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Test of the relationship between adolescents' 24-h activity behavior and anxiety symptoms using compositional data analysis

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Abstract

Background Physical activity plays a crucial role in promoting health, notably in mitigating anxiety symptoms. However, limited research has explored how different intensities of physical activity uniquely influence anxiety. This study investigated the dose–response relationship between Chinese adolescents' 24-h activity behavior and anxiety symptoms using compositional data analysis (CoDA).

Methods The temporal distribution of 24-h activity behaviors of 176 adolescents was objectively measured by accelerometers, and anxiety symptoms were assessed by the Self-Rating Anxiety Scale (SAS). Data were analyzed using CoDA and the isotemporal substitution model to statistically modify the intensity and duration of exercise in predicting anxiety.

Results Moderate-to-vigorous physical activity (MVPA), but not light physical activity (LPA), was negatively associated with adolescent anxiety symptoms; SB, SP and anxiety symptoms were positively inter-correlated. Isotemporal substitution analyses indicated that replacing 15 min of other activities with MVPA, or substituting SB with LPA, reduced anxiety symptom levels; conversely, the opposite substitutions increased it. Dose-effect analysis showed that the reallocation between LPA and SB had an equivalent but opposite impact on anxiety symptom levels. Meanwhile, When replacing other activities with MVPA, anxiety levels decreased slowly; when MVPA was replaced by other activities, anxiety levels increased rapidly.

Conclusion MVPA is a key factor in alleviating anxiety symptoms, but it is essential to consider adolescents' 24-h activity behaviors holistically. The primary goal should be to maintain existing levels of MVPA while reasonably promoting the replacement of SB with MVPA, thereby enhancing adolescents' physical and mental health.

Keywords Anxiety symptoms, Youth, 24 h activity, Component analysis, Isochronous substitution

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Introduction

Anxiety disorders are the most common type of mental disorder among adolescents, and can have long-term negative effects on their emotions, cognition, and behavior, subsequently leading to psychological and social problems [1, 2]. Currently, general anxiety disorders have an especially high prevalence among adolescents in many countries, including the United States and Turkey, even as high as 16.6% [1, 3, 4]. Similarly, adolescents in China also exhibit a high prevalence of anxiety disorders [5]. It is evident that general anxiety disorders have become a significant issue affecting the mental health of adolescents and an urgent problem that needs to be addressed.

Research has shown that physical activity such as high-intensity interval training, aerobic exercise, and tai chi can reduce anxiety symptoms in adolescents [6–9].

However, adolescents often enjoy sedentary and rest periods, consciously limiting their light physical activity (LPA) and moderate-to-vigorous physical activity (MVPA). Additionally, more sedentary behavior (SB) and less sleep period (SP) lead to increased anxiety in adolescents [10, 11]. Physical activity among adolescents is generally insufficient, and the level of physical activity tends to decrease with age [12]. A 2018 study in 49 countries indicated that children and adolescents exhibited low levels of physical activity and high levels of sedentary behavior [13]. Adolescents should accumulate at least 60 min per day of MVPA according to the 24-h movement guidelines. However, a 2022 meta-analysis of 63 studies in 23 countries found that only 7.12% of adolescents engaged in the recommended amount of physical activity in the 24-h movement guidelines [14]. Moreover, studies have found that adolescent girls engage in significantly less physical activity than boys across most countries and regions, and gender differences in anxiety levels have also been reported [1, 8]. However, empirical research exploring gender-specific patterns in physical activity and their associations with anxiety remains relatively scarce.

Considering that physical activity, SB and SP are interdependent within an individual's 24-h activity behavior pattern, a change in the duration of one behavior will inevitably lead to changes in the duration of one or more of the other behaviors [15]. Thus, to explore the relationship between a single activity behavior and adolescent anxiety disorders in isolation may undermine the study's validity. Therefore, Pedisic et al. proposed that 24-h activity data should be considered compositional data containing multiple components (physical activity, SB, SP) that sum to a constant value (24 h) [16, 17]. However, the assumptions of traditional linear regression analysis are not fully satisfied due to compositional data fixation and limitation as well as non-negativity, which can lead to pseudo-correlations and multicollinearity among the component data.

To address the problems of using linear regression with compositional data, some researchers have introduced compositional data analysis (CoDA) to the field of health promotion and combined it with the isotemporal substitution model (ISM) to estimate the effects of replacing different durations of one activity behavior with another on physical and mental health; the method was further applied to the analysis of 24-h activity behaviors [18–21]. Based on this, the effects of different time allocation patterns on health indicators can be more accurately estimated, so that more rational and effective health management programs for individuals can be developed.

Two studies have tested the relationship between self-reported 24-h activity behavior and anxiety symptoms using CoDA and ISM. Gilchrist et al. explored the relationship between 24-h activity behaviors and mental health in a sample of adolescents from 136 schools in Canada [22]. Replacing other activity behaviors with 15 min of sleep reduced adolescents' anxiety symptoms; however, replacing screen time (screen-based sedentary behaviors such as videogames) with MVPA had no significant effect on anxiety symptoms. By contrast, Wang et al. found that anxiety symptoms improved after replacing screen time with 15 min of MVPA [23]. The use of self-reports of the 24-h temporal distribution of activity behaviors may have contributed to the inconsistent results across studies.

One study has used accelerometers rather than self-reports to objectively measure the distribution of activity times for use in CoDA and ISM analyses to predict anxiety [24]. The researchers examined the relationship between 24-h activity behaviors and anxiety symptoms in Brazilian adolescents. However, the study only used 10, 30, and 60 min for isotemporal substitution analyses, and did not further investigate the dose-response characteristics of the time replacement between different activity behaviors. The effects of physical activity on physical and mental health tend to follow a dose-response relationship [25], and analysis of the dose-response gradient can identify the relationship between different types of activity behaviors and adolescents' anxiety symptoms at different times.

Accordingly, This study used accelerometers to objectively measure 24-h activity time distribution and analyzed the data using CoDA and ISM to reveal the relationship between 24-h activity behaviors and adolescents' anxiety symptoms. The results have the potential to deepen our understanding of the correlation between adolescents' 24-h activity behaviors and adolescents' anxiety, and provide practical reference for future intervention research. The specific research objectives were to examine: (1) gender differences in the temporal distribution of adolescents' 24-h activity behaviors(physical activity, SB, SP); (2) associations between each activity

behavior and anxiety symptoms after isotemporal substitution of different activity behaviors; and (3) the dose-response characteristics of changes in adolescents' anxiety after continuous isotemporal substitution of one behavior for other behaviors.

Methods

Participants

Convenience sampling was used to select four middle schools in Wuhan City, Hubei Province. Random whole cluster sampling by class in each school was used to select 245 first-year, second-year and third-year students. The inclusion criteria for this study required participants without diagnosed medical conditions or physical limitations affecting mobility, along with complete 24-h activity behavior data recorded according to the study protocol. Exclusions were applied based on these criteria, and the parents of eligible adolescents provided written informed consent.

Measurement of 24-h movement behaviors

The data collection period for this study was from October 16 to December 7, 2023. The triaxial accelerometer (Actigraph GT3X-BT, USA) was used to measure the adolescents' 24-h activity time distribution, with a sampling rate of 60 Hz. Prior to the formal test, the researcher explained to the adolescents, parents and teachers how and when the accelerometers should be worn and the precautions to be taken. For the formal test, the adolescents were asked to wear the accelerometer on the wrist of their nondominant hand for seven consecutive days (five weekdays and two weekend days). Each day, the researcher checked compliance and reminded them to record their bedtime、wake time and nap time. At the end of the seven days, the accelerometer was recovered and the data were processed using ActiLife (Version 6.13.5) to calculate SP, SB, LPA, and MVPA.

According to the valid screening criteria for physical activity proposed by Tudor-Locke et al., the adolescent's data were considered valid if the adolescents wore the accelerometer no less than 10 h a day for four days in a week (including three weekdays and one weekend day) [26, 27]. The cut-points proposed by Zhu et al., which are appropriate for the physical activity intensity levels of Chinese adolescents, were used to classify physical activity registered by the accelerometer. Specifically, SB was defined as activities within 0-100 counts per minute (cpm), LPA ranged from 101 to 2800 cpm, MPA was classified as 2801–4000 cpm, and VPA included activities ≥ 4001 cpm [28]. The sum of MPA time and VPA time was the total of moderate-to-vigorous physical activity (MVPA). Meanwhile, sleep duration was calculated using the refined sleep algorithm (RSA) proposed by Barreira et al. [29].

Questionnaire

Anxiety symptoms were measured using the Self-Rating Anxiety Scale (SAS) [30]. The scale consists of 20 items, each rated on a 4-point scale (1 = no / very little of the time, 2 = some of the time, 3 = quite a lot of the time, 4 = most / all of the time). The scale score is a standardized score calculated as the sum of all item scores x 1.25, with a range of 25–100 points. For example, if a participant's total raw score from the 20 items is 53, the standardized score is calculated as follows: $53 \times 1.25 = 66.25$. Higher scores represent higher anxiety [30]. The Jöreskog's rhô in this study was 0.801. Information about gender, age, height, and weight was collected by self-report, and all participants who wore the accelerometer completed the questionnaire in class.

Data analysis strategy

The data were analyzed using the compositions package and robCompositions package in R (4.3.1). Descriptive statistics were calculated for participant characteristics, and t-tests were conducted to compare anxiety scores between boys and girls. Meanwhile, descriptive statistics for the compositional data were used to present centralized and discrete trends in the 24-h activity behaviors data, including the computation of compositional geometric means and the variance matrix [19]. Because the variance of one component alone could not explain the interdependence among different activity behaviors, the discrete trends were described by means of a variance matrix using the logarithmic variance of the pairwise ratios in the set of four activity behaviors. A smaller variance indicates a higher degree of association between the two behaviors and a higher probability that the times of the two behaviors will be substituted for each other. A larger value represents a lower degree of association between the two behaviors and a lower probability that the times of the two behaviors will be converted to each other.

The predominance of SB, SP, and LPA in adolescents' 24-h activity behaviors and the lesser amount of MVPA time are not conducive to understanding differences in the temporal distribution of the four activity behaviors. Chastin et al. suggested that compositional geometric mean bar graphs for gender composition comparisons better reflect gender differences than conventional bar graphs [18]. Therefore, to promote interpretation, differences between the four activity behaviors are illustrated in geometric mean bar graphs with the log ratio ln(subgroups/overall) as the vertical coordinate. Additionally, to explore the associations between the temporal distributions of 24-h activity behaviors and adolescents' anxiety, compositional regression analysis was conducted using ilr-transformed 24-h activity behaviors data as independent variables (SB, SP, LPA, and MVPA) and

anxiety score as the dependent variable. The covariates were gender, only-child status (whether the adolescents was an only child or had siblings), and residency (whether the adolescents lived with parents or with other adults).

The 24-h activity behaviors time replacement analysis was conducted using a fitted multiple linear regression model. It has been found that a change in activity behavior for a 15 min interval can have a significant effect on health indicators [19]. Therefore, we first tested the association between 24-h activity behaviors time reallocation and anxiety symptoms in adolescents using 15 min as the replacement unit. Secondly, with reference to previous researchand combining the characteristics of the 24-h activities time distribution of adolescents in this study, the time substitution was then increased to 60 min in 5-mins increments to explore the dose effect of different substitution times in predicting anxiety symptoms [19].

Results

Descriptive characteristics of study sample

After excluding 64 (26%) students with incomplete accelerometer data and 5 (2%) students with incomplete questionnaires, the final sample comprised 176 (72%) students, including 91 boys (52%) and 85 girls (48%), with an average age of 13.44 ($SD = 1.5$) years and a mean BMI of 19.71 ($SD = 3.45$). See Fig. 1. The mean Self-Rating Anxiety Scale (SAS) score was 43.49 ($SD = 10.49$). The mean anxiety score for boys, 41.65 ($SD = 9.46$), was significantly lower than the mean for girls, 45.47 ($SD = 11.21$) ($t = -2.45$, $p = .015$). The compositional geometric means of the four activity behaviors (SB, SP, LPA, and MVPA) were 621 min, 538 min, 249 min, and 32 min, respectively. See Table 1.

Table 2 shows that the variance of ln(SB / SP) was 0.42. The variance of the log ratios for MVPA and the remaining three activity behaviors were all relatively large, indicating that adolescents were more stable in terms of their time spent on MVPA, and MVPA had the least interdependence with the other behaviors. If time substitution occurred, the probability of substitution with SP time was highest in comparison [ln(MVPA/SP) = 0.790 < ln(MVPA/LPA) = 0.801 < ln(MVPA/SB) = 0.989]. In addition, the minimum log-ratio variance was ln(SB/SP) = 0.042, indicating that adolescents' time spent on SB and SP was most likely to be replaced.

Ternary diagrams can better reveal the distribution of time for different activity behaviors and facilitate the comparison of the relative proportions of time distributions for different behaviors. As shown in Fig. 2, adolescents' SB time occupies a large proportion of their 24-h activity behavior, with a high-density cluster near the SB vertex, indicating limited flexibility in replacing SB with other activities. SP time is the next largest, while MVPA has the smallest proportion but the highest dispersion, this suggests substantial individual variability in reallocating time to MVPA.

Gender differences in adolescents' 24-h activity behaviors

To understand the link between adolescents' activity behavior and gender, we compared the log ratio of 24-h behavior (SB, SP, LPA, and MVPA) across gender against the sample mean using compositional geometric mean bar charts. As a result, he mean values for SP, LPA, and MVPA for boys were higher than the overall mean, while the opposite was true for girls. In addition, the greatest difference between boys and girls was in MVPA (Fig. 3).

Compositional data regression analysis

There was a significant negative correlation between anxiety scores and MVPA time ($\beta_{(MVPA)} = -6.95$, $p < .001$), which means that as MVPA time increased (with relative decreases in SB, SP and LPA time), anxiety scores decreased. Meanwhile, SP ($\beta_{(SP)} = 10.42$, $p < .001$) and SB ($\beta_{(SB)} = 11.18$, $p = .0149$) time showed a significant positive correlation with anxiety scores, indicating that as SP or SB time increased (with relative decreases in other behaviors), anxiety also rose. In contrast, there was no significant correlation between LPA time and anxiety ($\beta_{(LPA)} = -0.861$, $p = .634$).

Reallocation of 24-h activity and its impact on anxiety symptoms

The results showed that anxiety scores decreased by 2.47, 2.36, and 2.17 units after replacing SB, SP, and LPA with MVPA, respectively, while scores increased by 3.95, 3.85, and 3.67 units when MVPA was replaced by SB, SP, and LPA. In addition, anxiety scores decreased by 0.29 units when SB was replaced with LPA, and conversely increased by 0.29 units. The isotemporal substitution of other activity behaviors did not show significance. See Table 3.

Dose-response relationship of 24-h activity behavior substitution with anxiety symptoms

The analysis yielded a compositional mean of 32 min for MVPA and the 15-min isotemporal substitution analysis found that only the substitutions of MVPA with SB, SP, LPA, and the substitution of SB with LPA, were significant. Therefore, to reveal the dose-response characteristics of different substitution durations of 24-h activity behaviors on anxiety scores. This study used 5-min increments to replace any of the above activity behaviors that showed a significant replacement effect up to duration of -30 min to 60 min. The results showed that as MVPA isochronous substitution for SB, SP, and LPA time increased, adolescent anxiety appeared to decrease slowly, while conversely, it increased rapidly, and the increase was significantly greater than the decrease. See Fig. 4. This may

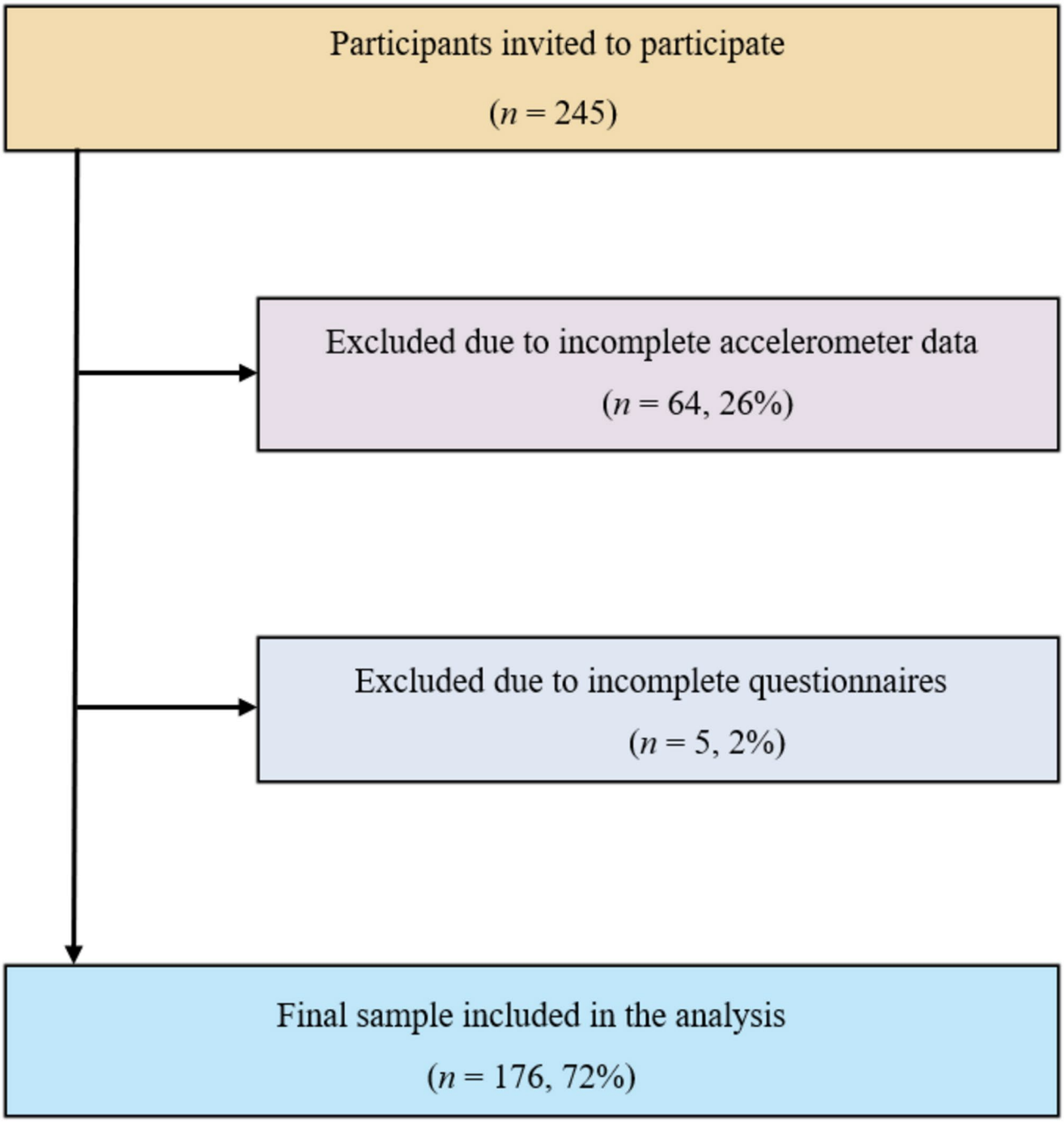

Fig. 1 Flow chart of participant inclusion and exclusion process

Table 1 Compositional geometric means and arithmetic mean of physical activity, SB, and SP within 24-h

Compositional Geometric Mean				**Arithmetic Mean**			
SB	SP	LPA	MVPA	SB	SP	LPA	MVPA
621	538	249	32	614	534	256	36
43.12%	37.36%	17.29%	2.23%	42.68%	37.10%	17.75%	2.47%

SB = sedentary behavior, SP = sleep period, LPA = light physical activity,
MVPA = moderate-to-vigorous physical activity.

Table 2 Compositional variation Matix of proportions of time spent in physical activity, SB and SP

	SB	SP	LPA	MVPA
SB	0.000	0.042	0.141	0.989
SP	0.042	0.000	0.096	0.790
LPA	0.141	0.096	0.000	0.801
MVPA	0.989	0.790	0.801	0.000

SB = sedentary behavior, SP = sleep period, LPA = light physical activity, MVPA = moderate-to-vigorous physical activity.

be related to the substantial differences in the proportion of SB, SP, LPA, and MVPA within the 24-h activity behaviors. If a particular behavior (such as MVPA) accounts for a relatively small proportion of total time, then even a 5-minute substitution may constitute a significant proportion of its total duration, leading to a more pronounced change in anxiety levels.

In addition, synthesizing the information in Fig. 4 with the isotemporal substitution benefit values revealed that a substitution time of 5 min may be the turning point

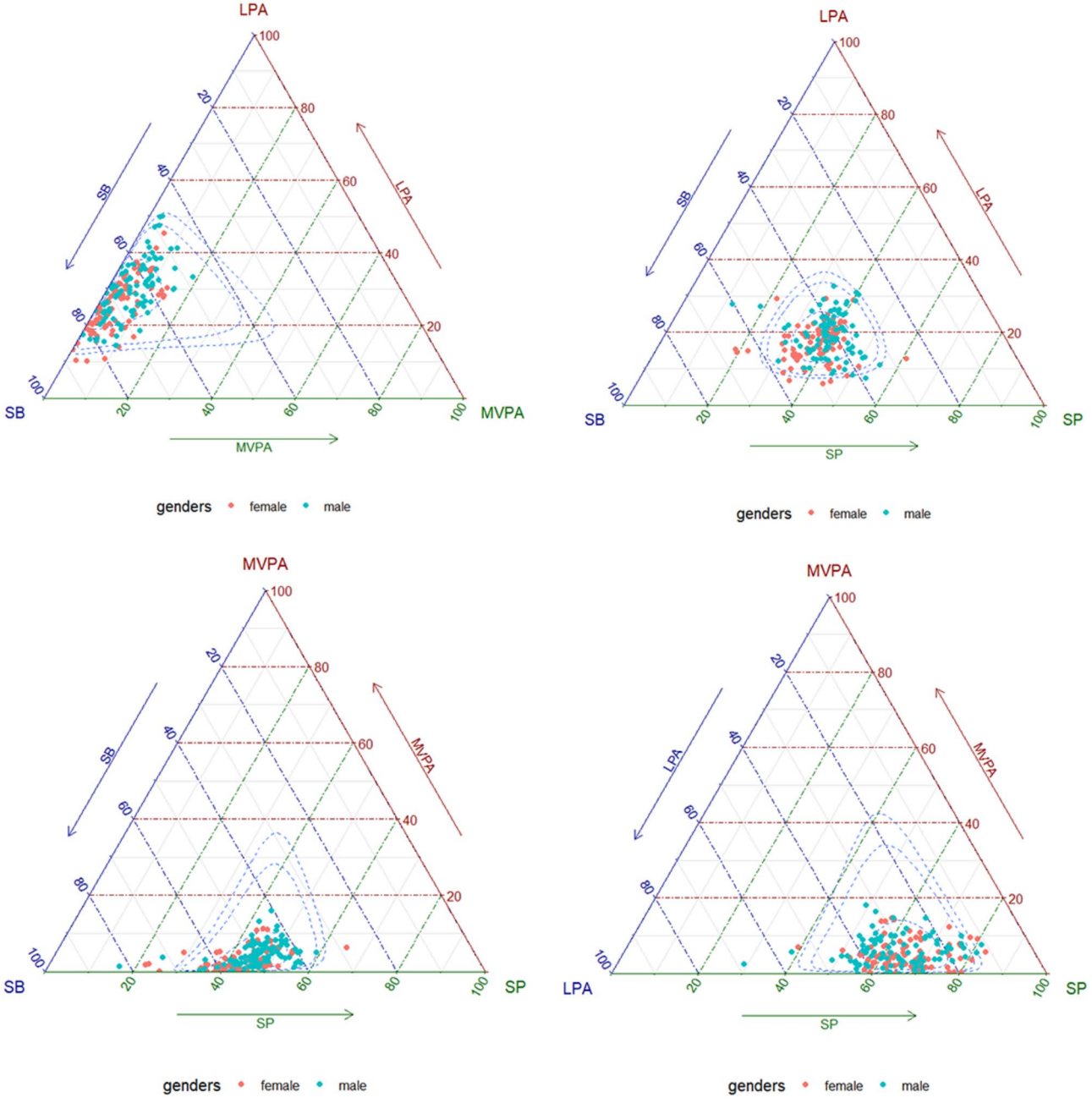

Fig. 2 Ternary plots of sleep period (SP), sedentary behavior (SB), light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA); dashed lines: form the 95% and 99% normal probability regions

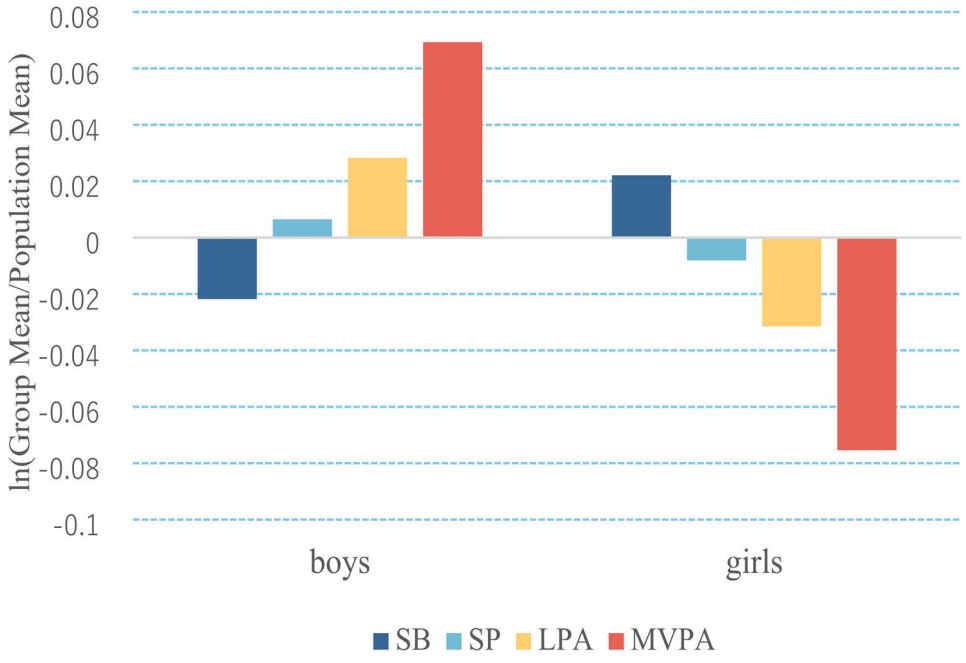

Fig. 3 Geometric bar graphs of component means for overall and gender subgroups of adolescent's 24-h activity behaviors

Table 3 Estimated difference (95% CI) in anxiety for 15-min isotemporal substitutions forsedentary behavior (SB), sleep period (SP), light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA)

	SB↑	SP↑	LPA↑	MVPA↑
SB↓	—	0.10 (-0.30, 0.09)	-0.29 (-0.51, -0.07)*	-2.47 (-2.82, -2.12)*
SP↓	0.10 (-0.10, 0.30)	—	-0.18 (-0.39, 0.03)	-2.36 (-2.80, -1.93)*
LPA↓	0.29 (0.07, 0.52)*	0.19 (-0.03, 0.41)	—	-2.17 (-2.60, -1.73)*
MVPA↓	3.95 (3.37, 4.54)*	3.85 (3.18, 4.51)*	3.67 (3.02, 4.32)*	—

↑Indicates an increase of 15 min in the activity duration, ↓indicates a decrease of 15 min. Adjustments were made for covariates (gender, age, height, weight, only child status, residence). *p <.05.

in the isotemporal substitution benefit. Specifically, when MVPA replaced SB, SP, and LPA for 5 min, anxiety decreased by 0.925, 0.890, and 0.828 units, respectively, and the rate of decrease gradually slowed down during the substitution process as the interval went from 10 min to 60 min. When SB, SP, and LPA replaced MVPA for 5 min, the anxiety score increased by 1.073, 1.038, and 0.977 units, but the rate of increase was significantly higher during the subsequent replacement time. Finally, the isotemporal substitution effects of LPA and SB time were relatively small, and their dose-response gradients showed a clear symmetry. Specifically, within a 60-min substitution time, whether SB time was isotemporally replaced with LPA time, or LPA time was replaced with SB time, anxiety scores gradually increased or decreased by about 0.1 units. See Fig. 5.

Discussion

This study utilized the compositional data analysis to examine the association between 24-h activity behavior and anxiety symptoms in adolescents. The findings indicate that reciprocal substitutions between MVPA and other activity behaviors, as well as between LPA and SB, had significant effects on anxiety symptoms, with the isotemporal substitution effect between MVPA and SB being the largest. Meanwhile, the effect of reciprocal substitution between MVPA and SB, SP and LPA was asymmetric. When MVPA was replaced by other activity behaviors, adolescents' anxiety levels increased rapidly and conversely decreased slowly.

Consistent with previous studies, adolescents in our study showed longer SB time and generally lower levels of physical activity, and MVPA in particular accounted for a very small percentage of 24-h activity behaviors [31, 32]. The variation matrix and ternary diagram also showed that MVPA was more difficult to substitutewith other activity behaviors time. This may be because adolescents require long periods of SB in 24 h to complete homework and study. Moreover, the physical activity of the adolescents population typically occurs in the fixed physical education courses and recess activities in school, which are relatively stable and not as easily replaced compared to other activity behaviors. In contrast, after-school physical activity varies greatly among individuals and is influenced by factors such as economic conditions, access to recreational facilities, and parental support. Meanwhile, the SB and SP times were the most likely to be replaced in terms of the variance of log ratios between the different

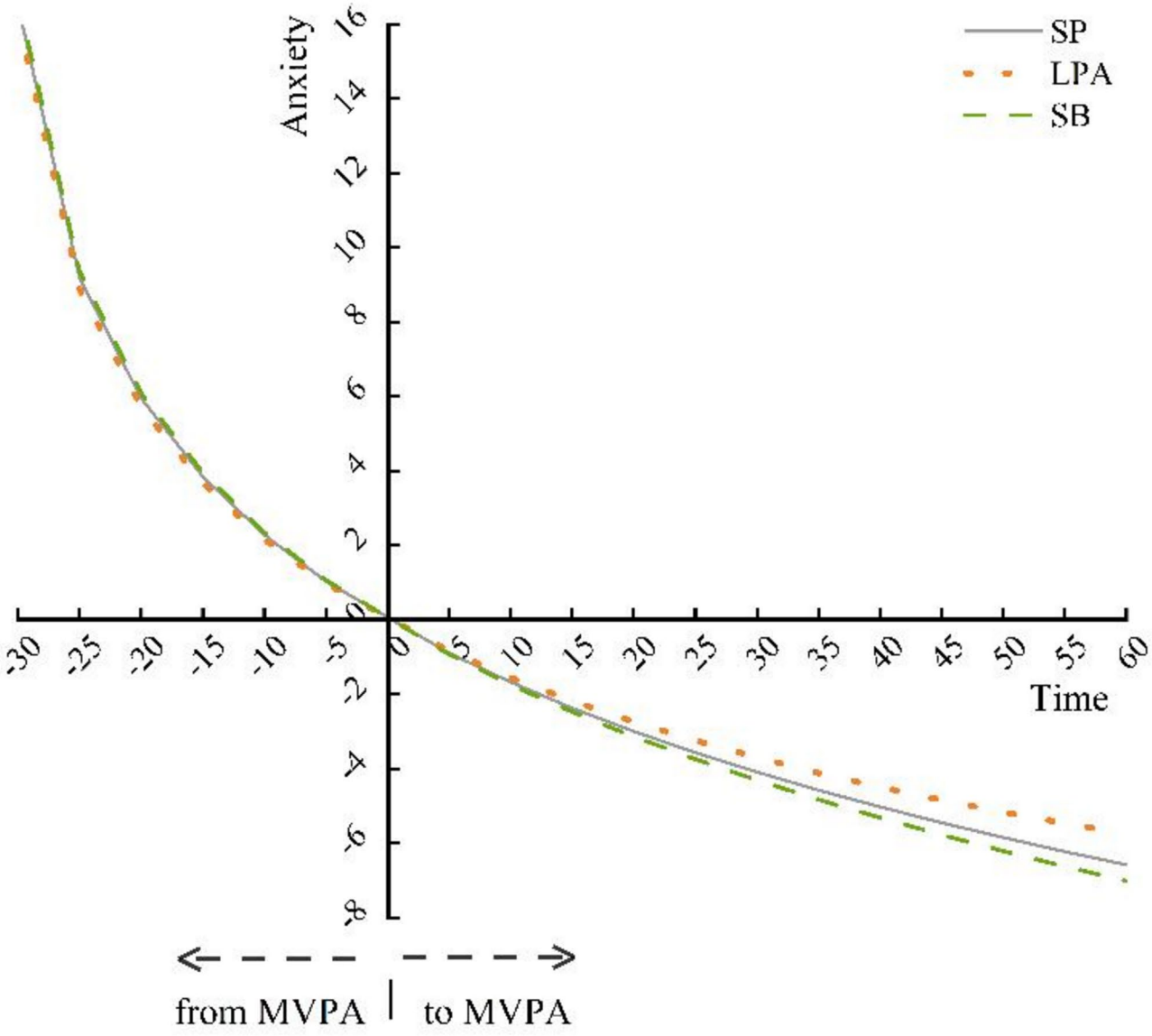

Fig. 4 Changes in anxiety scores after moderate-to-vigorous physical activity (MVPA) isotemporal substitution for other behaviors

activity behaviors. This is highly consistent with adolescents' tendency to stay up late to complete schoolwork [33, 34]. There is also replacement when parents encourage adolescents to get more sleep when there has been a lot of screen time and recreational SB. In addition, as shown in Table 1, the variance of the log ratio between SB and LPA was relatively small. This suggests that in the current educational environment, the best path to improve physical activity levels in adolescents may be to replace SB with LPA time firstly, and further increase MVPA time on top of that.

As can be seen in Fig. 3, there were distinct 24-h activity behavior patterns for girls and boys. Girls' SB time was higher than the overall compositional mean, while boys' SP, LPA and MVPA were higher for the corresponding means. These findings may be related to physiological differences, gender roles, and allocation of sports resources. For example, boys usually have an advantage in terms of physical fitness, which makes them more inclined to competitive, high-intensity physical activities, whereas girls place more emphasis on their health and physiological status when choosing the type of sport they do, and generally choose lower-intensity physical activities [8, 35]. Secondly, consistent with gender roles, boys are expected to engage in more confrontational physical activities, such as soccer, basketball, and rugby, which involve physical contact and strategic opposition. In contrast, girls are considered to be more suited to gentler activities, such as yoga and dance, which emphasize flexibility and coordination [36]. Finally, the uneven

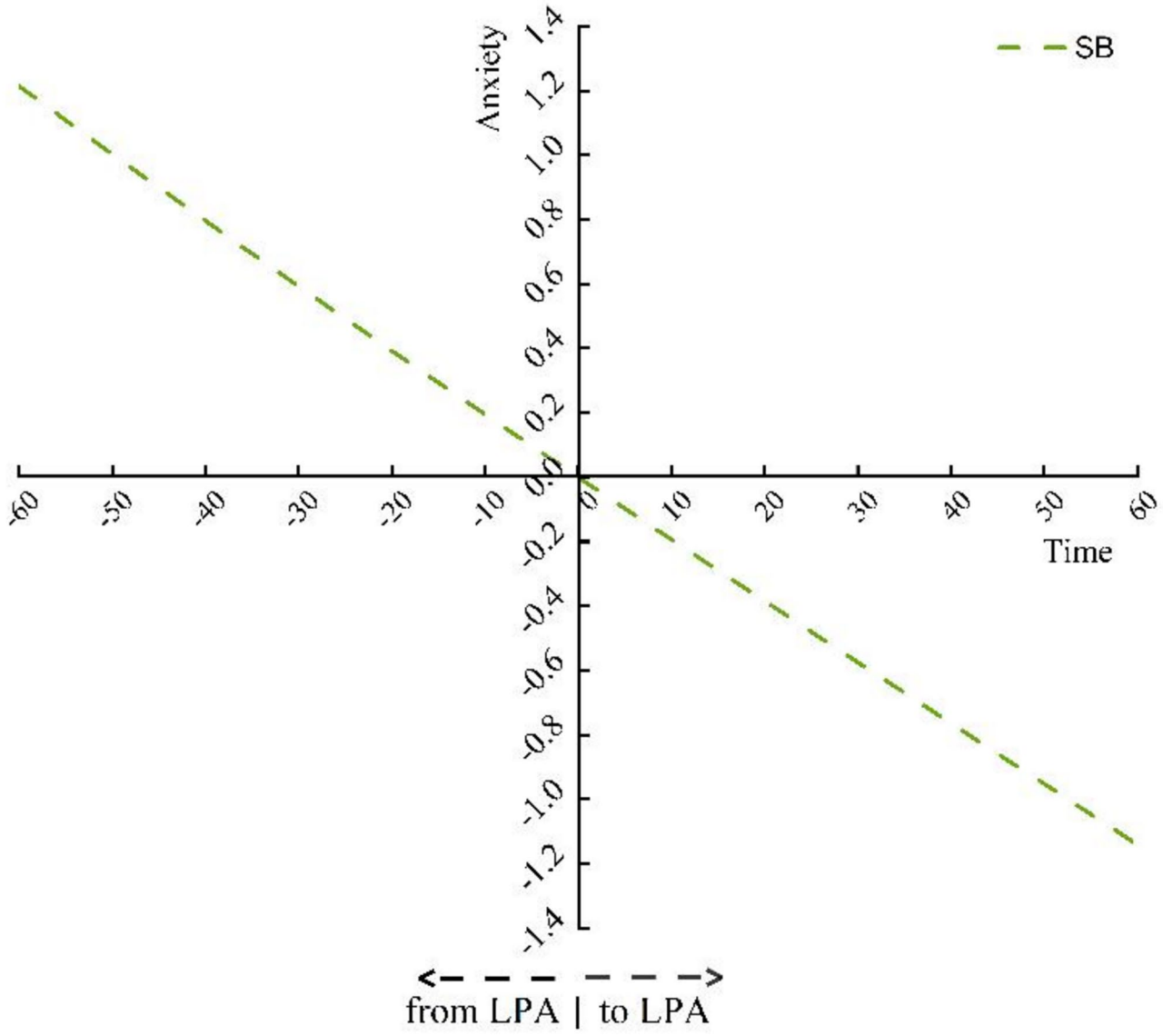

Fig. 5 Changes in anxiety after light physical activity (LPA) isotemporal substitution for sedentary behavior (SB)

distribution of resources for sports is also an important factor, with boys tending to be given more opportunities to engage in physical activity [8].

The adolescent girls in our study had significantly higher levels of anxiety than the boys. This finding is consistent with research showing that girls tend to have a higher prevalence of anxiety disorders than boys, and that this gender difference may begin in childhood and increase with age [1, 37]. This gender difference may be due to the fact that adolescent girls are more sensitive to interpersonal pressures, and will value their roles in social scenarios and relationships with their peers more highly than boys do [1]. It may also be related to hormonal changes during puberty. Adolescent girls are more likely to experience mood instability and increased anxiety due to fluctuations in hormone levels during the menstrual cycle [38, 39].

Based on ilr and linear regression, adolescents' MVPA time was significantly and negatively associated with anxiety levels. This result is consistent with Carter et al.'s finding that physical activity had an ameliorative effect on anxiety symptoms in adolescents [40]. In contrast, SB and SP time were positively correlated with anxiety level. Considering the interdependence among physical activity, SB, and SP, longer SB and SP time leave relatively less time spent in physical activity, which in turn can create anxiety symptoms. Additionally, some studies suggest that excessive sleep time, particularly beyond the recommended range, may be linked to poorer mental health outcomes, including heightened anxiety levels [41, 42]. In contrast to previous research, we found that the

association between LPA and adolescent anxiety symptoms was not significant [24]. The main reason may be that this study did not specifically differentiate between LPA, and different types of LPA may not have the same effect on anxiety symptoms. For example, there may not be an association between daily light walking and anxiety symptoms in adolescents.

Isotemporal substitution model estimated that MVPA had the greatest benefit in improving anxiety symptoms in adolescents. Specifically, replacing 15 min of SB, SP, or LPA with the same amount of MVPA each day significantly reduced anxiety scores. Among them, MVPA isotemporal substitution for SB had the highest benefit (-2.47). Additionally, a significant benefit was seen when using LPA to replace 15 min of SB, but the benefit value was relatively small (-0.29). This finding reaffirms the results of previous studies showing that both MVPA and LPA are important for the improvement of anxiety symptoms in adolescents [43–45]. It is noteworthy that substituting 15 min of MVPA with SB, SP, or LPA showed significant negative effects, with anxiety levels increasing by 3.95, 3.85, and 3.67 units, respectively. This further suggests that MVPA may be the most crucial type of activity for the physical and mental health development of adolescents. In addition, adolescents' anxiety symptoms were significantly improved when SP was converted to LPA or MVPA. However, under the influence of the current educational environment and academic pressures, adolescents may be more inclined to sacrifice SP time to compensate to academics and reallocate SP time to SB time. This trend may further constrain time for physical activity, thereby intensifying the detrimental effects of SB on anxiety symptoms.

This study conducted a dose-response analysis on the effect of reciprocal substitutions between MVPA and remaining three activity behaviors, as well as the reciprocal substitution between LPA and SB, on anxiety symptoms. There was an observed symmetry in the effect on anxiety levels when LPA and SB were replaced with each other. That is, whether LPA was replaced with SB, or SB was replaced with LPA, the effect only differed in the direction of the change in anxiety level, while the magnitude of the change was basically the same. This indicates that LPA has a relatively small effect on anxiety symptoms in adolescents, comparable to the effect of SB. However, the variation matrix showed that the feasibility of substituting LPA and SB in the actual replacement process is stronger. For example, we can replace recreational screen behaviors with outdoor walks or rides.

By contrast, there appeared to be an asymmetry in the effects of reciprocal substitution between MVPA and other activity behaviors. Anxiety symptom levels decreased gradually when MVPA replaced other behaviors but increased more sharply when MVPA was replaced. This finding is consistent with previous studies [20, 46, 47]. The reason may be related to the relatively small proportion of MVPA time within the 24-h period. For example, the compositional geometric mean of MVPA in this study was only 32 min, so removing 10 min is the same as removing over 31% of the MVPA time, naturally leading to a larger substitution effect. In contrast, removing 10 min from SB, SP, and LPA accounted for only 1.6%, 1.8%, and 4.0%, respectively, resulting in relatively weaker substitution effects. Therefore, given how easy it is to increase anxiety levels but difficult to decrease them, the first priority should be to maintain the adolescent's current level of MVPA activity. At the same time, it is important to leverage the ease of conversion between LPA and SB by first increasing adolescents' LPA activity levels and then gradually transitioning to MVPA [48].

Previous studies have also pointed out the existence of dose-response characteristics similar to those of the present study in the relationship between adolescents' 24-h activity behaviors and mental health, body fat percentage, and other health indicators [15, 49, 50]. These findings, along with this study, suggest that rather than focus on increasing the time spent in physical activity, it would be more effective to focus on the overall time allocation for SB, SP, LPA, and MVPA. Focusing solely on increasing MVPA time may result in fatigue and may indirectly increase SB time. Stabilizing the SB and SP time within a reasonable range while meeting physical activity needs may also be more beneficial to adolescents' physical health, mental health, and academic achievement. In addition, this study found 5 min to be an important turning point during the dose-response analyses. When the substitution time was 5 min, a large change in the rate of rise or fall of the substitution effect occurred, both when MVPA was used to replace other activity behaviors and when MVPA was replaced. This suggests that the 5-min substitution time may have the highest efficiency in the isotemporal substitution processes. According to the Canadian 24-h movement guidelines for children and youth, adolescents should engage in at least 60 min of MVPA per day, while the compositional geometric mean of MVPA for the adolescents in this study was only 32 min. Based on the dose-response curves, in actual conversion, other behaviors can first be reallocated to MVPA for 5 min to achieve the highest replacement efficiency while maintaining adolescents' motivation for physical activity. Then, starting from the 37 min baseline, a gradual transition to the MVPA duration recommended by the 24-h movement guidelines can be implemented to further improve adolescents' anxiety symptoms.

Limitations

The current study has some limitations. Firstly, physical activity was only categorized as LPA and MVPA without further differentiating between specific types of activity. Furthermore, this study focused only on total sleep duration, without taking into account other sleep-related factors such as sleep onset time and sleep quality. Secondly, due to the relatively small sample size, this study did not conduct separate isotemporal substitution analyses for boys and girls. Finally, this study is essentially a cross-sectional research design, which does not allow causal inferences. Future research could specifically differentiate between physical activity types and static behavior types and consider a longitudinal research design to allow stronger inferences about causality.

Conclusions

In this study, the association between 24-h activity behaviors and adolescents' self-reported anxiety symptoms was explored using accelerometers to collect objective data about activity. The results were analyzed using CoDA and ISM. The main findings were as follows. (1) Boys showed more active behaviors and relatively less SB than girls. (2) MVPA time distribution was relatively stable across adolescents' 24-h activity behaviors and showed a significant negative correlation with anxiety symptoms; SB and SP times were positively correlated with each other and with anxiety symptoms; LPA time was not significantly correlated with anxiety. (3) Reciprocal substitutions between MVPA and other activity behaviors as well as between LPA and SB had significant effects on anxiety symptoms, with the isotemporal substitution effect between MVPA and SB being the largest. (4) The effect of reciprocal substitution between LPA and SB was symmetric; whereas the effect of reciprocal substitution between MVPA and SB, SP and LPA was asymmetric. When MVPA was replaced by other activity behaviors, adolescents' anxiety levels increased rapidly and conversely decreased slowly, with a 5-min replacement time having the best replacement efficiency. Future research and practical interventions should focus on the pairings and combinations among SB, SP, LPA, and MVPA to ensure that adolescents are attaining the required amount of physical activity while also considering the time demands of SP and SB.

Abbreviations

SP	Sleep period
SB	Sedentary behavior
PA	Physical activity
LPA	Light physical activity
VPA	Vigorous physical activity
MVPA	Moderate to vigorous physical activity
ISM	Isotemporal substitution model
CoDA	Compositional data analysis
SAS	Self-rating anxiety scale

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Author contributions

NW and XBH conceptualized and designed the study, drafted the initial manuscript, and critically reviewed and revised the manuscript; ZYW, HL, YFW, JKL collected data, carried out the initial analyses, and critically reviewed and revised the manuscript. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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Data availability

The datasets generated during and/or analysed during the current study are obtainable from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The study was performed in accordance with the Declaration of Helsinki. This cross-sectional study received ethical approval from the Ethics Committee of the Wuhan Sports University (Approval No. 2025069). Informed consent was gained for all participants from their parents or guardians.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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