorded between 10:00 PM and 5:00 AM, as participants were not required to wear the devices during sleeping hours

Table 2 Associations of indoor and outdoor activity load with 2-year changes in myopic shift and axial length

Activity load, weighted hours/day[a]	2-year myopic shift					2-year progression of AL				
	n	β	SE	95% CI	*p* value	*n*	β	SE	95% CI	*p* value
Indoor[b]										
Model 1	3330	0.07	0.02	0.03 to 0.12	< 0.001	3330	−0.03	0.009	−0.05 to −0.01	0.007
Model 2	3167	0.06	0.03	0.003 to 0.12	0.037	3167	−0.03	0.01	−0.06 to −0.005	0.021
Outdoor[c]										
Model 1	3330	0.25	0.03	0.19 to 0.31	< 0.001	3330	−0.13	0.01	−0.15 to −0.10	< 0.001
Model 2	3167	0.21	0.04	0.13 to 0.29	< 0.001	3167	−0.12	0.02	−0.15 to −0.08	< 0.001
Model 3	3167	0.18	0.04	0.10 to 0.27	< 0.001	3167	−0.10	0.02	−0.13 to −0.06	< 0.001

Abbreviation AL axial length, *SE* Standard Error, *CI* Confidence Interval

[a] The activity load was defined as (1 × light activity time) + (2 × moderate activity time) + (3 × vigorous activity time)

[b] Indoor activity load analyses: Model 1: Unadjusted; Model 2: Adjusted for age, sex, parental myopia, BMI, near work time, and grade

[c] Outdoor activity load analyses: Model 1: Unadjusted; Model 2: Adjusted for age, sex, parental myopia, BMI, near work time, and grade; Model 3: Additionally adjusted for variables in Model 2 and light intensity

those with < 120 min of outdoor time (β = 0.04; 95% CI, −0.02–0.10; $p = 0.218$).

Outdoor activity load demonstrated more consistent and stronger protective associations (β = 0.18; 95% CI, 0.10–0.27; $p < 0.001$). The protective effect was significant in both girls (β = 0.22; 95% CI, 0.10–0.34; $p < 0.001$) and boys (β = 0.15; 95% CI, 0.04–0.27; $p = 0.007$), and in both grade 1 (β = 0.14; 95% CI,

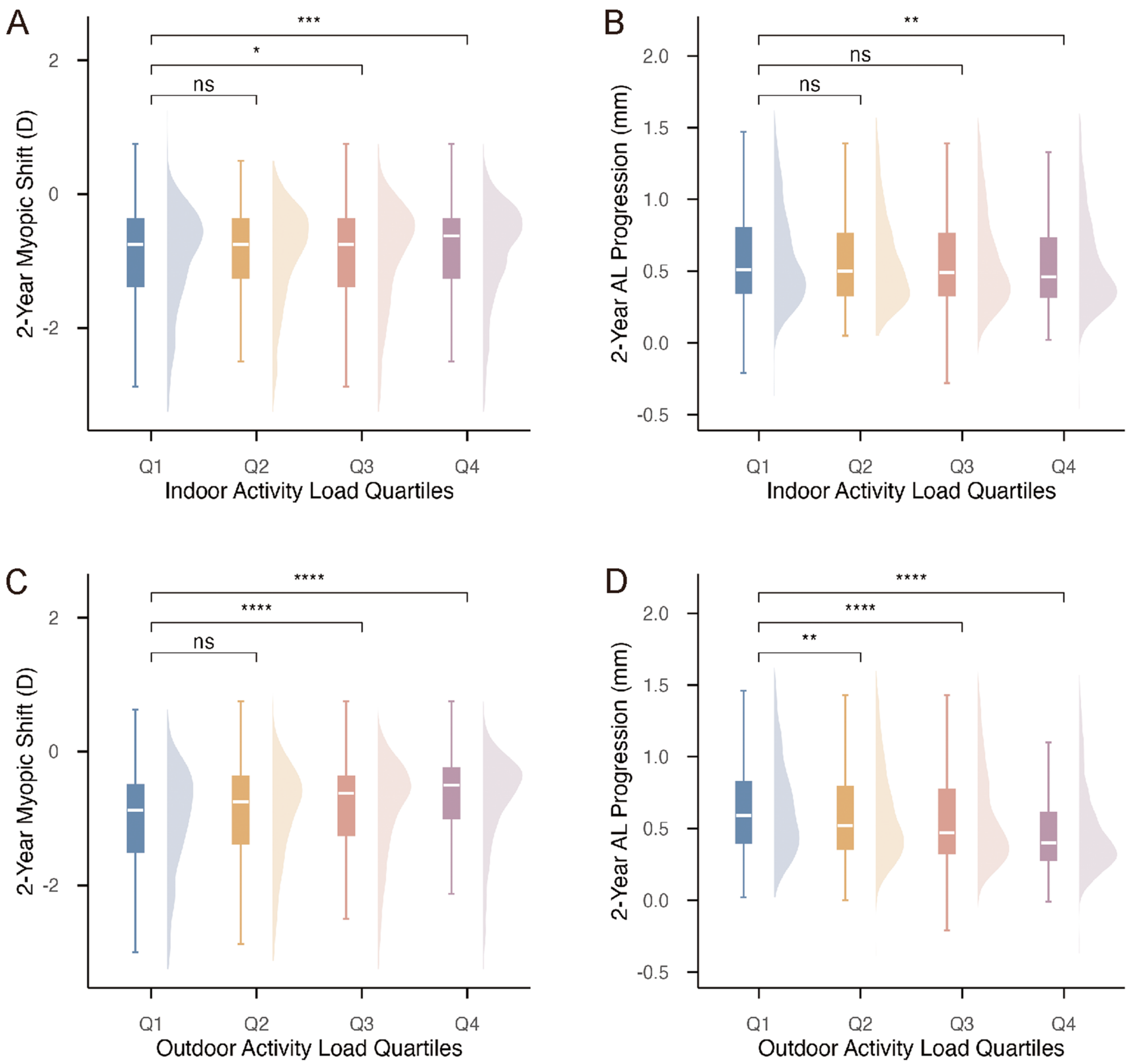

Fig. 3 Dose–response relationships between activity loads and 2-year changes in refraction and axial length. Box plots show median (horizontal line) and interquartile range (box). Violin plots show the distribution of data. **A** Indoor activity load and myopic shift; **B** Indoor activity load and AL progression; **C** Outdoor activity load and myopic shift; **D** Outdoor activity load and AL progression. $^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$, $^{****}p<0.0001$, ns = not significant. Q1-Q4 represent quartiles of activity load from lowest to highest. For indoor activity load, the quartile thresholds were Q1 (< 2.26 weighted hours/day), Q2 (2.26–2.62 weighted hours/day), Q3 (2.63–3.01 weighted hours/day), and Q4 (≥ 3.02 weighted hours/day). For outdoor activity load, the quartiles were Q1 (< 1.21 weighted hours/day), Q2 (1.21–1.46 weighted hours/day), Q3 (1.47–1.77 weighted hours/day), and Q4 (≥ 1.78 weighted hours/day). The activity load was defined as (1 × light activity time) + (2 × moderate activity time) + (3 × vigorous activity time)

0.03–0.26; $p=0.017$) and grade 2 students ($\beta=0.23$; 95% CI, 0.11–0.34; $p<0.001$). Children without parental myopia showed the strongest association ($\beta=0.28$; 95% CI, 0.17–0.38; $p<0.001$). The protective effect was significant in non-myopic children ($\beta=0.15$; 95% CI, 0.07–0.23; $p<0.001$) and was more pronounced in those with daily outdoor time less than 120 min ($\beta=0.22$; 95% CI, 0.11–0.33; $p<0.001$).

Discussion

In this 2-year prospective cohort study, we measured PA patterns of school-age children over 1 year using smartwatches, which enabled accurate distinction between indoor and outdoor activities. We found that activity load, a composite index integrating both time and intensity of PA, showed significant protective associations with myopic shift in both indoor and outdoor settings, with stronger effects

Table 3 Associations between activity load quartiles and limited myopia progression over 2 years

Activity load, weighted hours/day[a]	Limited myopia progression, *n* (%)[b]	OR (95% CI)	Adjusted OR (95% CI)[c]
Indoor[d]			
Q1	298/832 (35.8)	1.0 (Reference)	1.0 (Reference)
Q2	320/832 (38.5)	1.12 (0.92–1.37)	1.08 (0.88–1.32)
Q3	342/832 (41.1)	1.25 (1.03–1.52)	1.18 (0.96–1.44)
Q4	356/833 (42.7)	1.34 (1.10–1.63)	1.22 (1.00–1.50)
p for trend		0.004	0.048
Outdoor[e]			
Q1	268/832 (32.2)	1.0 (Reference)	1.0 (Reference)
Q2	283/832 (34.0)	1.08 (0.88–1.33)	1.12 (0.84–1.50)
Q3	340/832 (40.9)	1.45 (1.19–1.78)	1.34 (1.01–1.80)
Q4	426/833 (51.1)	2.20 (1.81–2.69)	1.77 (1.32–2.36)
p for trend		< 0.001	< 0.001

Abbreviation: *CI* Confidence Interval, *OR* odds ratio

[a] The activity load was defined as (1 × light activity time) + (2 × moderate activity time) + (3 × vigorous activity time)

[b] Limited progression was defined as a myopic shift ≤ −0.50 D over 2 years, corresponding to an average annual progression rate of ≤ −0.25 D

[c] Adjusted for age, sex, parental myopia, BMI, near work time, grade, and light intensity (for outdoor activity load only)

[d] For indoor activity load, the quartile thresholds were Q1 (< 2.26 weighted hours/day), Q2 (2.26–2.62 weighted hours/day), Q3 (2.63–3.01 weighted hours/day), and Q4 (≥ 3.02 weighted hours/day)

[e] For outdoor activity load, the quartiles were Q1 (< 1.21 weighted hours/day), Q2 (1.21–1.46 weighted hours/day), Q3 (1.47–1.77 weighted hours/day), and Q4 (≥ 1.78 weighted hours/day)

observed outdoors even after adjusting for light intensity. Moreover, dose–response analyses revealed that activity load (≥3.02 weighted hours/day for indoor and ≥ 1.47 weighted hours/day for outdoor) were associated with significantly reduced myopic shift, suggesting potential targets for intervention strategies. This study demonstrates that the intensity and pattern of PA offer protective benefits against myopia progression, independent of light exposure. This finding provides new insights into the relationship between PA and myopia development, potentially opening new avenues for myopia prevention strategies that incorporate both activity patterns and environmental factors.

While our study analyzed 2-year myopia outcomes using 1-year PA data, this methodological approach is supported by existing evidence. Our year-long continuous monitoring captured comprehensive seasonal variations in children's activity patterns. Additionally, longitudinal studies have shown that PA patterns tend to remain stable during the primary school years, with stability coefficients ranging from 0.51 to 0.67 [40]. Furthermore, the standardized nature of the Chinese primary school system, with consistent daily routines throughout the academic year, further supports the representativeness of our 1-year measurement [15]. This approach offers advantages over previous studies that relied on shorter measurement periods, such as the 1-week accelerometer assessment by Deere et al. or the method used by Lundberg et al., who collected 4 separate weeks of measurements over their 7-year study period [23, 24].

Earlier studies investigating this relationship have shown inconsistent results, largely due to methodological limitations. Several studies using questionnaires found protective associations between PA and myopia [41, 42], but were subject to recall bias inherent in subjective measurements. Jones et al. [22] specifically examined outdoor PA through questionnaires and, while confirming the protective effect of outdoor time, failed to demonstrate an independent effect of PA. Studies using device-based measurements also yielded mixed results. Lundberg et al. [26], using accelerometers, found no association between PA and refractive errors, while Deere et al. [24] observed that myopic children had more sedentary time and less moderate-to-vigorous PA. However, these studies were limited by their inability to distinguish between indoor and outdoor activities, a critical distinction given the known protective effect of outdoor exposure against myopia.

Building upon the landmark Sydney Myopia Study that first distinguished between indoor and outdoor activities through questionnaires [12], our study using device-based measurements revealed novel insights into the relationship between PA and myopia. While individual measures of PA—whether time spent in different intensity levels or step counts—showed no consistent associations with myopic shift in either indoor or outdoor settings, we found that when integrating both time and intensity into a comprehensive measure of activity load, significant protective associations emerged for

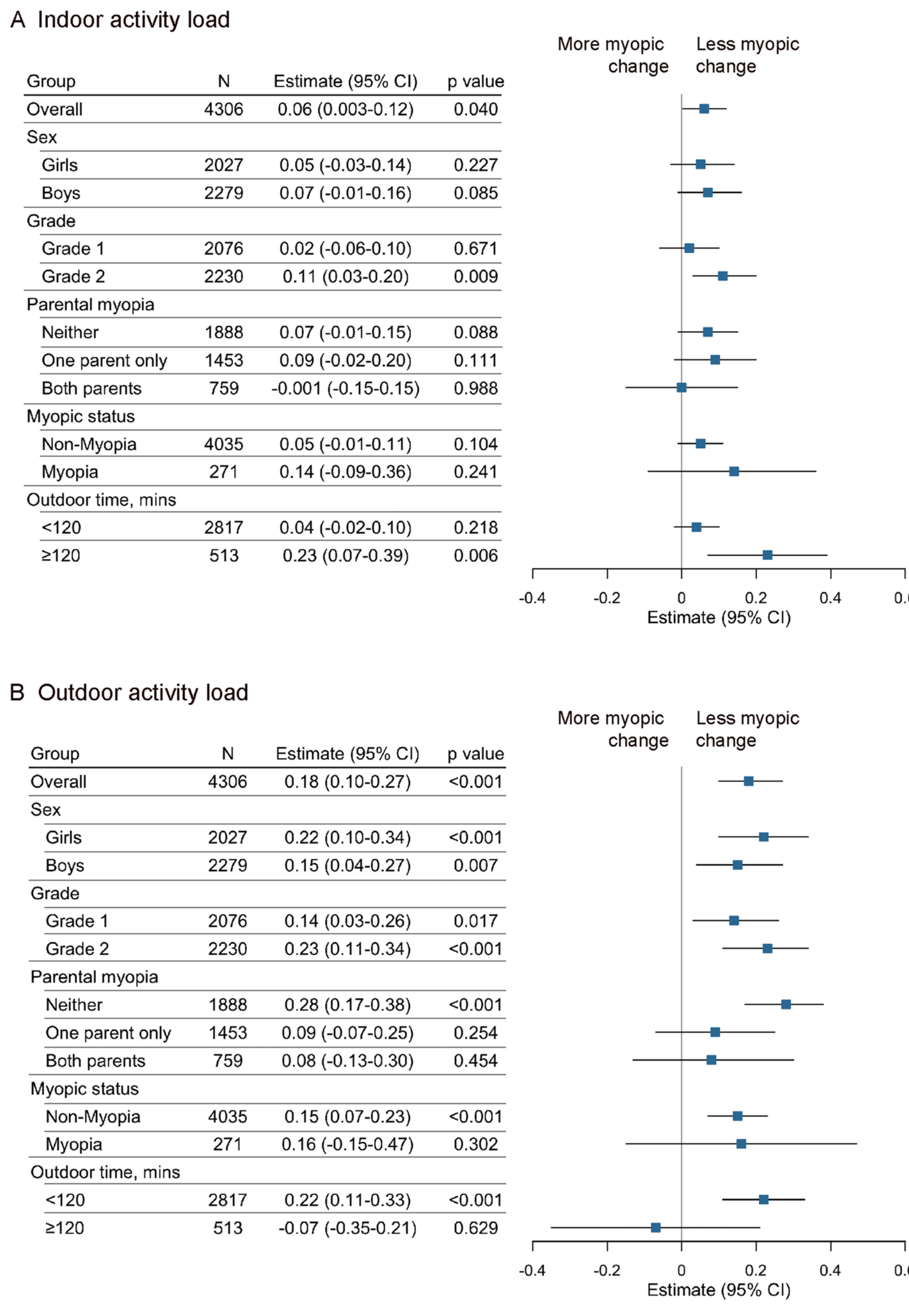

Fig. 4 Subgroup analyses of associations between activity loads and 2-year myopic shift. Forest plots showing the associations between (**A**) indoor and (**B**) outdoor activity loads with myopic shift across different subgroups. Points represent beta coefficients, and horizontal lines represent 95% confidence intervals (CI). Positive estimates indicate less myopic shift (protective effect). All analyses were adjusted for age, sex, parental myopia, BMI, near work time, and grade (except for the corresponding stratification variable in each subgroup), with outdoor analyses additionally adjusted for light intensity. The activity load was defined as (1 × light activity time) + (2 × moderate activity time) + (3 × vigorous activity time)

both indoor (β = 0.06; 95% CI, 0.003–0.12) and outdoor (β = 0.18; 95% CI, 0.10–0.27) settings. This finding suggests that the relationship between PA and myopia might be better understood through a more comprehensive assessment of activity patterns rather than examining time or intensity in isolation.

The contrasting findings between activity load and individual PA parameters provide insights into the complex relationship between PA and myopic shift. While individual measures showed no consistent associations, the composite activity load measure revealed significant protective effects, suggesting that the biological impact of

PA might be cumulative in nature. The protective effect of PA on myopia development likely requires reaching certain physiological thresholds and maintaining them over time. The activity load measure, by integrating both time and intensity of activities (1× for light, 2× for moderate, and 3× for vigorous activities time), may better reflect these cumulative physiological responses, such as sustained changes in choroidal blood flow, metabolic rates, and systemic circulation.

Our study revealed distinct differences in the protective effects of activity load between indoor and outdoor environments. Outdoor activity load demonstrated a stronger protective effect (β = 0.18; 95% CI, 0.10–0.27) compared to indoor environments (β = 0.06; 95% CI, 0.003–0.12), suggesting a potential synergistic effect between PA and outdoor exposure. Furthermore, this protective effect persisted after controlling for light intensity, indicating the existence of protective mechanisms beyond the known effects of light exposure.

Interestingly, our subgroup analysis based on daily outdoor time revealed distinct patterns in the effects of indoor and outdoor activity loads on myopic shift. Among children with limited outdoor exposure (< 120 min/day), outdoor activity load exhibited a significant protective effect against myopic shift (β = 0.22; 95% CI, 0.11–0.33; $p < 0.001$), whereas indoor activity load showed no significant effect in this group. Conversely, among children with sufficient outdoor exposure (≥ 120 min/day), indoor activity load emerged as significantly protective (β = 0.23; 95% CI, 0.07–0.39; $p = 0.006$), while additional outdoor activity load conferred no further benefit. These findings suggest a potential compensatory mechanism in myopia prevention, where the protective effects of indoor and outdoor activities vary depending on outdoor exposure thresholds. For children who do not meet the recommended outdoor time, maximizing outdoor activity intensity appears crucial for myopia protection. However, once sufficient outdoor time is achieved, indoor activity load becomes the key protective factor against myopia progression. This pattern highlights the importance of tailored myopia prevention strategies that consider both environmental contexts. Specifically, for children with insufficient outdoor exposure, increasing outdoor activity intensity may be a priority intervention, while for those already meeting recommended outdoor time, encouraging higher indoor activity loads may provide additional protection against myopia progression.

The protective effect of PA on myopia might be explained through multiple biological and molecular mechanisms. First, PA improves cardiovascular circulation, thereby increasing ocular blood perfusion [43]. Additionally, it may regulate axial elongation by stimulating the production of nitric oxide (NO), a key vasodilator that modulates choroidal blood flow [44]. Secondly, PA promotes the release of dopamine in the retina [45, 46], which has been demonstrated to inhibit axial elongation and play a protective role against myopia progression [47]. Thirdly, PA may exert a protective effect on myopia by influencing systemic metabolism, enhancing insulin sensitivity [48], and regulating insulin-like growth factor-1 (IGF-1) levels [49], thereby potentially modulating choroidal thickness [50]. Lastly, PA may provide intermittent relief for the accommodative system by interrupting prolonged near work, thereby reducing visual stress and mitigating potential risk factors for myopia development [51].

Our findings suggest that protective activity load thresholds of ≥ 1.47 weighted hours/day for outdoor and ≥ 3.02 weighted hours/day for indoor environments may contribute to myopia prevention. To help children meet these thresholds, school-based interventions could integrate structured outdoor activities (e.g., 90 min of light activity, 60 min of light plus 15 min of moderate activity, or 45 min of light plus 15 min of moderate and 10 min of vigorous activity) through physical education, recess, and after-school programs. In regions where outdoor activity is limited due to weather, pollution, or urban constraints, structured indoor activities (e.g., 180 min of light activity, 120 min of light plus 30 min of moderate activity, or 100 min of light plus 25 min of moderate and 15 min of vigorous activity) could serve as an alternative, implemented via indoor recess, classroom activity breaks, and structured before/after-school programs. Furthermore, wearable technology could facilitate real-time activity tracking, personalized feedback, gamification strategies, and activity alerts, enabling children, parents, and educators to effectively monitor and manage activity levels. These strategies provide practical and scalable approaches to integrating physical activity into myopia prevention programs, ensuring that both the quantity and quality of movement are optimized for protective benefits.

This study has several limitations that should be considered. Firstly, although our data were derived from an intervention trial, which might affect the generalizability of the findings, the device-based quantification of PA still provides valuable insights into the relationship between exposure and outcome. Additionally, our sample consisted predominantly of young children aged 6–9 years, and therefore the findings may not be generalizable to older age groups or populations with different activity patterns.

Secondly, while the use of smartwatches provided device-based measurements, certain physical activities may not have been fully captured due to device limitations. Wrist-worn devices tend to underestimate activities that involve minimal wrist movement despite high energy expenditure (e.g., cycling, swimming). The relatively low levels of moderate and vigorous physical activity observed in our study (9 and 3 min per day for indoor activities, and 12 and 2 min for outdoor activities) may partially reflect this limitation. However, these findings align with broader national data, which indicate that less than a quarter (22%) of Chinese school students engage in at least 60 min of daily physical activity, with a general downward trend over time [52].

Thirdly, as demonstrated in our analysis of smartwatch compliance, wearing rates were highest during school hours but declined in the evenings, suggesting that children may have removed their devices during after-school recreational activities or sports participation. These limitations should be addressed in future studies with more diverse populations and comprehensive activity monitoring approaches that could incorporate multiple sensor types or complementary assessment methods to capture a wider range of physical activities.

Conclusions

In conclusion, this 2-year prospective study using device-based measurements revealed that activity load, a composite measure integrating both time and intensity of PA, showed significant protective associations with myopic shift in both indoor and outdoor environments. Our findings provide new evidence for the relationship between PA and myopia, suggesting that both time and intensity of PA should be considered in myopia prevention strategies.

Abbreviations

AL	Axial length
BMI	Body mass index
CI	Confidence interval
D	Diopter
GPS	Global positioning system
MET	Metabolic equivalent
PA	Physical activity
SE	Spherical equivalent
SPM	Steps per minute
STORM	Shanghai Time Outside to Reduce Myopia

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12916-025-04136-5.

Additional file 1: STROBE Checklist. Completed STROBE checklist for cohort studies, outlining the reporting compliance of the current manuscript

Additional file 2: Table S1. Table S1 – Associations of Physical Activity Time and Intensity with 2-Year Myopic Shift and Axial Length Progression. Includes regression coefficients, standard errors, confidence intervals, and *p*-values stratified by indoor/outdoor activity and intensity.

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Authors' contributions

DC, JW, JC, PS, and XX conceived and designed the study. All authors contributed to the acquisition, analysis, or interpretation of data. DC drafted the manuscript. DC, ML, ZZ2, PS, LD, JY, and XX critically reviewed the manuscript for important intellectual content. XH, ML, DC, JW, JC, YD, ZZ1, BZ, LD, and JY conducted statistical analyses. XH and XX obtained funding. JW, LD, and XX provided administrative, technical, or material support. XH, LD, JY, and XX supervised the study. All authors read and approved the final manuscript.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This trial was conducted in accordance with the Helsinki Declaration for experimentation on humans and was approved by the Ethics Committee of Shanghai General Hospital (No. 2016KY138). All participating children and their parents at the school were provided with detailed information on the trial and informed consent was provided by the legal guardians of all the students. The trial is registered with ClinicalTrials.gov, identifier: NCT02980445.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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