

Effects of Physical Activity Level on the Moderated Mediation Model Linking BMI VO_2 max and Endurance Performance in Male University Students Under High Altitude Hypoxia

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Abstract

This study investigated the mediating mechanism linking body mass index (BMI), maximal oxygen uptake (VO_2 max), and endurance performance in the 1000 m run among male university students living at an altitude of 3650 m. It examined whether physical activity level moderated the BMI $\rightarrow$ VO_2 max $\rightarrow$ 1000 m run performance pathway and whether this moderation changed over time with high-altitude exposure and accumulated training. Following the National Student Physical Fitness Standard, 300 male students aged 18–22 years from two universities at 3650 m were followed over two academic years. BMI and 1000 m run time were measured, and VO_2 max was estimated. A supplementary questionnaire assessed self-directed extracurricular exercise to provide a multidimensional assessment of physical activity. Participants were compared in high- and low-physical-activity groups, and a moderated mediation model was fitted. The associations of physical activity with aerobic capacity and endurance performance showed marked time dependence. In the first year, the high-physical-activity (HPA) group had lower VO_2 max and poorer 1000 m run performance than the low-physical-activity (LPA) group, with no significant difference in BMI. In the second year, the HPA group showed significant improvements in aerobic capacity and endurance performance and outperformed the LPA group. VO_2 max consistently mediated the association between BMI and endurance performance. Physical activity moderated this pathway, with moderation emerging progressively during adaptation to high altitude; higher physical activity attenuated the indirect adverse association of BMI with endurance performance through VO_2 max. Sustained high physical activity may improve aerobic capacity and endurance performance, modify the associations among BMI, VO_2 max, and endurance performance, and facilitate adaptation to high-altitude hypoxia. These effects were time dependent. The findings provide a scientific basis for physical education, physical fitness interventions, and fitness management at universities in high-altitude regions.

Keywords

High-altitude hypoxia; Physical activity differences; Cardiorespiratory endurance; Aerobic performance; Longitudinal study.

1. Introduction

High-altitude hypoxia imposes a sustained challenge to aerobic metabolism by limiting oxygen uptake, transport, and utilization, thereby affecting endurance performance among university students. Recent studies indicate fluctuations in the physical fitness of students in high-altitude regions, with particularly pronounced declines in cardiorespiratory endurance [1]. The 1000 m run is a core measure of cardiorespiratory endurance in the National Student Physical Fitness Standard and an important component of overall physical fitness assessment [2]. At high

altitude, performance in this test is sensitive to changes in oxygen availability and is more readily affected by hypoxic exposure [3]. Differences in 1000 m run performance therefore reflect both endurance capacity and, to some extent, changes in the physical fitness of university students at high altitude.

Maximal oxygen uptake (VO_2max), a key indicator of the integrated efficiency of oxygen uptake, transport, and utilization, is widely regarded as the gold standard for aerobic capacity and is consistently associated with middle-distance endurance performance [4]. Under the limited oxygen availability at high altitude, VO_2max may link body weight status to endurance performance: body weight burden may affect aerobic capacity and consequently 1000 m run performance, influencing physical fitness assessment. Body mass index (BMI) is a general indicator of body weight burden and obesity. Higher BMI may increase relative oxygen demand during exercise, adversely affecting VO_2max and endurance performance [5]. Previous low-altitude studies suggest an inverted U-shaped association between BMI and aerobic endurance [6], indicating that body weight status may influence endurance in both directions. However, under high-altitude hypoxia, oxygen transport demands and metabolic stress increase. Whether the association between BMI and VO_2max , and its pathways to endurance performance and overall physical fitness, changes under these conditions has not been systematically established.

Physical activity (PA) is an important modifiable determinant of VO_2max . Previous research suggests that sustained physical activity improves aerobic capacity by enhancing cardiorespiratory function and oxygen utilization efficiency [7]. Studies of university students at high altitude have also demonstrated beneficial associations between physical activity and physical fitness [8]. However, most studies have analyzed overall fitness test indicators rather than systematically examining endurance mechanisms with VO_2max as the central variable. The underlying associations among BMI, VO_2max , and 1000 m run performance have rarely been examined at the level of pathway structure. Furthermore, most studies have used cross-sectional designs. Tian et al. [9] reported that 57.8% of university students did not meet physical activity recommendations and that BMI was significantly associated with meeting those recommendations. Dong et al. [10] found a higher prevalence of low physical fitness among adolescents in western high-altitude regions, with endurance performance closely related to body weight status. Husu et al. [11] reported that sedentary behavior accounted for 59% of waking time and suggested a potential association between BMI and exercise capacity. Zhang et al. [12] identified the role of body weight status in the physical fitness of Tibetan adolescents at high altitude. Li [13] reported that approximately 70% of students did not meet the criteria for regular participation in physical exercise, suggesting an underlying association between body weight burden and exercise participation. Although these studies characterized relevant associations, they could not establish temporal changes in the effects of physical activity or test whether physical activity alters the association between BMI and VO_2max . Physical activity among university students at high altitude is generally low and varies considerably. In a survey of 8721 university students at high altitude, Wang et al. [1] found that 76.7% engaged in less than 30 min of moderate-to-vigorous physical activity per day, and only 4.7% met World Health Organization recommendations. These differences suggest that physical activity may affect endurance and physical fitness both by directly improving aerobic capacity and by modifying the association between BMI and VO_2max . Longitudinal evidence remains limited. We therefore conducted a supplementary questionnaire survey to assess self-directed exercise outside scheduled training and provide a multidimensional assessment of physical activity among university students at high altitude.

This study addressed three questions concerning endurance performance and physical fitness among university students at high altitude: (1) whether BMI has an indirect association with 1000 m run performance through VO_2max ; (2) whether physical activity level moderates this

mediation pathway; and (3) whether moderation changes over time with adaptation to high altitude and accumulated training. Using a longitudinal design, we constructed a moderated mediation model centered on $VO_2\text{max}$ to examine the relationships among BMI, $VO_2\text{max}$, and 1000 m run performance under high-altitude hypoxia, together with the moderating role of physical activity and its temporal characteristics. Based on theory and previous findings, we hypothesized that $VO_2\text{max}$ mediates the association between BMI and endurance performance, that physical activity moderates this pathway, and that the strength of moderation may emerge progressively during adaptation. This design aimed to clarify mechanisms underlying differences in physical fitness among university students at high altitude and provide a theoretical basis for university fitness interventions and management.

2. Methods

2.1. Participants

A total of 300 male students aged 18–22 years were recruited from two universities located at an altitude of 3650 m. Based on sustained differences in physical activity exposure arising from the universities' physical education arrangements, participants were classified into a high-physical-activity (HPA) group and a low-physical-activity (LPA) group, with 150 students in each group. In addition to two regular physical education sessions per week, each lasting 90 min, the HPA group participated in additional fitness training six times per week for approximately 45 min per session over an extended period. The LPA group participated only in regular physical education classes.

This longitudinal observational study followed participants over two academic years. Outcomes included anthropometric measures (height, weight, and BMI) and endurance performance (1000 m run time), from which cardiorespiratory endurance ($VO_2\text{max}$) was estimated. All tests were administered by uniformly trained personnel using the Ministry of Education-designated digital university student fitness testing system (Shenzhen Hengkang Jiaye Technology Co., Ltd., model HK6800B). The system was calibrated before testing according to the relevant procedures and complied with applicable national standards. The study was approved by the Medical Ethics Committee of Tibet University (approval no. ZDYXLL2024020).

2.2. Statistical Analysis

Raw data were independently entered by two operators in EpiData 3.0 and checked for consistency. Statistical analyses were performed using SPSS 29.0 (IBM Corp., Armonk, NY, USA). Figures were prepared using GraphPad Prism 8.0.2 and Apache ECharts 6.0.0.

$VO_2\text{max}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) was estimated from 1000 m run time and relevant individual characteristics using the following equation [14]:

$$VO_2\text{max} = 1.640 - 0.004 \times g \times t + 0.037 \times w \quad (1)$$

Here, g denotes gender (1 for boys and 2 for girls), t denotes run time in seconds, and w denotes weight in kilograms. Participants' physical characteristics and exercise performance were summarized as mean $\pm$ standard deviation ($\bar{x} \pm s$). Between-group differences in each indicator at the same time point (first or second year), including differences between physical activity exposure groups and ethnic groups, were assessed using the Mann–Whitney U test. Within-group changes from the first to the second year were assessed using the Wilcoxon signed-rank test to evaluate time effects.

Based on the distributional characteristics of the variables, Spearman correlation analysis was conducted separately for the first and second years to examine associations among BMI,

VO₂max, and 1000 m run time. A moderated mediation model (Model 14) was then fitted using the SPSS PROCESS macro to examine whether physical activity moderated the BMI → VO₂max → 1000 m run performance pathway. Statistical significance was assessed using 5000 bootstrap samples, with a significance level of 0.05.

2.3. Exercise Behavior Questionnaire

To address limitations of grouping participants solely by physical activity exposure arising from university physical education arrangements, we collected additional behavioral data on self-directed exercise and perceived exercise load. A tailored questionnaire was developed with reference to the short form of the International Physical Activity Questionnaire (IPAQ), which has demonstrated good reliability and validity and is widely used among Chinese university students. The questionnaire incorporated the exercise context of students at high altitude to provide a multidimensional assessment of their physical activity under hypoxic conditions.

The survey focused on self-directed extracurricular exercise in three domains: weekly exercise frequency, duration per exercise session, and perceived exercise load and physical strain. The questionnaire was administered alongside physical fitness testing. Trained personnel distributed the questionnaires on site, provided completion guidance, and collected them immediately afterward. All participants provided informed consent to the survey. The procedures complied with the approval of the Medical Ethics Committee of Tibet University described in Section 2.1 (approval no. ZDYXLL2024020). A total of 300 questionnaires were distributed, and 300 valid questionnaires were returned, yielding a valid response rate of 100%. Descriptive analyses were performed using SPSS 29.0, consistent with the software used throughout the study. These results were used to assist interpretation of how differences in exercise behavior might influence the moderated mediation pathway linking BMI, VO₂max, and 1000 m run performance.

3. Results

3.1. Between Group Comparisons and Longitudinal Changes in BMI VO₂max and 1000 m Run Performance

Figure 1 and Table 1 show that, in the first year, the LPA group had significantly higher VO₂max than the HPA group ($P = 0.001$) and better 1000 m run performance, reflected in shorter run times ($P = 0.026$). BMI did not differ significantly between groups ($P > 0.05$). In the second year, the HPA group had higher VO₂max and better 1000 m run performance than the LPA group (both $P < 0.001$), while BMI remained similar between groups ($P > 0.05$). From the first to the second year, VO₂max and endurance performance improved significantly in the HPA group (both $P < 0.001$), with no significant change in BMI ($P > 0.05$). In the LPA group, VO₂max and endurance performance declined significantly (both $P < 0.001$), while BMI increased slightly ($P = 0.011$).

Figure 1 shows the relative levels of BMI, VO₂max, and 1000 m run performance in the HPA and LPA groups during the first and second years. All indicators were normalized to a common scale before visualization. Points closer to the red markers indicate relatively better performance on the corresponding indicator, whereas points closer to the blue markers indicate relatively poorer performance. Colors and line types distinguish the groups and measurement years.

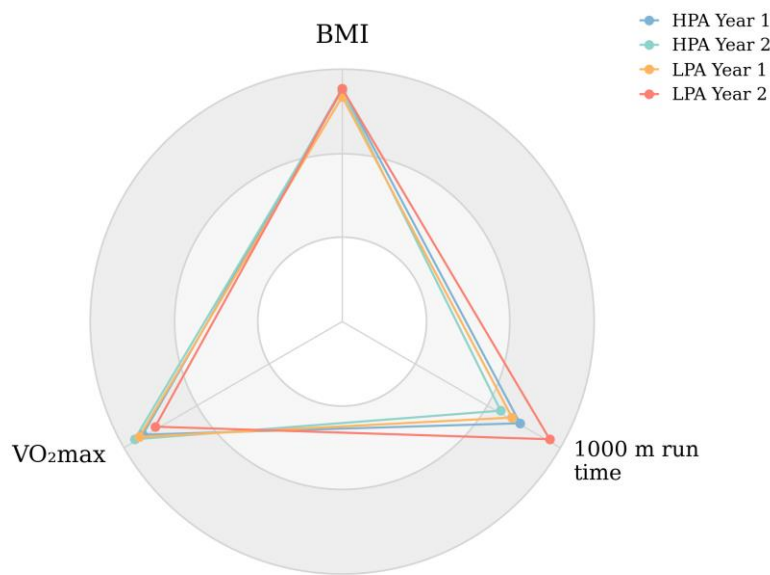


Fig. 1 Between-group comparisons and longitudinal changes in BMI, VO₂max, and 1000 m run performance in the HPA and LPA groups

Table 1. Between-group comparisons and longitudinal changes in BMI, VO₂max, and 1000 m run time

Group	Year or comparison	BMI	VO ₂ max (mL·kg ⁻¹ ·min ⁻¹)	1000 m run time (s)
HPA	Year 1	22.1 ± 2.8	44.7 ± 2.3	282.9 ± 28.8
	Year 2	21.9 ± 2.9	46.4 ± 2.1	255.1 ± 23.6
LPA	Year 1	21.5 ± 3.5	45.8 ± 3.3	273.4 ± 42.9
	Year 2	22.1 ± 3.6	41.8 ± 4.4	334.5 ± 68.7
P	Year 1 (HPA vs. LPA)	0.124	0.001	0.026
	Year 2 (HPA vs. LPA)	0.605	<0.001	<0.001
	HPA (Year 1 vs. Year 2)	0.089	<0.001	<0.001
	LPA (Year 1 vs. Year 2)	0.011	<0.001	<0.001

3.2. Correlations and Longitudinal Changes in BMI VO₂max and 1000 m Run Performance

Spearman correlation analysis was used to examine BMI, VO₂max, and 1000 m run time from the first to the second year among male students with different physical activity levels (HPA and LPA groups) at high altitude, as a basis for mediation analysis.

As shown in Table 2, in the first year BMI was significantly negatively correlated with VO₂max ($r_s = -0.633$, $P < 0.001$), indicating lower VO₂max at higher BMI. BMI was significantly positively

correlated with 1000 m run time ($r_s = 0.357$, $P < 0.001$), indicating longer run times at higher BMI. $VO_2\text{max}$ was very strongly negatively correlated with run time ($r_s = -0.919$, $P < 0.001$), indicating better performance, or shorter run times, at higher $VO_2\text{max}$.

In the second year, the negative correlation between BMI and $VO_2\text{max}$ remained significant ($r_s = -0.437$, $P < 0.001$) but was weaker than in the first year. The positive correlation between BMI and 1000 m run time also weakened but remained significant ($r_s = 0.172$, $P < 0.01$), suggesting a modest reduction over time in the association between BMI and running performance. $VO_2\text{max}$ remained strongly negatively correlated with run time ($r_s = -0.924$, $P < 0.001$), indicating a stable predictive association with performance.

Overall, among male students in the HPA and LPA groups, the adverse associations of BMI with $VO_2\text{max}$ and 1000 m run performance were weaker in the second year. In contrast, the strong negative correlation between $VO_2\text{max}$ and run time remained stable across both years, indicating the sustained importance of aerobic capacity for running performance.

Table 2. Spearman correlations among BMI, $VO_2\text{max}$, and 1000 m run time in the first and second years

Year	Indicator	BMI	$VO_2\text{max}$	1000 m run time
Year 1	BMI	1	/	/
	$VO_2\text{max}$	-0.633***	1	/
	1000 m run time	0.357***	-0.919***	1
Year 2	BMI	1	/	/
	$VO_2\text{max}$	-0.437***	1	/
	1000 m run time	0.172***	-0.924***	1

Table 2 presents Spearman correlations among BMI, $VO_2\text{max}$, and 1000 m run time in the HPA and LPA groups. Significance levels are denoted by ns, not significant; * $P < 0.05$; ** $P < 0.01$; and *** $P < 0.001$.

3.3. Moderated Mediation Analysis of BMI $VO_2\text{max}$ and 1000 m Run Performance

To examine moderation of the BMI $\rightarrow$ $VO_2\text{max}$ $\rightarrow$ 1000 m run performance pathway by physical activity, BMI was specified as the independent variable, $VO_2\text{max}$ as the mediator, 1000 m run time as the dependent variable, and PA as the moderator (HPA = 1, LPA = 2). As shown in Table 3 and Figure 2, in the first year the total effect of BMI on run time was significant ($\beta = -4.150$, $P < 0.001$). The negative association between BMI and $VO_2\text{max}$ was significant ($\beta = -0.569$, $P < 0.001$), indicating lower $VO_2\text{max}$ at higher BMI. The negative association between $VO_2\text{max}$ and run time was also significant ($\beta = -14.833$, $P < 0.001$), indicating better running performance at higher $VO_2\text{max}$. The second-stage interaction term ($VO_2\text{max} \times \text{PA}$) was not significant ($\beta = 0.423$, $P = 0.3465$), suggesting that PA did not moderate the $VO_2\text{max} \rightarrow$ 1000 m run time pathway and that the strength of this association did not differ significantly between physical activity levels. The conditional indirect effects were significant in both the HPA group ($\beta = 8.316$, $P < 0.001$) and the LPA group ($\beta = 8.557$, $P < 0.001$), indicating mediation in both groups without a significant between-group difference.

In the second year, the total effect of BMI on 1000 m run time was significant ($\beta = -3.221$, $P < 0.001$). The negative association between BMI and $VO_2\text{max}$ remained significant ($\beta = -0.496$, $P < 0.001$), as did the negative association between $VO_2\text{max}$ and run time ($\beta = -8.557$, $P < 0.001$), supporting the continued presence of the mediation pathway. The second-stage interaction

term ($\text{VO}_2\text{max} \times \text{PA}$) was significant ($\beta = -3.813$, $P < 0.001$), suggesting that PA moderated the $\text{VO}_2\text{max} \rightarrow 1000$ m run time pathway and that the strength of this association differed between physical activity levels. Conditional indirect effects were significant in both the HPA group ($\beta = 6.139$, $P < 0.001$) and the LPA group ($\beta = 8.031$, $P < 0.001$). The effect was larger in the LPA group; here, effect magnitude refers to the numerical size of the indirect effect rather than better or poorer performance.

Table 3. Moderated mediation effects in the first and second years

Year	Path or effect	Standardized coefficient (β)	P value	95% CI
Year 1	Total effect (BMI $\rightarrow$ 1000 m run time)	-4.150***	<0.001	[-4.6197, -3.6797]
	Mediation path (BMI $\rightarrow$ VO_2max)	-0.569***	<0.001	[-0.6492, -0.4884]
	Interaction ($\text{VO}_2\text{max} \times \text{PA}$)	0.423	0.3465	[-0.4600, 1.3061]
	Mediation effect ($\text{VO}_2\text{max} \rightarrow$ run time)	-14.833***	<0.001	[-15.3902, -14.2754]
	Conditional indirect effect (HPA group)	8.316***	<0.001	[7.2100, 9.5129]
	Conditional indirect effect (LPA group)	8.557***	<0.001	[7.2703, 9.9950]
Year 2	Total effect (BMI $\rightarrow$ 1000 m run time)	-3.221***	<0.001	[-3.6702, -2.7709]
	Mediation path (BMI $\rightarrow$ VO_2max)	-0.496***	<0.001	[-0.6303, -0.3623]
	Interaction ($\text{VO}_2\text{max} \times \text{PA}$)	-3.813***	<0.001	[-4.7722, -2.8543]
	Mediation effect ($\text{VO}_2\text{max} \rightarrow$ run time)	-8.557***	<0.001	[-10.3936, -6.7196]
	Conditional indirect effect (HPA group)	6.139***	<0.001	[4.5222, 7.8200]
	Conditional indirect effect (LPA group)	8.031***	<0.001	[5.7314, 10.3664]

Table 3 presents moderated mediation effects involving BMI, VO_2max , and 1000 m run time in the first and second years. Significance levels are denoted by ns, not significant; * $P < 0.05$; ** $P < 0.01$; and *** $P < 0.001$.

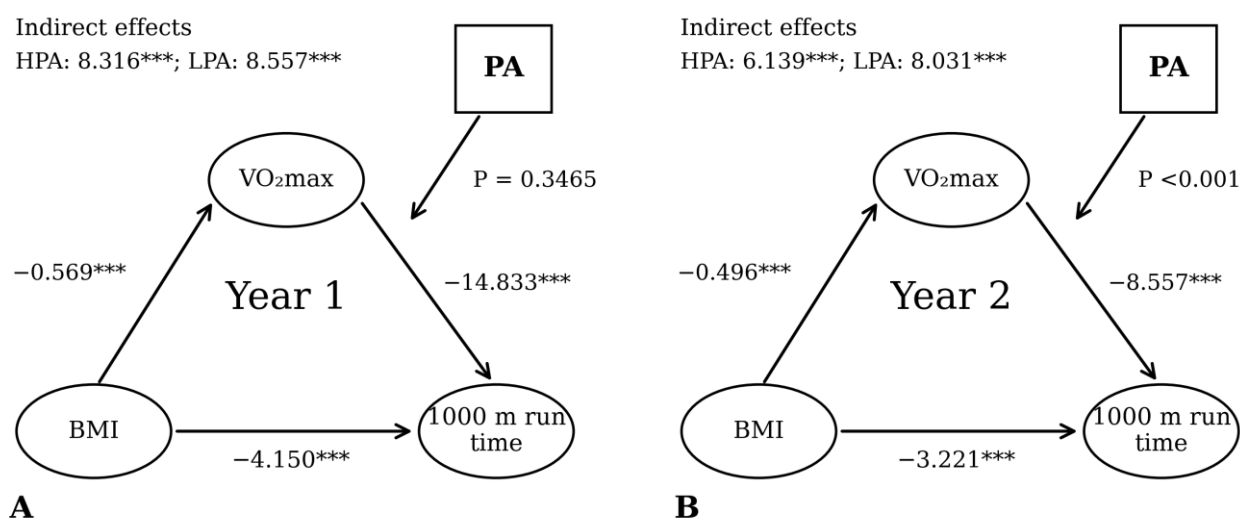


Fig. 2 Moderated mediation models in the first and second years

Figure 2 shows moderated mediation effects involving BMI, VO₂max, and 1000 m run time. Panel A represents the first year, and Panel B represents the second year. Significance levels are denoted by ns, not significant; *P < 0.05; **P < 0.01; and ***P < 0.001.

3.4. Exercise Behavior and Perceived Physical Strain

Exercise is a key modifiable determinant of physical fitness among university students and provides supplementary information for grouping participants by physical activity level. A tailored questionnaire was used to describe self-directed extracurricular exercise among the 300 male students at high altitude. The results are presented below.

Most participants reported exercising independently one or two times per week (53.2%), followed by three or four times (26.8%). A further 19.3% exercised at least five times per week, while only 0.7% reported no exercise. Thus, more than half exercised fewer than three times per week. The most common session duration was 30–60 min (52.1%), followed by less than 30 min (17.9%), 60–90 min (19.4%), and at least 90 min (10.6%). More than 70% reported session durations within 60 min. Regarding perceived strain, 3.5% reported no noticeable physical strain and very low intensity, 42.1% reported low intensity with essentially no fatigue, 48.2% reported mild but acceptable fatigue, and 6.2% reported high exercise load and pronounced fatigue (Table 4). More than 90% therefore reported low-to-moderate extracurricular exercise intensity.

Overall, self-directed extracurricular exercise among male university students at high altitude was characterized by low frequency, short-to-moderate session duration, and low-to-moderate intensity, with marked differences in participation and perceived load. These patterns were consistent with the rationale for the HPA and LPA grouping. They supplemented information on scheduled training with individual behavioral data and provided a practical basis for subsequent analysis of moderation of the BMI → VO₂max → 1000 m run performance pathway by physical activity.

Table 4. Self-directed extracurricular exercise among male university students at high altitude

Item	Response	Percentage (%)
Weekly self-directed exercise frequency	0 sessions	0.7
	1–2 sessions	53.2
	3–4 sessions	26.8
	≥5 sessions	19.3
	<30 min	17.9
Duration per session	30–60 min	52.1
	60–90 min	19.4
	≥90 min	10.6
	No noticeable strain; very low intensity	3.5
Perceived exercise load and fatigue	Low intensity; essentially no fatigue	42.1
	Mild fatigue within an acceptable range	48.2
	High exercise load; pronounced fatigue	6.2

4. Discussion

4.1. Time Dependence of Physical Activity Associations With Aerobic Capacity Under High Altitude Hypoxia

In the first year, the HPA group did not outperform the LPA group in $VO_2\text{max}$ or 1000 m run performance. This finding may reflect an early phase in which the benefits of physical activity under high-altitude hypoxia were still accumulating. Previous research suggests that significant increases in $VO_2\text{max}$ generally require several weeks of sustained training, with improvements more readily observed after 8–12 weeks [15]. The first-year findings therefore do not necessarily indicate that physical activity is ineffective for endurance; they may instead reflect incomplete adaptation. Short-term exposure to high altitude also limits oxygen availability. Acute hypoxic exposure can reduce blood oxygen saturation and cardiac output, restricting oxygen delivery to muscles [16]. Consequently, even individuals with high physical activity may show limited short-term aerobic performance while physiological adaptation is developing.

With prolonged adaptation to high altitude and accumulated physical activity, the HPA group showed higher $VO_2\text{max}$ and better 1000 m run performance than the LPA group in the second year. This pattern suggests that the benefits of physical activity require time to become fully apparent and may increase as the body adapts to hypoxia. Previous research indicates that prolonged high-altitude exposure, such as at least 40 days at 3510 m, can enhance blood oxygen transport through increased hematocrit. Sustained physical activity may also improve skeletal muscle microcirculation. Together, these processes may enhance muscle oxygen perfusion and utilization, thereby improving aerobic capacity [17].

This gradual convergence of differences may cause the mechanisms regulating aerobic capacity to become more similar across individuals. In contrast, the LPA group showed declining $VO_2\text{max}$ and 1000 m run performance in the second year. Previous studies have reported a positive association between physical activity and $VO_2\text{max}$, with more active individuals generally showing higher $VO_2\text{max}$ [18]. Meanwhile, arterial oxygen saturation decreases by

approximately 5%–8% for each 1000 m increase in altitude, and alveolar gas exchange efficiency is reduced [19]. Under high-altitude hypoxia, insufficient physical activity may make it difficult to maintain or further improve aerobic function, resulting in limited adaptation.

Overall, aerobic capacity improved with longer exposure to high-altitude hypoxia and accumulated physical activity. Although students with different activity levels differed early in adaptation, these differences gradually diminished as adaptation progressed. This suggests that improvements in aerobic capacity depend jointly on time spent adapting to high altitude and sustained physical activity, rather than on either factor alone. The questionnaire indicated that most students engaged in self-directed extracurricular exercise infrequently and at low-to-moderate intensity. This may be an important behavioral explanation for the decline in aerobic capacity in the LPA group with prolonged high-altitude exposure.

4.2. Associations Among BMI VO_2 max and 1000 m Run Performance and Their Temporal Characteristics

After identifying time-dependent moderation of aerobic capacity by physical activity, we examined the associations among BMI, VO_2 max, and 1000 m run performance from the perspective of body weight status and their changes across stages. VO_2 max was significantly negatively correlated with 1000 m run time in both years, indicating that it remained a central indicator of middle-distance endurance performance regardless of adaptation stage [20]. This finding supports the earlier observation that physical activity may improve endurance by increasing VO_2 max. In the first year, BMI was strongly negatively correlated with VO_2 max and positively correlated with run time, suggesting a relatively pronounced influence of body weight burden on aerobic capacity and endurance during early adaptation to high altitude.

In the first year, the benefits of physical activity for aerobic capacity had not fully emerged, while the constraint on VO_2 max associated with body weight burden, as represented by BMI, was relatively prominent. The association between BMI and endurance performance was consequently stronger. In the second year, the associations of BMI with VO_2 max and 1000 m run time weakened, although the negative association with VO_2 max persisted. This change was consistent with the increasing benefits associated with physical activity. It suggests that, with longer residence at high altitude and accumulated activity, aerobic capacity increasingly reflects functional adaptation rather than body weight burden alone [21]. Nevertheless, the persistent negative correlation between BMI and VO_2 max in both years indicates that body weight status remains relevant to aerobic capacity and endurance under high-altitude hypoxia. The associations among BMI, VO_2 max, and endurance performance therefore showed stage-specific characteristics. Body weight burden was more prominent during acute adaptation, while factors related to functional improvement became more important during chronic adaptation. Body weight status nevertheless retained an influence throughout. These findings provide a basis for examining the moderating role of physical activity in this pathway.

4.3. Physical Activity and the Moderated Mediation Pathway Linking BMI VO_2 max and 1000 m Run Performance

Building on these correlations, the moderated mediation model was used to examine the role of physical activity in the BMI $\rightarrow$ VO_2 max $\rightarrow$ 1000 m run performance pathway. In the first year, VO_2 max consistently mediated the association between BMI and run time, but moderation of the VO_2 max $\rightarrow$ 1000 m run time pathway by physical activity was not significant. This suggests that, during early adaptation, VO_2 max was related to endurance performance with similar strength at different physical activity levels [20]. Although physical activity may already have influenced aerobic capacity, it had not altered the overall pathway through which BMI was associated with run time via VO_2 max [22].

In the second year, the mediation pathway persisted, and moderation of the $VO_2\text{max} \rightarrow 1000 \text{ m run time}$ pathway by physical activity became significant. This suggests that physical activity began to influence how efficiently aerobic capacity translated into performance [23]. Conditional indirect effects also differed in magnitude between physical activity levels, indicating that during chronic adaptation physical activity may both improve $VO_2\text{max}$ and modify its association with 1000 m run performance.

Together, the findings indicate stage-specific mechanisms underlying aerobic capacity at high altitude. During acute adaptation, BMI had a relatively stable indirect association with endurance through $VO_2\text{max}$, whereas moderation by physical activity had not yet emerged. During chronic adaptation, the accumulated effects of physical activity increased, and moderation of the relationship between $VO_2\text{max}$ and run time became apparent, thereby modifying the strength of the $\text{BMI} \rightarrow VO_2\text{max} \rightarrow \text{endurance performance}$ pathway [24].

This study examined the combined associations of physical activity and body weight status with aerobic endurance under high-altitude hypoxia from both temporal and pathway perspectives. It identified time-dependent associations of physical activity and clarified its role within the pathway through moderated mediation analysis, providing empirical evidence relevant to endurance training and body weight management among university students at high altitude. The marked variation in self-directed extracurricular exercise was also consistent with grouping based on scheduled physical activity exposure, further supporting the moderating role of physical activity in the $\text{BMI} \rightarrow VO_2\text{max} \rightarrow 1000 \text{ m run performance}$ pathway.

5. Conclusion

At an altitude of 3650 m, the associations of physical activity level with aerobic capacity and endurance performance in male university students were markedly time dependent. In the first year, the LPA group had higher $VO_2\text{max}$ and better 1000 m run performance than the HPA group, with no difference in BMI. Following high-altitude exposure and accumulated training over the two academic years, the HPA group surpassed the LPA group on both indicators in the second year and improved relative to the initial assessment. The LPA group declined on both indicators, with only a small increase in BMI. These findings suggest that the benefits of sustained physical activity for aerobic capacity under high-altitude hypoxia require time to emerge, becoming apparent after adaptation to hypoxia and sustained training stimuli.

BMI, $VO_2\text{max}$, and endurance performance in the 1000 m run were consistently linked in male university students, with $VO_2\text{max}$ serving as a central mediator between BMI and endurance. Specifically, BMI was indirectly associated with run time through its negative association with $VO_2\text{max}$: higher BMI corresponded to greater adiposity-related oxygen demand, lower $VO_2\text{max}$, and poorer endurance performance. This mechanism is more pronounced under restricted oxygen availability at high altitude and provides a central physiological rationale throughout the study.

Physical activity moderated this pathway in a time-dependent manner. In the first year, acute hypoxic effects and insufficient accumulated training meant that moderation of the $\text{BMI} \rightarrow VO_2\text{max} \rightarrow 1000 \text{ m run performance}$ pathway had not yet emerged. Indirect effects were significant in both activity groups, but the difference was not evident. In the second year, with chronic adaptation and continued training, moderation became apparent. Higher physical activity attenuated the indirect adverse association of BMI with endurance through $VO_2\text{max}$, whereas lower activity strengthened it. $VO_2\text{max}$ and endurance performance continued to improve in the HPA group and declined in the LPA group, suggesting that physical activity may dynamically reshape the association between BMI and endurance. Variation in self-directed extracurricular exercise further supported the consistent moderating role of physical activity in this pathway.

Overall, aerobic capacity and endurance performance among university students under high-altitude hypoxia improved with adaptation and accumulated sustained physical activity. Physical activity may attenuate the indirect adverse association of BMI with endurance through VO_2max and thereby improve physical fitness. The findings address the three questions posed in the introduction and provide practical guidance for individualized physical education, university fitness interventions, and targeted fitness management at high altitude. They also extend the theoretical account of the BMI $\rightarrow$ VO_2max $\rightarrow$ endurance performance pathway under hypoxic conditions and inform the development of endurance training interventions for young people in such environments.

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