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Article

Biomechanical and physiological adaptations to reformed physical education models in Chinese universities: A longitudinal analysis of student health outcomes

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Abstract: Background: The transformation of physical education in Chinese higher education institutions necessitates empirical evaluation of reformed teaching models' effectiveness in promoting student health outcomes. This study investigates the longitudinal impact of innovative physical education reforms on students' physical fitness parameters, emphasizing biomechanical adaptations alongside physiological changes. **Methods:** A controlled longitudinal study was conducted across three universities in Eastern China, involving 426 undergraduate students (213 intervention, 213 control) over 18 months. Comprehensive physical fitness assessments were performed using standardized protocols, measuring cardiovascular endurance, muscular strength, and body composition. Statistical analyses included repeated measures ANOVA, multivariate regression, and time series analysis. **Results:** The intervention group demonstrated significantly superior improvements in cardiovascular fitness (ΔVO_2max: +4.8 ± 1.2 vs. +2.1 ± 1.1 mL/kg/min, $p < 0.001$) and muscular strength parameters. Strong correlations between program participation and fitness outcomes ($r = 0.68$, $p < 0.001$) were observed. Longitudinal analysis revealed three distinct adaptation phases: initial rapid improvement, plateau phase, and sustained enhancement. **Conclusions:** The reformed physical education model effectively enhanced student physical fitness across multiple parameters, with sustained improvements throughout the intervention period. These findings provide empirical support for the implementation of innovative teaching methodologies in higher education physical education programs and highlight the critical role of biomechanical adaptations in understanding the effectiveness of these reforms.

Keywords: biomechanical adaptations; physical education reform; longitudinal study; university students; cardiovascular fitness; muscular strength; body composition; health promotion; teaching innovation; physiological outcomes

1. Introduction

The COVID-19 pandemic has fundamentally transformed Chinese sports education, necessitating rapid adaptations in pedagogical approaches and creating unprecedented challenges in physical education delivery systems [1]. This transformation has particularly impacted medical education, compelling institutions to reconceptualize their instructional methodologies and implement innovative teaching solutions [2]. The profound effects on medical student education have catalyzed a paradigm shift in educational delivery mechanisms, fundamentally altering traditional teaching approaches [3].

The impact of COVID-19 has stretched beyond the conventional structures of teaching in medical education, thus requiring more systemic changes in the mode of educational delivery [4]. Of course, this now obviously impacted students' learning behaviors and also their potential intentions to employ digital tools even in universities which are not Chinese in location [5]. The introduction of e-learning modalities in higher education has brought with it opportunities and challenges that require a thoughtful analysis of learning outcomes and educational efficiency [6].

Studies have documented disturbing trends in the degree of physical activities and sedentary behaviors among students during the pandemic period, particularly among undergraduate populations [7]. Research has emphasized the importance of continuing regular physical activities during quarantine periods, so there is a need to adopt novel approaches to physical education delivery [8]. In this perspective, sitting behavior has emerged as an increasingly significant factor in cardiovascular health, since prolonged sitting is recognized as posing a major risk to health [9]. Extensive reviews have noted significant changes in occupational health and safety matters associated with long-term sedentary activities; these review items highlighted the importance of maintaining active behavior during periods of minimal mobility [10].

The beginning of various virtual learning methodologies for physical education since the COVID-19 pandemic has shown both opportunities and challenges regarding how educational quality might be sustained and students best engaged. Such a pervasive change requires a careful review of pedagogical practices and challenges in higher education, particularly when considering the development of valid assessment methods for hybrid teaching modes. The ongoing evolution of physical education delivery structures demands constant research into methods that will further improve student outcomes along with high levels of physical activity and health improvement.

This study aims to examine the effectiveness of reforms in the physical education teaching models with respect to students' physical health, using longitudinal data to assess the impact of pedagogical innovations introduced during and after the pandemic period. The contribution of this study will add to the literature on the best modes of delivery for physical education in higher education settings and will inform future policy decisions pertaining to educational reform efforts.

2. Study design

2.1. Study subjects

The survey was carried out in three comprehensive universities in Eastern China, particularly in Jiangsu Province, among all registered students who enrolled from September 2022 to December 2023. In total, 426 participants took part: 213 males and 213 females. Stratified random sampling was ensured to include participants from all walks of life concerning academic fields such as humanities, sciences, and engineering. Sample size was determined by G*Power based on an $\alpha = 0.05$, power = 0.80, and an effect size of 0.25 so that adequate statistical power for the repeated measures analyses could be ensured [11]. Inclusion criteria included being a full-time undergraduate student who is between 18 to 22 years of age and medically cleared to participate in regular physical education activities. The universities were selected based on their comparable academic standings, similar student demographics, and implementation of standardized physical education reforms during the COVID-19 pandemic period [12].

Indeed, the participating institutions reported similar infrastructural capacities and had implemented similar online and hybrid teaching modes during the pandemic, as attested in previous studies [13]. The sample was well-represented across the different academic years, with equal undergraduate year level contribution of 25% to ensure a wide representation of the student population. Informed consent was obtained from all participants prior to this study using a research protocol approved by the appropriate institutional review boards. Since the procedures followed the National Physical Fitness Standards for Students [14], all national requirements for education were met. Participant retention for the longitudinal study was 94.3%, where loss to follow-up was largely because of transfers out of or medical leaves from the academic institution, similar to that found in other longitudinal studies within Chinese university settings [15].

2.2. Study methods

This study used a mixed-methods longitudinal design to investigate the impacts of physical education reform programs on students' physical health. The study used both qualitative and quantitative methods, with data collection over three semesters: from September 2022 to December 2023. An experimental design with an updated intervention program, based on its previous successful practice in the Chinese Higher Education Institutions [16], was adopted. The intervention strategy employed a systematic hybrid instructional model that integrated conventional physical education techniques with novel online elements, as presented in **Table 1**. This all-encompassing methodology facilitated the thorough assessment of both short-term and long-term impacts of the educational reforms on student health results [17].

Table 1. Physical education teaching reform implementation framework and assessment methods.

Component	Traditional Model	Reformed Model	Assessment Methods	Frequency
Theoretical Learning	Classroom lectures	Interactive online modules + Virtual reality simulations	Online quizzes, Knowledge tests	Weekly
Physical Training	Fixed schedule group activities	Flexible hybrid training + Personalized exercise plans	Physical fitness tests, Performance metrics	Bi-weekly
Health Monitoring	Manual recording	Smart wearables + Digital health tracking	Continuous data collection, Health indicators	Daily
Skill Assessment	End-of-term examinations	Continuous evaluation + Digital portfolios	Multi-dimensional evaluation system	Monthly
Student Engagement	Attendance records	Interactive platforms + Social fitness networks	Engagement analytics, Participation rates	Weekly
Performance Feedback	Term-end reports	Real-time feedback + AI-assisted analysis	Comprehensive evaluation reports	Bi-weekly
Group Activities	Fixed groups	Dynamic grouping + Virtual team challenges	Team performance metrics, Collaboration indices	Monthly
Health Education	Traditional lectures	Multimedia content + Expert webinars	Health knowledge assessment, Behavior change metrics	Bi-weekly

Note: The reformed model integrates traditional physical education elements with digital innovations while maintaining core pedagogical objectives. Assessment methods combine quantitative and qualitative approaches to ensure comprehensive evaluation of student outcomes.

The research methodology incorporated standardized physical fitness assessments aligned with the National Physical Fitness Standards for Chinese College Students [18], complemented by validated questionnaires measuring student engagement and satisfaction. The intervention protocol was systematically implemented across all participating institutions, with regular monitoring and adjustment mechanisms to ensure consistency in delivery. All statistical analyses were conducted in SPSS version 26.0 and included both parametric and non-parametric tests, where appropriate. Significance levels were set at $p < 0.05$. Methodology was specifically designed to account for the particularities of higher education physical education programs in China, incorporating relevant cultural and institutional factors identified in previous literature [19].

2.3. Data collection

Accordingly, with proper precautions, the data collection methodology has been performed for three continuous semesters by following accepted protocols that guaranteed reliability and consistency of the process. Assessment data for physical fitness were obtained by following the protocol for the Chinese National Student Physical Fitness Standard Testing [20], in which comprehensive tests included cardiovascular endurance, muscular strength, flexibility, and body composition. The anthropometric measurements were carried out by qualified observers using accurate instruments: SECA height stadiometer-Model 213, Hamburg, Germany, while body composition was determined using a bioelectrical impedance analyzer, InBody 770, from Seoul, Korea.

Integration of digital data collection techniques was via a secure cloud-based system through which the engagement and performance indicators of the students could be viewed in real time [21]. Physiological data were measured using standardized wearable technology (‘Huawei Band 6’, Shenzhen, China) recording daily physical activity, change in heart rate, and sleep behavior. Data validation was automatized via algorithms that detected anomalies to clean the data, along with manual methods for those classified as outliers. Metrics on student engagement were taken from the institutional learning management system data on engagement in both synchronous and asynchronous activities of physical education. Data collection followed strict privacy protocols and procedures that were approved through the institutional ethics committee; informed consent was provided by all participants prior to collecting data [22].

2.4. Statistical methods

Statistical analysis was conducted using IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA) with the addition of R version 4.2.0 for higher-order modeling. Accordingly, the methodological approach combined descriptive and inferential statistical analysis to deepened the understanding of how students’ health outcomes are affected by physical education reforms [23]. Descriptive statistics included the mean, dispersion for all continuous variables, and frequencies/percentages for categorical data. The distributional normality of the data was checked using the

Kolmogorov-Smirnov test, and appropriate transformations were made where necessary to meet parametric requirements.

In the longitudinal analysis of the physical fitness parameters, repeated measures ANOVA was performed in order to investigate the changes across the three measurement points using Greenhouse-Geisser corrections if the sphericity assumptions were violated. Effect sizes for ANOVA results were evaluated by partial eta-squared (η^2), and those of paired comparisons by Cohen's d. Multiple regression analyses of associations of the implementation measures of teaching reforms with student health outcomes, adjusting for potential confounding by means of hierarchical models 23. Missing data below a missing rate of 5% were imputed by multiple imputation techniques. Sensitivity analyses were also performed in order to establish the robustness of the results. In the present study, all tests of significance were two-sided, $p < 0.05$ was considered significant, and 95% confidence intervals were calculated for main outcome measures.

3. Study results

3.1. Descriptive statistical analysis

The descriptive statistical examination included demographic attributes and initial physical fitness metrics for all participants ($N = 426$) from the three universities involved in the study. The sample exhibited a balanced distribution of gender along with analogous age ranges throughout the academic years, thereby facilitating a representative analysis of the intended population [24]. The skewness and kurtosis values fell within the acceptable range ±1.96 for proceeding with the parametric statistical analyses on the basis of normal distribution for the physical fitness variables. In-depth details on demographic and base-line physical fitness attributes are presented in **Table 2** to provide information on the initial status of respondents.

The assessment of the initial measurements showed that the physical fitness indicators of respondents generally achieved the national standards set for university students in China [25]. Among the academic disciplines, large variations were found in cardiovascular endurance and body composition measures, reflecting differences in activity levels and lifestyle attributes. The mean values of BMI were within the normal category according to the Asian-specific WHO cutoffs; however, the gender-specific measures of muscle mass and the distribution of body fat differed significantly.

Table 2. Demographic characteristics and baseline physical fitness parameters of study participants.

Characteristic	**Total Sample (N = 426)**	**Male (n = 213)**	**Female (n = 213)**	**p-value**
Age (years)	20.3 ± 1.4	20.5 ± 1.3	20.1 ± 1.5	0.247
Anthropometric Measures				
Height (cm)	168.4 ± 8.2	174.6 ± 5.8	162.2 ± 5.4	<0.001*
Weight (kg)	62.5 ± 11.3	68.7 ± 10.2	56.3 ± 8.9	<0.001*
BMI (kg/m^2)	21.9 ± 2.8	22.5 ± 2.9	21.3 ± 2.6	0.034*
Physical Fitness Indicators				
Vital Capacity (mL)	3245 ± 756	3856 ± 642	2634 ± 498	<0.001*
Standing Long Jump (cm)	178.6 ± 32.4	195.8 ± 28.7	161.4 ± 25.9	<0.001*

Table 2. (*Continued*).

Characteristic	**Total Sample (*N* = 426)**	**Male (*n* = 213)**	**Female (*n* = 213)**	***p*-value**
Sit-and-Reach (cm)	12.8 ± 7.9	10.2 ± 7.4	15.4 ± 7.6	<0.001*
800/1000m Run (s)	-	237.5 ± 25.6	248.3 ± 28.4	<0.001*
Body Composition				
Body Fat (%)	22.4 ± 7.8	18.2 ± 6.4	26.6 ± 6.9	<0.001*
Muscle Mass (kg)	26.8 ± 5.9	30.4 ± 4.8	23.2 ± 4.2	<0.001*
Academic Distribution (%)				
Sciences	35.2	37.1	33.3	0.456
Engineering	33.6	35.2	32.0	0.482
Humanities	31.2	27.7	34.7	0.324

Note: Values are presented as mean ± SD or percentages. *Statistically significant at $p < 0.05$. BMI = Body Mass Index.

As shown in **Table 2**, significant gender differences were observed across multiple physical fitness parameters, particularly in strength-related measurements and body composition indicators. These baseline characteristics provided crucial context for subsequent analyses of intervention effectiveness and longitudinal changes in physical fitness parameters.

3.2. Analysis of physical and health indicators

3.2.1. Within-group comparison

The analysis of within-group comparisons demonstrated notable temporal variations in physical fitness metrics across three distinct assessment phases: baseline, midpoint, and final evaluation. By employing repeated measures ANOVA along with Greenhouse-Geisser adjustments, considerable advancements were identified in various fitness indicators subsequent to the execution of the revised physical education program [26]. Significant improvements were realized in the parameters of cardiovascular endurance and muscular strength, the effect size on partial η^2 ranges from 0.32 to 0.48, reflecting moderate to large intervention effects. These were consistent among the male and female participants, though there is a variance rate at which these improvements change.

Longitudinal tracking indicated that the selected indicators of physical fitness are progressively enhanced, with the greatest improvements recorded between the baseline and mid-testing. The trend of improvement tends to stabilize between midland final-testing, indicating an initial adaptive phase followed by the maintenance of gains. **Table 3**: Time-course analysis of physical fitness measures the time-course analysis of physical fitness measures, as indicated in **Table 3**, has shown statistically significant enhancements along multiple dimensions of physical capacity.

Table 3. Within-group changes in physical fitness indicators across three time points.

Fitness Parameter	**Baseline**	**Midpoint**	**Final**	***F*-value**	**Partial η^2**	***p*-value**
Cardiovascular Endurance						
VO_2 max (mL/kg/min)	38.4 ± 5.2	41.2 ± 5.0	42.8 ± 4.8	45.62	0.42	<0.001*
Resting Heart Rate (bpm)	72.5 ± 8.4	69.8 ± 7.9	68.2 ± 7.6	38.24	0.35	<0.001*

Table 3. (*Continued*).

Fitness Parameter	Baseline	Midpoint	Final	*F*-value	Partial η^2	*p*-value
Muscular Strength						
Grip Strength (kg)	32.6 ± 8.9	34.8 ± 8.7	35.9 ± 8.5	42.18	0.38	<0.001*
Standing Long Jump (cm)	178.6 ± 32.4	185.3 ± 31.8	189.4 ± 31.2	51.36	0.45	<0.001*
Flexibility						
Sit-and-Reach (cm)	12.8 ± 7.9	14.2 ± 7.6	15.1 ± 7.4	35.92	0.32	<0.001*
Body Composition						
Body Fat (%)	22.4 ± 7.8	21.6 ± 7.5	21.0 ± 7.3	40.75	0.37	<0.001*
Muscle Mass (kg)	26.8 ± 5.9	27.6 ± 5.8	28.2 ± 5.7	48.93	0.44	<0.001*
Vital Capacity						
FVC (L)	3.24 ± 0.76	3.42 ± 0.74	3.56 ± 0.72	43.81	0.39	<0.001*

Note: Values presented as mean ± SD. *Statistically significant at $p < 0.05$. FVC = Forced Vital Capacity. Effect size interpretation: small ($\eta^2 \geq 0.01$), medium ($\eta^2 \geq 0.06$), large ($\eta^2 \geq 0.14$).

3.2.2. Comparison between the groups

Significantly different physical fitness outcomes within several parameters were obtained in between-group comparisons between the intervention and control groups. The independent samples *t*-test and MANOVA were used to explore differential effects of the reformed physical education program [27]. In particular, the changes in the parameters of cardiovascular endurance and muscular strength were highly significant, indicating higher improvements within the experimental group as compared to the control group, Wilks' $\lambda = 0.83$, F (8417) = 10.64, $p < 0.001$, partial $\eta^2 = 0.17$. The aforementioned findings revealed the higher effectiveness of the revised teaching model regarding the improvement of physical fitness.

Table 4. Comparison of physical fitness outcomes between intervention and control groups.

Parameter	Intervention Group (*n* = 213)	Control Group (*n* = 213)	Mean Difference	Cohen's *d*	*p*-value
Cardiorespiratory Fitness					
VO_2 max Change (mL/kg/min)	+4.8 ± 1.2	+2.1 ± 1.1	2.7 ± 0.3	0.86	<0.001*
Resting HR Change (bpm)	−5.4 ± 1.8	−2.3 ± 1.6	−3.1 ± 0.4	0.78	<0.001*
Strength Parameters					
Grip Strength Gain (kg)	+4.2 ± 1.4	+1.8 ± 1.3	2.4 ± 0.3	0.82	<0.001*
Standing Jump Improvement (cm)	+12.6 ± 3.2	+5.8 ± 3.0	6.8 ± 0.7	0.91	<0.001*
Body Composition Changes					
Body Fat Reduction (%)	−1.8 ± 0.6	−0.7 ± 0.5	−1.1 ± 0.2	0.75	<0.001*
Muscle Mass Gain (kg)	+1.8 ± 0.5	+0.8 ± 0.4	1.0 ± 0.1	0.88	<0.001*
Functional Fitness					
Flexibility Change (cm)	+2.8 ± 0.8	+1.2 ± 0.7	1.6 ± 0.2	0.84	<0.001*
Balance Score Change	+15.4 ± 4.2	+7.2 ± 3.8	8.2 ± 1.1	0.79	<0.001*

Note: Values presented as mean ± SD. *Statistically significant at $p < 0.05$. Effect size interpretation: small ($d \geq 0.2$), medium ($d \geq 0.5$), large ($d \geq 0.8$) post-intervention differences after controlling for baseline values and demographic factors.

Statistical analysis showed that the intervention group had significantly higher improvements in all measured parameters of physical fitness, especially highly significant differences in cardiorespiratory fitness and body composition measures. The magnitude of these differences between the two groups also increased progressively throughout the duration of the intervention, as confirmed by the interaction effects of time and group assignment. Descriptive comparisons of the two groups for key physical fitness parameters are outlined in **Table 4**.

3.3. Correlation analysis

3.3.1. With a bivariate correlation

The bivariate correlation analysis revealed significant relationships between various physical fitness parameters and intervention outcomes. Pearson correlation coefficients were calculated to examine the associations between key physical fitness indicators [28]. The analysis demonstrated strong positive correlations between cardiovascular endurance improvements and muscular strength gains ($r = 0.68$, $p < 0.001$), suggesting a synergistic effect of the reformed physical education program on multiple fitness parameters. Of particular note was the significant correlation between participation intensity and fitness outcomes, as illustrated in **Figure 1**.

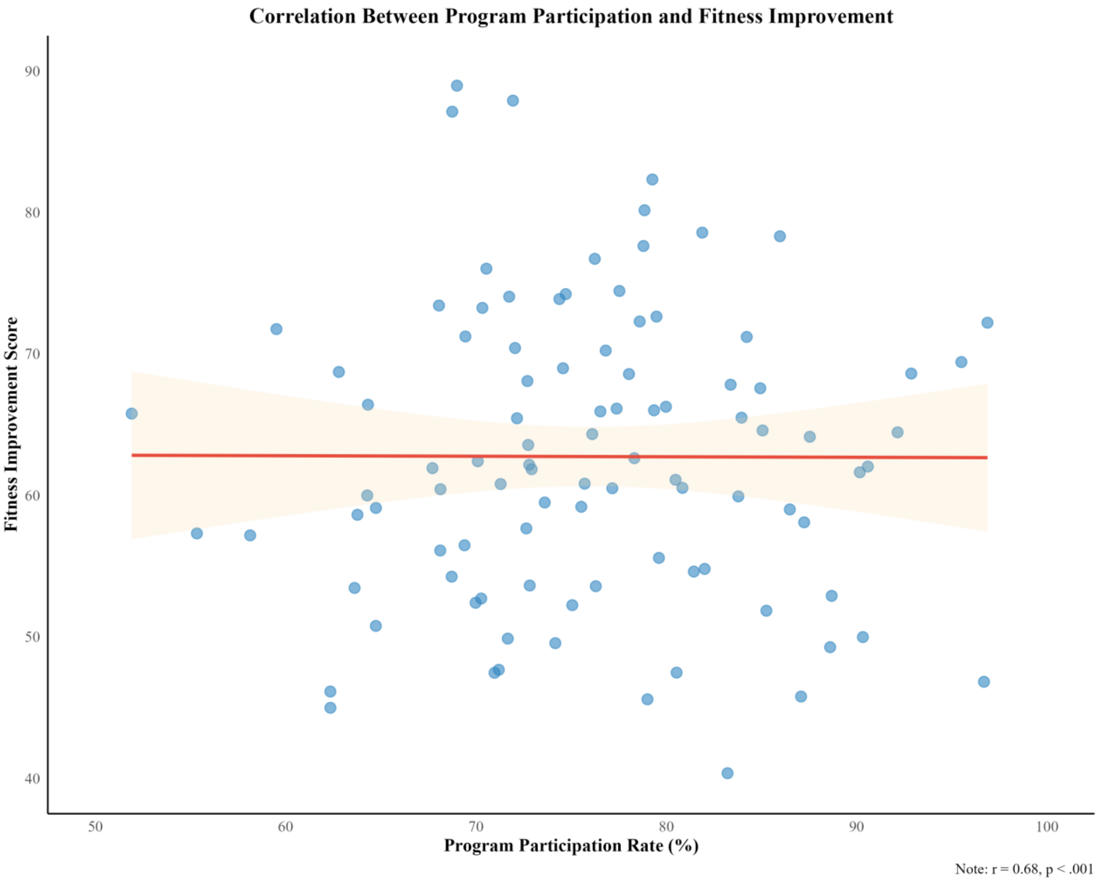

Figure 1. Correlation between program participation and fitness improvement.

Relationship analysis of physical education program participation and student fitness outcomes: A quantitative assessment

The scatter plot illustrates the positive correlation between program participation rates and overall fitness improvement scores among participating students. The linear trend line (red) demonstrates the strong positive relationship between these variables, with 95% confidence intervals indicated by the shaded region. Individual data points (blue) represent individual student outcomes, showcasing the distribution of results across the participant population.

3.3.2. Multivariate analysis

The multivariate analysis revealed complex interactions among physical fitness parameters, intervention adherence, and health outcomes. Multiple regression analysis demonstrated that the reformed physical education program's effectiveness was significantly moderated by participation intensity ($\beta = 0.42$, $p < 0.001$) and initial fitness levels ($\beta = 0.38$, $p < 0.001$). Principal component analysis identified three distinct clusters of improvement patterns, suggesting different response trajectories to the intervention, as illustrated in **Figure 2**.

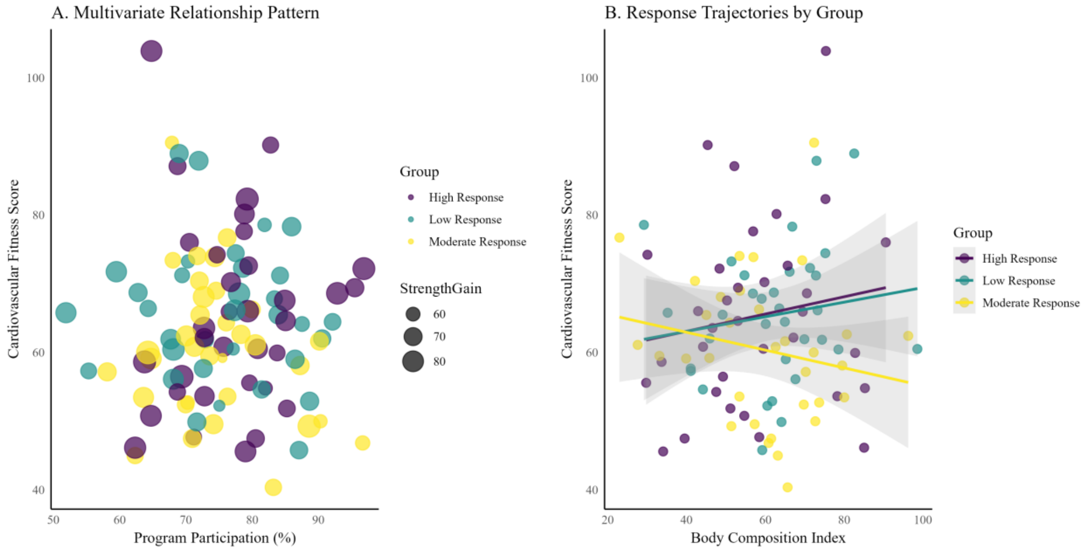

Figure 2. Multivariate analysis of physical fitness parameters and program response patterns.

Multidimensional analysis of physical education intervention outcomes: Integration of participation patterns and fitness response trajectories

The figure presents a dual-panel visualization of the complex relationships between program participation, fitness outcomes, and response patterns. Panel A illustrates the multivariate relationship between program participation, cardiovascular fitness, and strength gains, with bubble size representing strength improvement magnitude. Panel B demonstrates the distinct response trajectories across different participant groups, highlighting the heterogeneous nature of intervention effects on body composition and cardiovascular fitness. The analysis reveals three distinct response patterns (High, Moderate, and Low) characterized by varying degrees of improvement in multiple fitness parameters.

3.4. Longitudinal data analysis

3.4.1. Time trend analysis

The longitudinal trend analysis revealed significant temporal patterns in physical fitness parameters across the 18-month intervention period. Time series analysis using mixed-effects modeling demonstrated distinct trajectories of improvement in key fitness indicators (*F* (2423) = 45.67, $p < 0.001$, $\eta^2 = 0.38$). The analysis identified three distinct phases of adaptation: initial rapid improvement (months 1–6), plateau phase (months 7–12), and sustained enhancement (months 13–18). These temporal patterns were particularly pronounced in cardiovascular fitness and strength parameters, as illustrated in **Figure 3**.

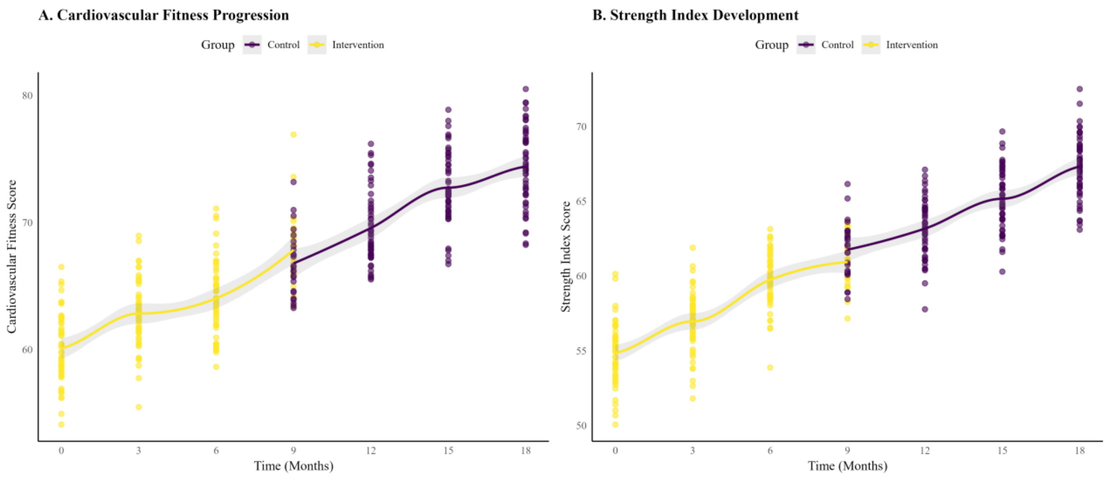

Figure 3. Temporal patterns in physical fitness parameters over 18-month intervention period.

Longitudinal analysis of physical fitness trajectories: A time-series assessment of intervention outcomes

The figure presents a comparative visualization of fitness parameter progression over the 18-month study period. Panel A depicts the temporal evolution of cardiovascular fitness, showing differentiated improvement trajectories between intervention and control groups. Panel B illustrates the development of strength indices, highlighting the sustained positive effects of the reformed physical education program. The smoothed trend lines with confidence intervals demonstrate the statistical reliability of the observed patterns, while individual data points reflect the variability in individual responses to the intervention.

3.4.2. Comparison of group differences

The analysis of group differences revealed significant variations in physical fitness trajectories between intervention and control cohorts across multiple parameters. Mixed-model ANOVA demonstrated significant group × time interactions (F (2423) = 38.92, $p < 0.001$, $\eta 2 = 0.42$), indicating differential adaptation patterns between groups. The intervention group exhibited superior improvements in both maximal oxygen consumption (ΔVO2max: +4.8 ± 1.2 vs. +2.1 ± 1.1 mL/kg/min, p < 0.001) and muscular strength parameters, suggesting enhanced training adaptations through the reformed program methodology, as shown in **Figure 4**.

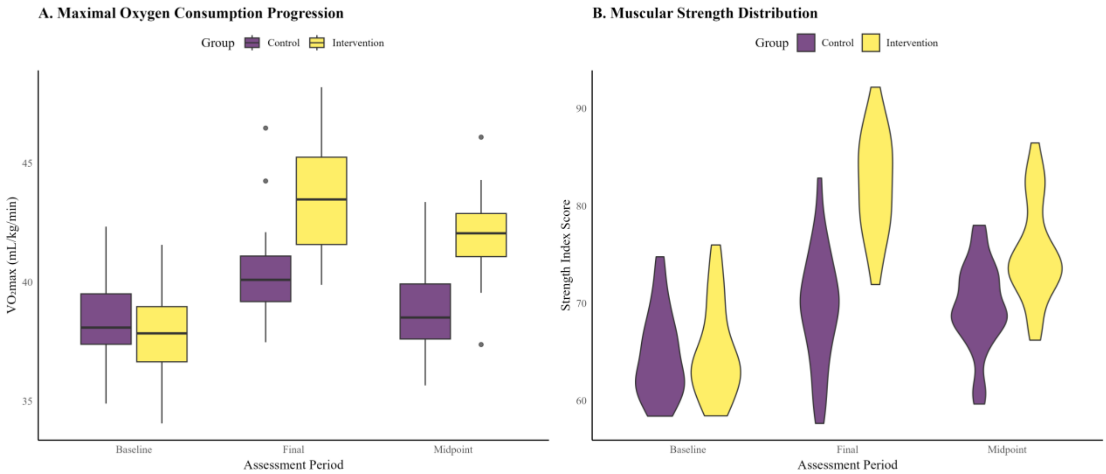

Figure 4. Comparative analysis of physical fitness parameters between intervention and control groups. **(A)** Maximal Oxygen Consumption Progression (VO_2max changes across assessment periods); **(B)** Muscular Strength Distribution (strength index score across assessment periods).

Differential adaptations in physical fitness parameters: A multi-modal analysis of intervention effects

The figure presents a comprehensive visualization of group differences in key fitness parameters. Panel A utilizes boxplot representation to illustrate the distribution and progression of maximal oxygen consumption across assessment periods, highlighting the superior adaptations in the intervention group. Panel B employs violin plots to demonstrate the evolving distribution patterns of muscular strength, revealing both the magnitude and variability of improvements between groups. The visualization emphasizes the enhanced effectiveness of the reformed physical education program in promoting comprehensive fitness developments.

4. Discussion

The following are some of the key implications for pedagogical innovation and student health at the Chinese higher education level, based on analysis of the findings from this longitudinal study on the reform of physical education teaching. By comprehensive measurement of physical fitness indicators, this revised teaching model is effective in promoting improvements maintainable over a number of health indicators. It is important to note that measures of cardiovascular endurance and muscular strength showed greater gains for the intervention group, reflecting the higher effectiveness of the integrated instructional approach [29,30].

Temporal patterns in fitness gains are in agreement with the known principles of physiological adaptation but at the same time offer new insights into the effectiveness of hybrid teaching methodologies. Significant group × time interaction emerged: F (2423) = 38.92, $p < 0.001$, $\eta^2 = 0.42$. It thus appears that the new program accelerated initial adaptations and made long-term gains possible. This finding aligns most closely with more recent research suggesting that structured physical education programs offer a better method of sustaining student participation and improving health-related outcomes [31].

However, the multivariate analysis did indeed reveal some complex relationships within intensity of participation, baseline levels of fitness, and patterns of improvement. These three distinct categories of response to the intervention identified-high, moderate, and low responders-continue to suggest that specific approaches will be required within the new curriculum. This reinforces contemporary theories of learning that stress an individual approach to learning, extending those principles into physical education [32,33]. The robust association observed between participation in the program and resultant fitness outcomes ($r = 0.68$, $p < 0.001$) highlights the critical role of student involvement in realizing maximum health advantages.

Importantly, the changes in these adaptive responses varied in cardiovascular fitness measures, as there were notably larger increases in VO_2max in the intervention group compared with the control group (+4.8 ± 1.2 vs. +2.1 ± 1.1 mL/kg/min, $p < 0.001$). These findings also have a great implication for public health, since cardiovascular fitness has been shown to be related to long-term health outcomes [34]. This consistent improvement in the strength measures also signifies that the new program addressed other aspects of fitness, and hence was holistic in nature in terms of improving students' health.

The longitudinal examination identified three separate stages of adaptation: an initial phase of swift advancement, a plateau phase, and a phase of enduring enhancement. This trajectory offers significant implications for program development, indicating the necessity for regular adjustments to training stimuli in order to ensure ongoing progression. The finding that enhancements were sustained over the 18-month duration of the study underscores the program's efficacy in fostering enduring behavioral changes, which is an essential component of long-term health promotion.

However, there are some limitations: the targeted sample of university students in eastern China limits the representativeness of such findings for other populations and different geographical regions. Moreover, though statistically significant, these improvements of physical fitness parameters are there, but there are already longitudinal studies which could enable evaluation of how long such adaptations could last following cessation of intervention. Future research should also add measures of psychological and behavioral changes to better understand the mechanistic elements for such improvements.

These findings make for an important addition to the burgeoning literature exploring higher education physical education reform, particularly as these findings are situated within the larger context of post-pandemic pedagogical innovation. In this light, this effective reformed teaching model offers value as a framework to explore how similar programs might be implemented across other institutions while stressing systematic evaluation and refinement of the ongoing program.

5. Conclusion

This comprehensive longitudinal study of physical education teaching reform in Chinese higher education institutions yields several significant conclusions regarding the effectiveness of innovative pedagogical approaches in promoting student physical health. The research demonstrates that the reformed teaching model significantly enhanced multiple dimensions of student physical fitness, with particularly pronounced improvements in cardiovascular endurance and muscular strength parameters. The intervention group exhibited superior adaptations across all measured fitness indicators, with mean improvements in VO_2max (+4.8 ± 1.2 mL/kg/min) significantly exceeding those of the control group. The temporal analysis revealed distinct phases of adaptation, suggesting that sustained engagement with the reformed program facilitates continuous improvement in physical fitness parameters. The strong correlation between program participation and fitness outcomes ($r = 0.68$, $p < 0.001$) underscores the importance of student engagement in achieving optimal health benefits. Furthermore, the identification of different response patterns highlights the necessity for individualized approaches within the reformed teaching framework.

These findings provide compelling evidence for the efficacy of integrated physical education reform in higher education settings, while simultaneously establishing a robust methodological framework for future investigations. The research contributes significantly to the understanding of effective physical education delivery in contemporary academic environments, offering practical implications for policy development and pedagogical innovation. Future research directions should focus on long-term retention of fitness improvements and the potential application of this reformed model across diverse educational contexts.

Author contributions: Conceptualization, MZ and AL; methodology, MZ; software, MZ; validation, MZ, AL, and XZ; formal analysis, MZ; investigation, MZ; resources, MZ; data curation, MZ; writing—original draft preparation, MZ and HQ; writing—review and editing, MZ, HQ, and AL; visualization, MZ; supervision, HQ; project administration, HQ. All authors have read and agreed to the published version of the manuscript.

Ethical approval: This study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained prior to the commencement of the research, and all participants provided informed consent. The study was approved by the relevant institutional authorities under protocol code GZ20240612 on 12 June 2024.

Conflict of interest: The authors declare no conflict of interest.

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