

Sex-Specific Associations Between Pubertal Stage and Objectively Measured Physical Activity in Early Adolescence: Evidence from the ABCD Study

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Article

Keywords: sex differences, pubertal stage, physical activity, sedentary time, adolescence

Posted Date: October 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10879656/v1>

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Additional Declarations: No competing interests reported.

Abstract

Physical activity declines during adolescence, but sex-specific patterns across pubertal stages remain incompletely understood. We analysed 21-day Fitbit data from 4,794 adolescents (47.8% female; median age, 12 years) in the Adolescent Brain Cognitive Development Study. Daily moderate-to-vigorous physical activity (MVPA), sedentary time and step count were examined across Pubertal Development Scale stages using sex-stratified multivariable linear regression. Females accumulated fewer steps (mean, 8,754 versus 10,431 steps/day) and less MVPA (22.4 versus 48.6 min/day) than males (both $p < 0.001$), whereas sedentary time did not differ by sex. With advancing puberty, sedentary time increased and step counts declined in both sexes. After covariate adjustment, sedentary time was higher from early puberty onward in males and from mid-puberty onward in females, whereas significant step-count reductions emerged at mid-puberty in males and at late puberty in females. MVPA was not associated with pubertal stage after adjustment. Mean MVPA remained below 60 min/day in every sex-stage group. These findings identify mid-to-late puberty as a potential window for sex-sensitive strategies to reduce sedentary time and preserve daily movement.

Introduction

Physical inactivity is one of the major modifiable contributors to obesity and type 2 diabetes in adolescent populations [1, 2], and its consequences extend well beyond metabolic health. Many behavioral risk factors developed during this time are associated with later morbidity and mortality, including tobacco use and unhealthy dietary patterns. The World Health Organization's Global Action Plan on Physical Activity 2018–2030 underscored the urgency of addressing adolescent physical inactivity, reporting that 81% of adolescents aged 11–17 years worldwide do not meet recommended physical activity levels [3].

Current guidelines recommend that children and adolescents aged 6–17 years accumulate at least 60 minutes of moderate-to-vigorous physical activity (MVPA) daily, conferring substantial benefits for bone health, cardiorespiratory fitness, weight management, and mental well-being [4, 5]. Yet physical activity levels decline progressively from childhood through adolescence globally [6], a trajectory that may establish long-term sedentary patterns and increase non-communicable diseases (NCD) [7]. Understanding the potential determinants of this decline, including socioeconomic status, neighborhood safety, urbanicity, and school-based opportunities, is therefore essential for developing targeted interventions.

One underexamined determinant is pubertal development, a pivotal biological transition characterized by substantial hormonal changes and the emergence of secondary sexual characteristics, with considerable inter-individual variability in both timing and tempo [8]. Early-maturing adolescents may experience asynchrony between accelerated physical development and relatively immature cognitive-emotional capacities, potentially influencing physical activity engagement through altered peer dynamics and shifting social expectations [9, 10]. Although pubertal timing has been linked to childhood obesity, socioeconomic factors, academic performance, and various health behaviors [11, 12], its interaction with physical activity patterns across different intensity levels remains insufficiently characterized.

Sex differences in adolescent physical activity are well-documented, with girls consistently exhibiting lower activity levels than boys across multiple countries and contexts [3, 13]. In 2016, insufficient physical activity prevalence among girls reached 90% or higher in 27 countries, compared with only two countries for boys [3]. While boys consistently demonstrate higher MVPA, sex differences in sedentary behavior and light-intensity activity are

comparatively minimal [13]. Girls in early puberty also show higher rates of physical activity discontinuation than boys [8], suggesting that sex-specific divergences may emerge precisely during the pubertal transition, when adolescents make consequential decisions about sustained activity engagement. The biological and psychosocial mechanisms underlying these disparities, however, remain incompletely understood.

Previous research has relied predominantly on self-reported physical activity, which is vulnerable to recall bias and social desirability effects [14]. Wearable devices such as accelerometers and fitness trackers now enable continuous, objective monitoring of physical activity and sedentary time, providing minute-by-minute data that allow precise quantification across intensity categories [14, 15]. Leveraging this data availability advance, the present study investigates sex-specific associations between pubertal stage, physical activity, and sedentary time using Fitbit data from the ABCD Study, with the aim of informing sex-sensitive strategies for promoting sustained physical activity during adolescence.

Results

Sample characteristics

Among the 4,794 participants included in the analysis (Tables 1a and 1b), the median age was 144 months (SD: 7.83), 47.8% were female, and 71% identified as non-Hispanic White. Parental education, marital status, family income, and residential area were evenly distributed by sex, while significant sex differences were observed in race/ethnicity, age, and neighborhood safety. Pubertal stage distributions also differed by sex, with female adolescents demonstrating more advanced sexual maturation (e.g., Mid-pubertal, Female vs. Male: 49.76 vs. 19.91).

Table 1

a. Adolescent demographic, pubertal, health and physical activity characteristics by sex, ABCD Study (N = 4,794).

Variables	Overall N = 4794	Male N = 2501	Female N = 2293	P value
BASELINE	N (%)	N (%)	N (%)	
Race/ethnicity				0.002
Non-Hispanic White	3412 (71.17)	1815 (72.57)	1597 (69.65)	
Non-Hispanic Black	414 (8.64)	178 (7.12)	236 (10.29)	
Non-Hispanic Asian	109 (2.27)	54 (2.16)	55 (2.40)	
Other	44 (0.92)	20 (0.80)	24 (1.05)	
Hispanic	815 (17.00)	434 (17.35)	381 (16.61)	
YEAR 2				
Age, month (median, Q1-Q3) (range: 136–150)	144 (137, 150)	144 (137,150)	143 (136, 150)	0.006
Puberty stage				< 0.001
Prepubertal	1095 (22.84)	978 (39.10)	117 (5.10)	
Early Pubertal	1159 (24.18)	919 (36.75)	240 (10.47)	
Mid-pubertal	1639 (34.19)	498 (19.91)	1141 (49.76)	
Late pubertal	901 (18.79)	106 (4.24)	795 (34.67)	
Physical activity				
MVPA (Mean, SD)	35.90 (30.51)	48.58 (33.63)	22.35 (19.03)	< 0.001
MVPA (median, Q1-Q3) (range: 0-218.75)	27.64 (13.47, 49.95)	41.56 (23.47, 66.68)	17.58 (8.71, 30.54)	< 0.001
Sedentary time (Mean, SD)	660.62 (139.91)	663.79 (140.33)	657.19 (139.41)	0.084
Sedentary time (median, Q1-Q3) (range: 63.20–1440.00)	637.85 (573.17, 718.32)	641.77 (576.14, 726.00)	633.11 (569.93, 710.41)	0.080
Daily steps (Mean, SD)	9619.93 (3167.82)	10431.44 (3403.55)	8754.12 (2632.08)	< 0.001
Daily steps (median, Q1-Q3) (range: 1205.00-28988.83)	9333.01 (7404.01, 11471.48)	10117.74 (10117.74, 12581.65)	8666.86 (6927.81, 10444.18)	< 0.001
Body Mass Index (BMI; median, Q1-Q3)	19.0 (17.0, 22.3)	18.8 (16.9, 22.1)	19.3 (17.1, 22.5)	0.003

Note. Values are n (%) unless otherwise indicated. Continuous variables were compared using Wilcoxon rank-sum tests and categorical variables using Pearson chi-squared tests. BMI, body mass index; MVPA, moderate-to-vigorous physical activity; Q1, first quartile; Q3, third quartile; SD, standard deviation.

Variables	Overall N = 4794	Male N = 2501	Female N = 2293	P value
(range: 16.90-22.52)				
Routine healthcare visit, past year -No	2,618 (54.61)	1,349 (53.94)	1,269 (55.34)	0.300
Routine healthcare visit, before past year -No	3,674 (76.64)	1,937 (77.45)	1,737 (75.75)	0.200
Asthma -Yes	773 (16.12)	456 (18.23)	317 (13.82)	< 0.001
Allergies -Yes	1,501 (31.31)	831 (33.23)	670 (29.22)	0.003
Medical operation -Yes	897 (18.71)	519 (20.75)	378 (16.48)	< 0.001
Note. Values are n (%) unless otherwise indicated. Continuous variables were compared using Wilcoxon rank-sum tests and categorical variables using Pearson chi-squared tests. BMI, body mass index; MVPA, moderate-to-vigorous physical activity; Q1, first quartile; Q3, third quartile; SD, standard deviation.				

Table 1
b. Parent, household and neighborhood characteristics by sex, ABCD Study (N = 4,794).

Variables	Overall N = 4794	Male N = 2501	Female N = 2293	P value
PARENT INFORMATION				
Education				< 0.900
Less than High School	163 (3.40)	81 (3.24)	82 (3.58)	
High School Graduate or GED	340 (7.09)	176 (7.04)	164 (7.15)	
Some College / associate degree	1326 (27.66)	702 (28.07)	624 (27.21)	
Bachelor's Degree	1576 (32.87)	815 (32.59)	761 (33.19)	
Graduate or Professional Degree	1389 (28.97)	727 (29.07)	662 (28.87)	
Marital status				0.200
Married or Living with Partner	3847 (80.25)	2030 (81.17)	1817 (79.24)	
Never Married	317 (6.61)	160 (6.40)	157 (6.85)	
Formerly Married (Widowed/Divorced/Separated)	630 (13.14)	311 (12.43)	319 (13.91)	
Annual income level				0.396
<\$25,000	352 (7.34)	189 (7.56)	163 (7.11)	
\$25,000 – \$49,999	514 (10.72)	249 (9.95)	265 (11.55)	
\$50,000 – \$99,999	1327 (27.68)	681 (27.23)	646 (28.17)	
\$100,000 – \$199,999	1776 (37.05)	948 (37.90)	828 (36.11)	
≥\$200,000	706 (14.73)	370 (14.79)	336 (14.65)	
Refused to answer	119 (2.48)	64 (2.56)	55 (2.40)	
Parental perception of neighborhood safety				0.031
Disagree	268 (5.59)	136 (5.44)	132 (5.75)	
Neutral	532 (11.10)	250 (10.00)	282 (12.30)	
Agree	3994 (83.31)	2115 (84.57)	1879 (81.95)	
Residential area				0.987
Urbanized Area	4165 (86.88)	2175 (86.96)	1990 (86.78)	
Urban Clusters	175 (3.60)	88 (3.52)	87 (3.79)	
Rural	454 (9.47)	238 (9.52)	216 (9.42)	
Note. Values are n (%). Categorical variables were compared using Pearson chi-squared tests.				

Sex differences were also apparent in health and physical activity indicators. Female participants had a significantly higher BMI than male participants (Median: 19.3 vs. 18.8, $p = 0.003$). Male participants were more

likely to report medical conditions than female participants; for example, asthma prevalence was 18% among males and 14% among females ($p < 0.001$). With respect to physical activity, females exhibited significantly lower daily step counts (Mean: 8754.12 vs. 10431.44 steps/day, $p < 0.001$) and strikingly less MVPA (Mean: 22.35 vs. 48.58 min/day, $p < 0.001$) than males. Daily sedentary time did not differ significantly between sexes (Mean: 657.19 vs. 663.79 min/day, $p = 0.084$).

Physical activity and sedentary behavior by sex and pubertal stage

Table 2 describes physical activity patterns across pubertal stages by sex. In both sexes, sedentary time increased and step counts decreased progressively with advancing puberty ($p < 0.001$). Sedentary time rose from the pre-pubertal to late puberty in males (635.41 ± 128.22 min/day to 706.11 ± 128.03 min/day) and females (599.05 ± 135.90 min/day to 695.12 ± 138.51 min/day). Correspondingly, daily steps declined from $10,844.92 \pm 3,414.21$ to $9,398.30 \pm 3,111.52$ steps/day in males and from $9,761.69 \pm 2,801.64$ to $8,046.85 \pm 2,632.44$ steps/day in females.

Table 2
Fitbit-measured physical activity by pubertal stage and sex among adolescents in the ABCD Study.

Variables	Moderate-to-vigorous physical activity (minute/day)	Sedentary (minute/day)	Total steps (steps/day)
Male	Mean (SD)	Mean (SD)	Mean (SD)
Prepubertal (N = 978)	47.85 (33.13)	635.41 (128.22)	10844.92 (3414.21)
Early Pubertal (N = 919)	49.23 (33.05)	663.98 (140.86)	10502.26 (3324.53)
Mid-pubertal (N = 498)	50.43 (35.48)	697.30 (143.19)	9724.19 (3205.32)
Late pubertal (N = 106)	44.75 (32.36)	706.11 (128.03)	9398.30 (3111.52)
ANOVA P value within males	0.303	< 0.001	< 0.001
Female			
Prepubertal (N = 117)	20.19 (17.83)	599.05 (135.90)	9761.69 (2801.64)
Early Pubertal (N = 240)	19.62 (17.80)	618.03 (129.90)	9292.70 (2764.08)
Mid-pubertal (N = 1,141)	22.12 (18.50)	642.70 (139.51)	9062.89 (2483.20)
Late pubertal (N = 795)	24.19 (20.78)	695.12 (138.51)	8046.85 (2632.44)
ANOVA P value within females	0.004	< 0.001	< 0.001
ANOVA P value by sex	< 0.001	< 0.001	< 0.001
ANOVA P value by pubertal stage	0.280	< 0.001	< 0.001
Sex × pubertal stage	0.055	0.067	0.021
Note. Values are mean (SD). ANOVA, analysis of variance; MVPA, moderate-to-vigorous physical activity; SD, standard deviation.			

MVPA showed a more nuanced pattern. It did not differ significantly across pubertal stages in males ($p = 0.303$), but varied significantly in females in unadjusted analyses ($p = 0.004$). Notably, no pubertal stage in either sex achieved the WHO-recommended 60 minutes of daily MVPA.

Multivariable regression analyses

Tables 3a–3c present results from multivariable linear regression models examining associations between pubertal stage and each physical activity outcome, after adjusting for age, BMI, medical history, and sociodemographic factors. We also showed the results for the three outcomes: MVPA, sedentary time, and daily step count.

Table 3

a. Bivariate and multivariable linear regression models of moderate-to-vigorous physical activity in relation to pubertal stage and sex.

Variables	Bivariate model	Bivariate model	Adjusted overall	Adjusted overall	Adjusted male	Adjusted male	Adjusted female	Adjusted female
Pubertal stage	Beta (SE)	p values	Beta (SE)	p values	Beta (SE)	p values	Beta (SE)	p values
Prepubertal	REF		REF		REF		REF	
Early Pubertal	-1.367 (1.188)	0.272	0.300 (1.124)	0.789	0.415 (1.478)	0.780	-1.929 (2.106)	0.356
Mid-pubertal	-13.720 (1.103)	< 0.001	0.263 (1.205)	0.827	0.219 (1.804)	0.904	-0.283 (1.833)	0.877
Late pubertal	-17.811 (1.256)	< 0.001	-1.666 (1.474)	0.260	-6.223 (3.290)	0.059	0.256 (1.921)	0.893
Note. Multivariable models were adjusted for age, BMI, race/ethnicity, medical history, parental education, marital status and income, residential area and neighborhood safety. REF, reference category; SE, standard error.								

Table 3

b. Bivariate and multivariable linear regression models of sedentary time in relation to pubertal stage and sex.

Variables	Bivariate model	Bivariate model	Adjusted overall	Adjusted overall	Adjusted male	Adjusted male	Adjusted female	Adjusted female
Pubertal stage	Beta (SE)	p values	Beta (SE)	p values	Beta (SE)	p values	Beta (SE)	p values
Prepubertal	REF		REF		REF		REF	
Early Pubertal	20.145 (5.598)	< 0.001	18.584 (5.664)	0.001	20.214 (6.173)	0.001	11.793 (15.123)	0.437
Mid-pubertal	22.223 (5.181)	< 0.001	36.426 (6.071)	< 0.001	44.730 (7.534)	< 0.001	27.494 (13.165)	0.038
Late pubertal	56.223 (5.901)	< 0.001	69.880 (7.426)	< 0.001	53.034 (13.742)	< 0.001	66.896 (13.802)	< 0.001
Note. Multivariable models were adjusted for age, BMI, race/ethnicity, medical history, parental education, marital status and income, residential area and neighborhood safety. REF, reference category; SE, standard error.								

Table 3

b. Bivariate and multivariable linear regression models of sedentary time in relation to pubertal stage and sex.

Variables	Bivariate model	Bivariate model	Adjusted overall	Adjusted overall	Adjusted male	Adjusted male	Adjusted female	Adjusted female
Pubertal stage	Beta (SE)	p values	Beta (SE)	p values	Beta (SE)	p values	Beta (SE)	p values
Prepubertal	REF		REF		REF		REF	
Early Pubertal	20.145 (5.598)	< 0.001	18.584 (5.664)	0.001	20.214 (6.173)	0.001	11.793 (15.123)	0.437
Mid-pubertal	22.223 (5.181)	< 0.001	36.426 (6.071)	< 0.001	44.730 (7.534)	< 0.001	27.494 (13.165)	0.038
Late pubertal	56.223 (5.901)	< 0.001	69.880 (7.426)	< 0.001	53.034 (13.742)	< 0.001	66.896 (13.802)	< 0.001
Note. Multivariable models were adjusted for age, BMI, race/ethnicity, medical history, parental education, marital status and income, residential area and neighborhood safety. REF, reference category; SE, standard error.								

After covariate adjustment, MVPA did not differ significantly across pubertal stages in either males or females, indicating that the unadjusted female pattern observed in Section 3.2 was attenuated by the covariates included in the model. Sedentary time, by contrast, showed robust and consistent associations with pubertal stage. Compared with pre-pubertal adolescents, the overall model indicated significantly higher sedentary minutes at early ($\beta = 18.85$, $p = 0.001$), mid- ($\beta = 36.43$, $p = 0.001$), and late pubertal stages ($\beta = 69.88$, $p = 0.001$), reflecting a stepwise increase across development. In sex-stratified analyses, this pattern held consistently across all pubertal stages in males (e.g. late pubertal vs. prepubertal, $\beta = 53.03$, $p \leq 0.001$), while in females, statistically significant increases were observed only at mid- and late pubertal stages (e.g., mid-pubertal vs. prepubertal, $\beta = 27.49$, $p \leq 0.038$). The progressive increase in predicted mean sedentary minutes is illustrated in Fig. 1b.

A similar pattern was observed for daily step counts, which declined steadily with advancing pubertal stage. In the overall model, adolescents at mid- ($\beta = -656.3$, $p < 0.001$) and late pubertal stages ($\beta = -1,350.0$, $p < 0.001$) accumulated significantly fewer daily steps than pre-pubertal peers. Sex-stratified analyses revealed that among males, both mid- and late pubertal stages were associated with significant step count reductions (e.g., mid-pubertal vs. prepubertal, $\beta = -823.9$, $p \leq 0.001$), while among females, a significant decline was observed only at the late pubertal stage ($\beta = -1347.3$, $p < 0.001$). These declining trends are illustrated in Fig. 1c.

Discussion

In our cross-sectional study on pubertal stage and physical activity in a large, diverse sample of U.S. adolescents, two major findings emerged. First, both sexes demonstrated higher sedentary time and lower daily step counts at more advanced pubertal stages, whereas MVPA was not significantly associated with pubertal stage after covariate adjustment. Second, the stage-associated patterns differed by sex: among males, higher sedentary time and lower daily steps were observed beginning in mid-puberty, whereas these decreases were most evident in late puberty among females. The study showed that neither sex achieved the recommended 60 minutes of daily MVPA at any pubertal stage. The findings point to puberty as a critical and sex-differentiated factor for physical activity promotion, with sedentary time and overall movement volume emerging as particularly salient behavioral targets.

These findings align with previous research documenting progressive declines in physical activity (e.g., daily steps) and increases in sedentary behavior across pubertal stages [16, 17, 18]. For instance, a longitudinal study from the EarlyBird cohort showed that the adolescent decline in physical activity reflected reductions in overall movement, including light-intensity activity, rather than MVPA alone [19]. Several biological, psychosocial, and behavioral mechanisms may contribute to these associations. Endocrine changes regulating sexual maturation may reduce physical performance capacity and motivation for activity [20]. Evidence from the ALSPAC cohort showed that advanced maturation in boys was associated with lower overall accelerometer counts, lower light physical activity, and greater sedentary time, though associations with MVPA were less consistent [21]. Concurrent neurobiological changes in reward and dopaminergic systems may reduce exercise's reinforcement value [22], while psychosocially, advancing maturation is associated with withdrawal from active play toward screen-based activities [23]. However, the directionality of these associations remains uncertain. Physical activity and sedentary behavior may themselves influence pubertal timing through adiposity, insulin sensitivity, and adrenal androgen pathways, as suggested by the PANIC Study, which found that changes in physical activity, sedentary time, and metabolic factors may affect adrenal androgen development and pubertal progression [24]. These findings should therefore be interpreted as associations rather than evidence of causal directionality in either direction.

While the overall direction of change in physical activity was consistent across sexes, the timing of significant transitions differed in important ways. In males, increases in sedentary time and declines in step counts emerged progressively from mid-puberty onward. In females, comparable changes reached statistical significance only during late puberty, even after adjusting for age, BMI, and socioeconomic factors. These findings suggest that the relationship between pubertal maturation and physical activity behavior is sex-differentiated in its timing, with meaningful implications for when interventions should be introduced for each sex. Besides pubertal stage, pubertal timing may offer a complementary interpretive lens. Pubertal time refers to whether an individual matures earlier or later relative to peers. Early-maturing girls face elevated risk of sedentary behavior [25], potentially through social and psychological pathways including earlier adoption of adult-like sedentary activities and avoidance of behaviors perceived as age-inappropriate. Early maturation in girls has also been associated with poorer mental health outcomes, as lower self-esteem, body dissatisfaction, and higher depressive symptoms [17], each of which may independently reduce motivation for physical activity.

Interpreting these patterns requires distinguishing between two related but distinct constructs: pubertal stage, the exposure variable in the present study, and pubertal timing, which refers to whether an individual matures earlier or later relative to peers. While the present findings speak specifically to stage-based patterns, evidence on pubertal timing offers a complementary interpretive lens. More broadly, sex-specific patterns likely reflect differences in body composition, physical self-perception, peer norms, perceived competence, and access to preferred forms of physical activity during puberty [26, 27, 28]. Future studies would benefit from examining pubertal stage and timing simultaneously to disentangle their underlying interactions.

A particularly striking finding was that adolescents of both sexes failed to meet the WHO-recommended 60 minutes of daily MVPA at every pubertal stage examined, with females engaging in substantially less MVPA than males throughout. This aligns with global surveillance data showing that most adolescents worldwide have insufficient activity [3] and prior research documenting lower MVPA in girls relative to boys [20, 22].

However, the association between pubertal stage and MVPA in females was attenuated to non-significance after covariate adjustment, and no stage association was observed in males. These results indicate that the included covariates explained the greatest impact of pubertal stage on MVPA, and pubertal stage is not an independent

factor for MVPA. Given that sedentary time and daily steps showed more consistent and robust associations with pubertal stage than MVPA, reducing sedentary time and preserving overall daily movement may be equally important intervention targets during adolescence. Daily steps and sedentary minutes are practical and interpretable metrics for families, schools, clinicians, and community programs, as they reflect habitual movement across the full day rather than a single intensity threshold.

Several limitations should be considered when interpreting these findings. First, the cross-sectional design precludes causal inference; the observed associations between pubertal stage and physical activity outcomes may reflect unmeasured confounding, and longitudinal studies are needed to establish temporal relationships. It should also be noted that although all multivariable models adjusted for age, chronological age, pubertal maturation, and residual confounding by age-related developmental factors cannot be fully excluded. Second, physical activity was characterized solely in terms of duration and intensity, without capturing qualitative dimensions such as activity type or context, distinctions that may differentially influence motivation and participation across pubertal stages. Third, while the present study distinguishes conceptually between pubertal stage and pubertal timing, it did not formally investigate timing as a potential moderator; future work should consider both constructs simultaneously to clarify their independent and interactive contributions. Fourth, although several sociodemographic, family, and contextual factors were adjusted for, residual confounding from unmeasured variables, including school policies, community resources, peer norms, screen-based behaviors, sleep, and mental health symptoms, may remain. Finally, as the sample was drawn from a developed country context, findings may not generalize to adolescents in lower-resource or culturally diverse settings where structural barriers, social norms, and opportunities for physical activity differ substantially.

These findings carry clear implications for the design of physical activity interventions. Most fundamentally, the sex- and stage-specific patterns identified here demonstrate that uniform approaches are insufficient; effective promotion strategies must be tailored to the developmental stages. For males, the mid-pubertal period emerges as the primary intervention window, when sedentary behavior and declines in step counts first became apparent. For females, the critical window appears to be late puberty, when the most pronounced behavioral changes occur. Importantly, intervention targets should extend beyond MVPA to encompass sedentary time reduction and the preservation of overall daily movement, given that these outcomes showed stronger and more consistent associations with pubertal stage in the present study. In both sex groups, interventions should address biological factors, such as body image concerns and physical discomfort associated with pubertal changes, as well as psychosocial factors, including peer influences, shifting social norms around physical activity, and the growing appeal of sedentary alternatives. School-based programs, community initiatives, and healthcare providers are well-positioned to incorporate pubertal stage as a routine consideration when designing and delivering physical activity promotion strategies.

This large-scale study using objective physical activity measurement demonstrates that both males and females experience progressive increases in sedentary behavior and declines in step counts across mid- and late puberty, with neither sex achieving WHO-recommended MVPA levels at any pubertal stage. Critically, the timing and magnitude of these changes differ by sex across pubertal stages. These sex- and stage-specific patterns highlight the insufficiency of uniform approaches to physical activity promotion and point to distinct intervention windows for each sex group. Future research should employ longitudinal designs to establish temporal relationships, formally examine the independent and interactive contributions of pubertal stage and pubertal timing, and identify modifiable factors to inform the development of interventions across various developmental windows.

Methods

Sample and data

Data were from the ABCD Study, a prospective, longitudinal consortium study that enrolled 11,868 children aged 9–10 years between 2016–2022 across 22 U.S. sites [29]. Schools within a 50-mile radius of each data collection site were identified and randomly selected, with recruitment procedures designed to approximate the demographic distribution of the American Community Survey [29]. Surveys were available in English and Spanish. Eligibility criteria were largely inclusive; participants were excluded only if they had MRI contraindications, a history of major neurological disorders, prematurity at birth < 28 weeks and/or hospitalization at birth > 30 days, uncorrected vision, and known substance abuse problems. Detailed descriptions of the study design, assessments, and objectives have been published in the previous study[29, 30] and data are publicly available through the National Data Archives (NDA).

Ethical oversight was maintained throughout. The ABCD Study obtained written informed consent from parents or legal guardians and assent from participating adolescents, and all protocols were approved by a centralized Institutional Review Board at the University of California San Diego [31]. The current analysis used de-identified data from the baseline and 2-year follow-up assessments and was determined to be exempt from review by the Carilion Clinic–Virginia Tech Institutional Review Board. All methods were performed in accordance with the relevant guidelines and regulations and with the Declaration of Helsinki. The present study involved secondary analysis of de-identified ABCD Study data and did not involve additional recruitment or direct interaction with participants.

For the present analysis, participants were additionally excluded if they met any of the following criteria: (1) absence of valid Fitbit data meeting quality standards over the 21 days of wearing; (2) missing medical history data; (3) inconsistencies between sex assigned at birth and gender identity on sex-specific pubertal questionnaires; (4) missing caregivers' information on education, income, and marital status; and (5) missing information on residential area and neighborhood safety. Outliers were identified as values greater than or less than three standard deviations from the mean and were excluded from analyses. Because the ABCD Study includes siblings, only one child per family was retained to ensure sample independence.

Measures

Demographic variables and covariates

Caregivers provided information on adolescents' race/ethnicity, sex at birth, date of birth, body mass index (BMI), medical history, and basic caregiver demographics (e.g., marital status, income, education). Race/ethnicity variable was categorized as: non-Hispanic White, non-Hispanic Black, non-Hispanic Asian, Hispanic, and Other (e.g., Native American/American Indian, Pacific Islander, multiracial). Five medical history variables were retained after consultation with pediatric psychiatrists: (1) non-routine healthcare visit in the past year (yes/no), (2) lifetime non-routine healthcare visit (yes/no), (3) asthma diagnosis (yes/no), (4) history of allergies (yes/no), and (5) history of surgery (yes/no).

Caregivers' information included education levels, marital status, and income. Education levels were collapsed into five groups for descriptive purposes: below high school (HS; <13 years), HS/Generalized Education Diploma (~ 13

years), Some college (< 2 years post HS), Four-year degree (bachelor's degree post HS), Postgraduate education (> 4 years post-HS). Marital status included four values: married or living with partners, never married/single, formerly married, and other (including, decline to answer, or don't know). Income Neighborhood safety was assessed via a single caregiver-reported item: "I feel safe walking in my neighborhood day or night" with five response options from strongly disagree to strongly agree, recategorized as disagree, neutral, or agree. Caregiver perceptions were used because caregivers typically determine where adolescents may travel and what activities they may pursue.

Pubertal stage

Pubertal development was measured using the 5-item Pubertal Development Scale (PDS) [32], which provides estimates corresponding to Tanner stage [33]. Items were sex-specific: for males (based on self- and caregiver report, assigned male at birth), the scale assessed vocal changes, body hair growth, and facial hair; for females (based on self- and caregiver report, assigned female at birth), items assessed breast development, body hair growth, and menarche. Tanner scores were categorized into five stages: (1) pre-puberty; (2) early puberty; (3) mid puberty; (4) late puberty; (5) post-puberty. Participants in the post-pubertal category were excluded from this study due to the limited sample size (i.e., 56 in total, 1 male and 55 females).

Physical activity

Physical activity was objectively measured using Fitbit devices worn continuously for 21 days at the 2-year follow-up assessment. Fitbit validity and reliability for measuring physical activity in children and adolescents have been established previously [34, 35]. Data were processed following standardized protocols for consumer-grade wearables [36, 37]. Three outcomes were examined: (1) daily average minutes of MVPA, (2) daily average minutes of sedentary time, and (3) daily average step count. MVPA was defined as activity ≥ 3 metabolic equivalents (METs), consistent with American College of Sports Medicine guidelines [36].

Statistical analysis

Descriptive characteristics were summarized by sex, with independent t-tests for continuous variables and chi-squared test for categorical variables. Next, we examined differences in physical activity outcomes across pubertal stages using one-way analysis of variance (ANOVA), with analyses conducted for the full sample and stratified by sex. Three physical activity outcomes were examined (1) daily average minutes of MVPA, (2) daily average minutes of sedentary time, and (3) daily average steps. To evaluate associations between pubertal stage and physical activity outcomes, we first conducted (unadjusted) bivariate analyses between pubertal stages and daily average minutes of MVPA. We then fitted multivariable linear regression models controlling for age, sex, BMI, race/ethnicity, medical history, parental information (education, marital status, and income), and residential area, and neighborhood safety. To examine whether the association is different across different sex groups, we conducted stratified analysis by males and females. This analytical approach was applied to all study outcomes. Statistical significance was set at $\alpha = 0.05$ (two-tailed). All analyses were performed using R 4.3.0. Results reporting is based on the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) [38].

Use of generative artificial intelligence

OpenAI's ChatGPT was used solely to assist with reference verification, reference-style normalization and manuscript formatting. It was not used to generate or analyse data. The authors retain full responsibility for the manuscript.

Abbreviations

ABCD
Adolescent Brain Cognitive Development
ALSPAC
Avon Longitudinal Study of Parents and Children
ANOVA
analysis of variance
BMI
body mass index
HS
high school
MRI
magnetic resonance imaging
MVPA
moderate-to-vigorous physical activity
NCD
non-communicable disease
NDA
NIMH Data Archive
PANIC
Physical Activity and Nutrition in Children
PDS
Pubertal Development Scale
SD
standard deviation
STROBE
Strengthening the Reporting of Observational Studies in Epidemiology
WHO
World Health Organization.

Declarations

Competing interests

The authors declare no competing interests.

Competing interests

Funding

Author Contribution

M.L., H.X. and J.H. designed the study. B.Y.L. conducted the data analysis. M.L., H.X. and J.H. drafted the manuscript. Q.Q., B.Y.L., M.L., M.S., H.X. and J.H. interpreted the data and critically revised the manuscript. M.L. and H.X. contributed equally. All authors reviewed and approved the final manuscript.

Acknowledgement

Data used in this article were obtained from the Adolescent Brain Cognitive Development (ABCD) Study (<https://abcdstudy.org>), held in the NIMH Data Archive. The ABCD Study is supported by the National Institutes of Health and additional federal partners under award numbers U01DA041048, U01DA050989, U01DA051016, U01DA041022, U01DA051018, U01DA051037, U01DA050987, U01DA041174, U01DA041106, U01DA041117, U01DA041028, U01DA041134, U01DA050988, U01DA051039, U01DA041156, U01DA041025, U01DA041120, U01DA051038, U01DA041148, U01DA041093, U01DA041089, U24DA041123 and U24DA041147. A full list of supporters is available at <https://abcdstudy.org/federal-partners.html>, and participating sites and investigators are listed at https://abcdstudy.org/consortium_members/. ABCD consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in this analysis or manuscript. This article reflects the authors' views and may not reflect those of the NIH or ABCD consortium investigators.

Data Availability

The data supporting the findings of this study are openly available in the ABCD Study Dataset, Data Release 5.1, at <https://nda.nih.gov/abcd>. The ABCD data used in this report came from <https://doi.org/10.15154/8873-zj65>.

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Figures

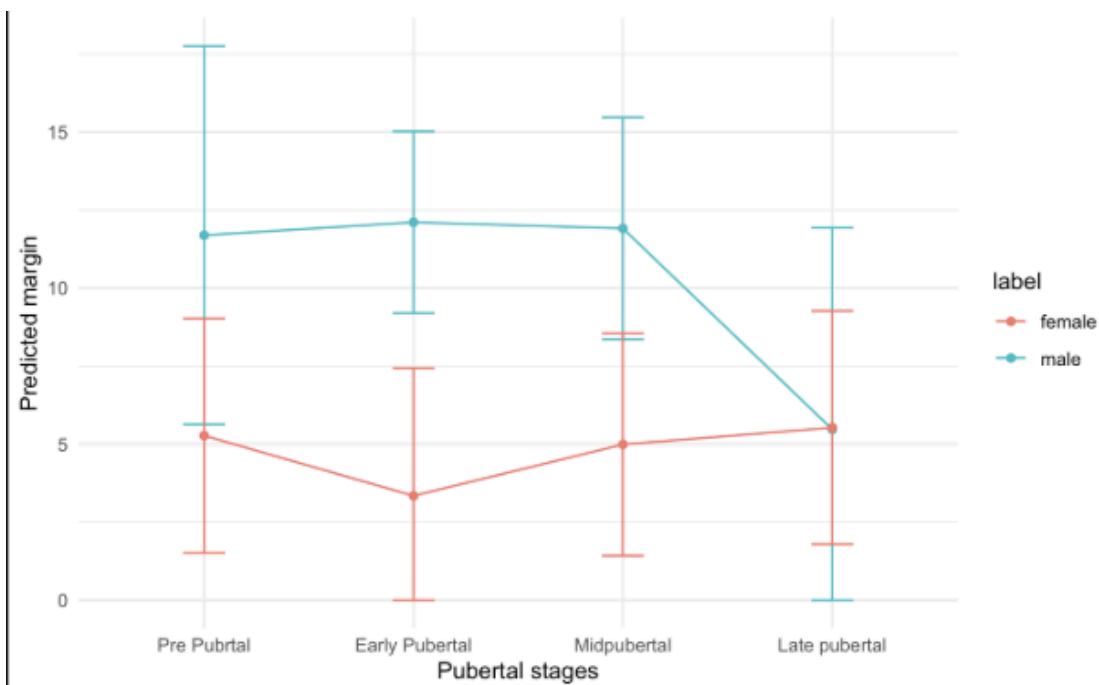


Figure 1

Figure 1a. Predicted average moderate-to-vigorous physical activity minutes per day.

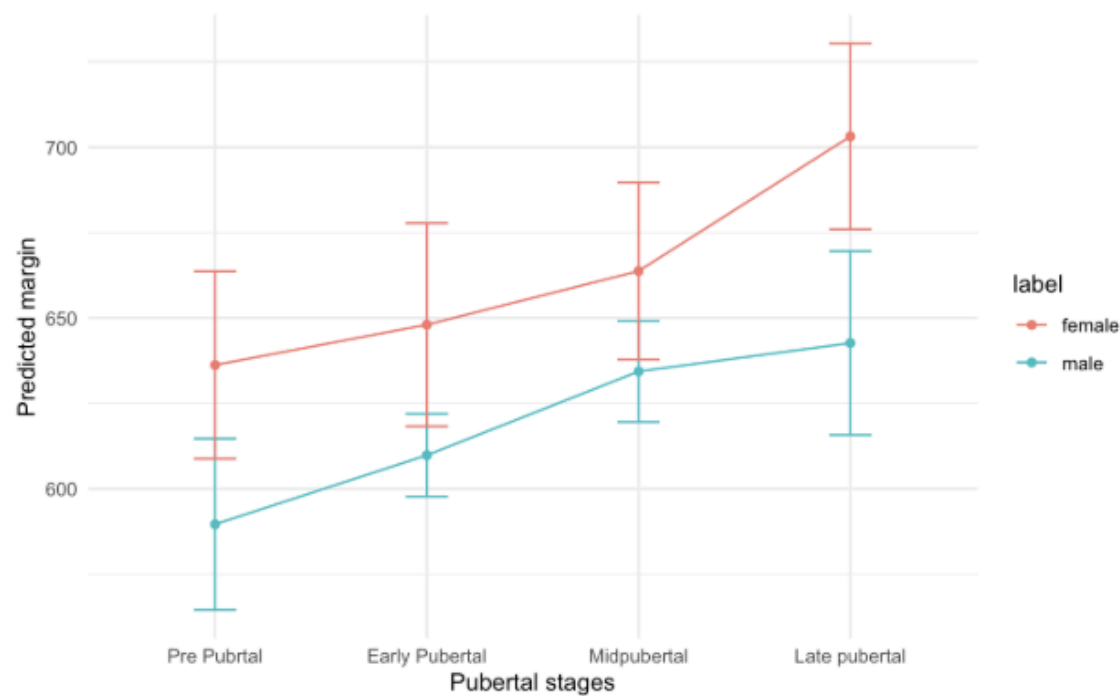


Figure 2

Figure 1b. Predicted average sedentary minutes per day.

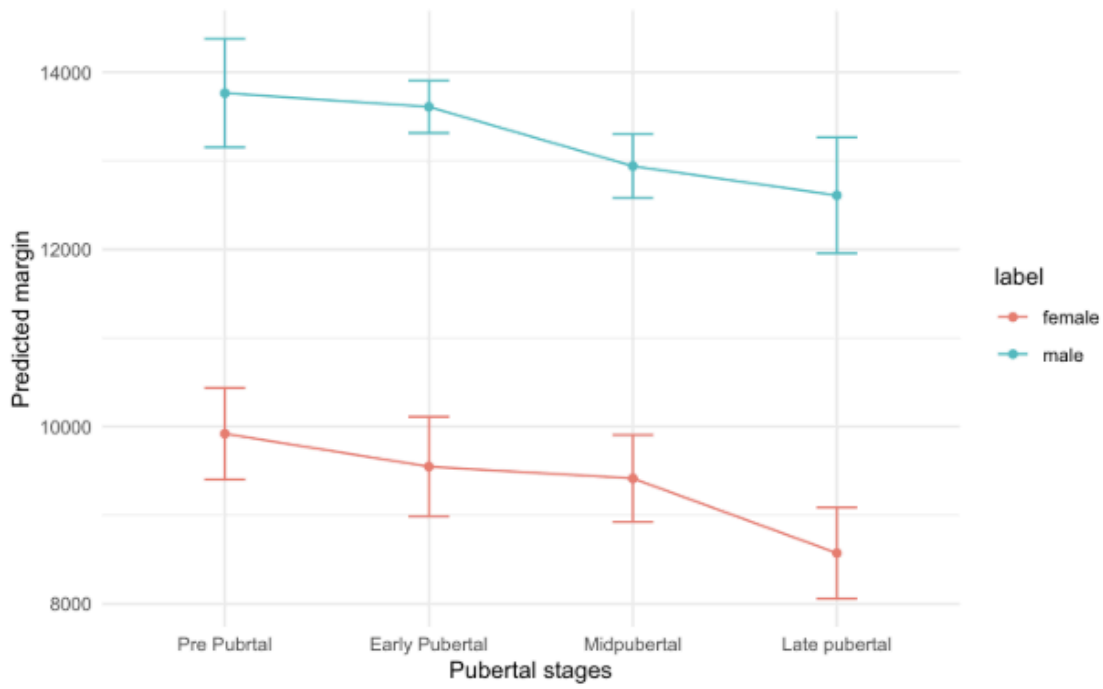


Figure 3

Figure 1c. Predicted average total steps per day.