Bielik *et al. BMC Pediatrics* (2025) 25:20
https://doi.org/10.1186/s12887-024-05353-2

BMC Pediatrics

RESEARCH

Open Access

The prediction model of academic achievement based on cardiorespiratory fitness and BMI status for ninth-grade students

Viktor Bielik[1*†], Vladimír Nosáľ[2†], Libuša Nechalová[1,3], Milan Špánik[4], Katarína Žilková[5] and Marian Grendar[6†]

Abstract

The purpose of this study was to predict an academic achievement model based on cardiorespiratory fitness (CRF) and body mass index (BMI) in ninth-graders. The study sample included 6 530 adolescents from 341 public schools in Slovakia. Criterion-referenced competency tests measuring academic performance in mathematics and mother language (Slovak), CRF, and BMI were assessed in the academic year 2022–2023. The results from the Random Forest Regression (RFR) machine learning algorithm suggest that adolescents who meet the international CRF and BMI criterion-referenced standards have a higher probability of getting a higher academic achievement score than unfit students with overweight or obesity. The chances of achieving the highest level of academic performance rose by 165% in mathematics and by 484% in mother language for boys who were fit and of normal weight compared to unfit boys with obesity. Unfit boys with obesity and unfit overweight girls had significantly lower odds of having the highest level of academic achievement compared to fit and normal-weight adolescents in mathematics (OR = 0.38; 95% CI, 0.20–0.71; $p = 0.003$; OR = 0.32; 95% CI, 0.18–0.55; $p < 0.001$) and mother language, respectively (OR = 0.17; 95% CI, 0.09–0.34; $p < 0.001$; OR = 0.17; 95% CI, 0.08–0.38; $p < 0.001$). Our results suggest that CRF is a significant predictor, with fit and normal-weight boys showing higher odds of better academic performance, but the model's modest predictive power suggests other factors also play a role.

Key message

What is known:

• Previous research has demonstrated a significant relationship between weight status, physical fitness, and academic performance, primarily by evaluating students' grades at the end of the school year. Yet, the predictive power was unknown.

†Viktor Bielik, Vladimír Nosáľ and Marián Grendár contributed equally to this work.

*Correspondence:
Viktor Bielik
viktor.bielik@uniba.sk

Full list of author information is available at the end of the article

What is new:

• Unlike previous studies that focused on end-of-year grades, this research used criterion-referenced tests and a multivariate multinomial logistic regression model to find that cardiorespiratory fitness is a significant predictor of academic achievement, with fit and normal-weight boys showing the highest odds of better performance.

Keywords Academic performance, Physical fitness, Random forest machine learning, School-aged children

Introduction

Physical fitness and regular physical activity, including sports participation, have been linked to several physical health benefits for children and adolescents, including improved cardiovascular risk [1] factors, increased bone mineral content and density [2], favorable lean body mass [3], and the prevention of metabolic syndrome and type 2 diabetes [4, 5]. In addition to physical benefits, findings from the meta-analysis suggest that physical exercise can improve mental health in schoolchildren [6]. Furthermore, regular exercise has been associated with decreased anxiety and depression symptoms, improved mood, better stress management, and higher self-esteem and confidence [7, 8]. Therefore, teenagers' happiness and mental health are significantly influenced by physical activity [9].

Another significant benefit of physical fitness for schoolchildren is brain health and cognition [10]. Cardiorespiratory fitness (CRF) may be associated with functional connectivity between the frontal and hippocampus subregions in children with overweight or obesity [11]. Thus, better cognitive function could lead to better academic results. However, the results of a single-factor BMI analysis showed a weak, nonlinear correlation with academic achievement [12]. Additionally, the "fat but fit" paradigm suggests that CRF levels can mitigate the impact of obesity on certain cardiometabolic risk factors and health-related quality of life in schoolchildren [13]. Some findings revealed that increases in CRF may positively influence the development of specific brain regions and academic indicators, thereby mitigating the harmful effects of overweight and obesity on brain structure during childhood [14]. Several other studies have found a significant association between academic performance and the combined effects of weight status and physical fitness [15–17]. In contrast, CRF, estimated from performance in the 20-meter shuttle run or assessed using a graded maximal cycle ergometer test, did not show a significant association with academic grades in language and mathematics when considered as a single factor [18, 19].

Though, most of the research reported academic achievement based on students' marks at the end of the academic year [19, 20]. It is possible that the approaches used by teachers to assess students' performance based on grades may have differed not only across the country but also within the school. Thus, the purpose of this study was to use standardized external testing in mathematics and Slovak language to examine the relationship between academic performance, body weight status, and CRF among ninth-grade students in a larger cohort.

Several machine learning models have been employed to predict academic performance; however, the findings regarding physical fitness factors remain limited [21]. Findings from ensemble learning models highlight the combined influence of factors such as sex, physical fitness, and body composition on the academic achievement of primary school students [22]. Therefore, this study had the ambition to predict a model of academic achievement based on sex, physical fitness, and BMI status for ninth-grade students.

Methods and materials

Study design and participants

This project was applied to students from 341 public schools distributed in all eight regions of Slovakia in the academic year 2022–2023. It was part of the national physical fitness project of the Slovak Olympic and Sports Committee (OLOV). More details about the OLOV project are described elsewhere [23]. OLOV issued a call for participation in the project, which was distributed to all elementary schools at the beginning of the academic year. Students and their parents were informed through their homeroom and physical education teachers. The academic performance of 6 530 adolescents in the ninth grade, ranging in age from 15 to 16 years, was included in the treatment of the data for further analysis. Eligibility required complete data for both cardiorespiratory fitness (CRF) and body mass index (BMI), as well as valid results from criterion-referenced academic tests in Mathematics and Slovak language.

The study received approval from the Ethic Committee of the Faculty of Physical Education and Sport at the Comenius University of Bratislava (No. 06/2024), National Institute of Education and Youth in Slovakia, Slovak Olympic and Sports Committee, and the principals of each of the included schools. The study met criteria and ethical standards in sport and exercise science research [24]. All participants were fully informed about the objectives of the study, and informed written consent was obtained from their legal guardians.

Measures and procedures

The academic performance in mathematics and Slovak language (mother language) of all ninth-grade students was assessed on March 22 and 23, 2023, using state-based (MONITOR) for all primary schools. The preparation and implementation of testing lies in the competence of the Department of Evaluation Tools Development for Lower Secondary Education, which continues in the school year 2011/2012 in accordance with Law No. 245/2008 on education (School Act) and amending acts and the Regulation of Ministry of Education No. 320/2008 on primary schools. More details about the MONITOR are described elsewhere [25]. For data analysis in the current study, students were grouped into 5 levels of academic achievement.

To assess the physical fitness of ninth-grade adolescents, the standardized student test battery EUROFIT was applied [26]. The EUROFIT includes numerous health-related and skill-related fitness tests widely used in European countries [27]. The Leger formula [28] has been used to estimate maximal oxygen uptake (VO_2max) from performance on the 20-meter shuttle run test and assess CRF against international criterion-referenced standards for healthy CRF [29]. The formula is as follows:

$$\begin{aligned} \mathrm{VO_2max\ (ml/kg/min)} = 31.025 + 3.238 \times \ \mathrm{speed\ (km/h)} \\ - 3.248 \times \ \mathrm{age\ \ (years)} \\ + 0.1536 \times \ \mathrm{speed\ (km/h)} \times \ \mathrm{age\ \ (years)} \end{aligned}$$

Where:

- Speed (km/h): The final speed reached during the shuttle run, which corresponds to the last completed stage.
- Age (years): The participant's age.

The international criterion-referenced standards of 42 and 35 ml/kg/min for boys and girls, respectively, for healthy CRF were applied to distinguish between fit and unfit adolescents [29]. Physical fitness, weight, and height were collected during physical education classes in the academic year 2022/2023. Physical education teachers were supervised by experienced examiners to avoid errors in measurement and collection of data.

Body weight was assessed to the nearest 0.1 kg wearing minimal clothes and without shoes, and height was measured to the nearest 0.1 cm. BMI was calculated by the formula [weight (kg)/height (m)^2]. According to the sex- and age-related criteria established by the International Obesity Task Force, participants were divided into three categories: normal weight, overweight, and obesity [30].

Data analysis

The contingency table of academic performance scores from mathematics and Slovak language against a binned number of rounds was normalized by rows (to get the proportion of students in a number of rounds bin for a fixed subject exam score). The row-normalized contingency table was visualized by Heatmap. Multinomial logistic regression was used to model the association between a score from Mathematics (Slovak language) and a factor status obtained as an interaction of sex (levels: girl, boy), fitness (levels: fit, unfit) and weight (levels: normal weight, overweight, obesity). Using the Wilkinson-Rogers notation, the model can be stated as follows: response ~ age + region + status, where the factor status was formed as the Cartesian product of sex, fitness, and weight factors. Subjects with less than 10 completed shuttles (CRF test) and with more than 100 shuttles were excluded from analyses. Furthermore, underweight adolescents were excluded from analysis. Based on the model fit, the Odds Ratios (OR) were computed together with their 95% confidence intervals and p-values. The model was also used to obtain predictions of class and to quantify the classification ability of the predictors by the correct classification rate. Effect size (goodness of fit) in the multinomial regression was quantified by McFadden's R^2. For all tests, statistical significance was set at $p < 0.05$. In addition to the multinomial logistic regression, Random Forest for Regression (RFR) was trained on the entire dataset, using the default settings. The predictors used were school, town, region, BMI, sex, number of shuttles and age. Importance of predictors was assessed by the Variable IMPortance (VIMP). Predictive power was quantified by the Out-of-Bag (OOB) R^2. OOB-based partial dependence conditional plots (coplots) were constructed using the OOB data to assess the dependence of the predicted values on predictors, conditioned upon sex [31–39].

Results

Data were analyzed from a total of 341 schools from all eight regions of Slovakia. A total of 6 877 children began the survey from which 347 children did not provide informed written consent or valid ID's or identifying information and were not included in the analyses. This resulted in a total available sample of 6 324 children, with boys making up 53% of the sample. The sample characteristics are presented in Table 1.

The RFR algorithm has identified the number of shuttles as the most important predictor of the academic achievement both in Mathematics and Slovak language (Fig. 1). For Mathematics, the second most important predictor was Town, and its importance was half of that of the number of shuttles. In the case of Slovak language, the second most important predictor was sex, and its

Table 1 The sample characteristics

Characteristic [*n* (%)]	Boy (*n* = 3 360)	Girl (*n* = 2 964)
Age		
15	1 853 (55%)	1 824 (62%)
16	1 507 (45%)	1 140 (38%)
Cardiorespiratory fitness		
Fit	1 479 (44%)	1 176 (40%)
unFit	1 881 (56%)	1 788 (60%)
BMI		
Normal	2 517 (75%)	2 367 (80%)
Obesity	327 (9.7%)	150 (5.1%)
Overweight	516 (15%)	447 (15%)
Status (CRF_BMI)		
Fit_Normal	1 304 (39%)	1 062 (36%)
Fit_Obesity	24 (0.7%)	13 (0.4%)
Fit_Overweight	151 (4.5%)	101 (3.4%)
unFit_Normal	1 213 (36%)	1 305 (44%)
unFit_Obesity	303 (9.0%)	137 (4.6%)
unFit_Overweight	365 (11%)	346 (12%)
Academic achievement in mathematics		
Level 0: [0,20]	173 (5.1%)	220 (7.4%)
Level 1: (20,40]	664 (20%)	663 (22%)
Level 2: (40,60]	979 (29%)	789 (27%)
Level 3: (60,80]	849 (25%)	803 (27%)
Level 4: (80,100]	695 (21%)	489 (16%)
Academic achievement in mother language		
Level 0: [0,20]	141 (4.2%)	97 (3.3%)
Level 1: (20,40]	696 (21%)	370 (12%)
Level 2: (40,60]	1 052 (31%)	849 (29%)
Level 3: (60,80]	983 (29%)	1 022 (34%)
Level 4: (80,100]	488 (15%)	626 (21%)

Discrete variables were summarized by counts and percentages. Academic achievement is a five-level ordinal variable: 0 [0,20]; 1 (20,40]; 2 (40,60]; 3 (60,80]; and 4 (80,100]. Abbreviations: CRF cardiorespiratory fitness, BMI body mass index

importance was only by 20% lower than that of the number of shuttles. Predictive power, as measured by the OOB method, was for both responses (Mathematics, Slovak language) modest (R^2=0.12, 0.13; respectively).

Partial dependence conditional plots, derived from the trained RFR machine learning algorithm, were used to visualize the net impact of predictors on the response variable. Figures 2 and 3 display these plots for number of shuttles and BMI predictors, and mathematics/Slovak language response, conditional on sex.

Contingency table of categorized subject academic achievement score vs. fitness and BMI class was visualized by the heatmap for boys (Fig. 4) and girls (Fig. 5). The results of the multinomial logistic regression, using the unFit+Obesity classification as the reference group, are shown in Table 2. Fit+normal weight boys compared to unFit+BwO had significantly higher odds for having a greater level of academic achievement in Slovak language: level 3 (OR=3.47; 95% CI, 1.93–6.24; p<0.001), and level 4 (OR=5.84; 95% CI, 2.92–11.67; p<0.001). In mathematics Fit+normal weight boys compared to unFit+BwO had significantly higher odds for having the greatest level of academic achievement (OR=2.65; CI, 1.41– 4.99; p<0.001). Higher odds for having better academic achievement were not significant when Fit+normal weight girls where compared with unFit+GwO.

The results of the multinomial logistic regression when Fit+normal weight classification has been used as a reference are shown in Table 3. UnFit+BwO compared to Fit+normal weight boys had significantly lower odds for having a greater level of academic achievement in Slovak language: level 3 (OR=0.29; 95% CI, 0.16–0.52; p<0.001); and level 4 (OR=0.17; 95% CI, 0.09–0.34; p<0.001). Simiriarly, in mathematics unFit+BwO compared to Fit+normal weight boys had significantly lower odds for having a greater level of academic achievement (OR=0.38; 95% CI, 0.20–0.71; p=0.003). Unfit+Overweight girls compared to Fit+normal weight girls had significantly lower odds for having a greater level of academic achievement in Slovak language level 3 (OR=0.33; 95% CI, 0.15–0.72; p=0.005); and level 4 (OR=0.17; 95% CI, 0.08–0.38; p<0.001). Simiriarly, in mathematics unfit+Overweight girls compared to Fit+normal weight girls had significantly lower odds for having a greater level of academic achievement: level 3 (OR=0.43; 95% CI, 0.26–0.71; p<0.001), and level 4 (OR=0.32; 95% CI, 0.18–0.55; p<0.001).

Discussion

In this cross-sectional study, we hypothesized that there would be a combined relationship between cardiorespiratory fitness (CRF) and body weight status with academic performance in ninth-grade students. Furthermore, we hypothesized that CRF would be a stronger predictor of higher academic achievement than BMI in both young males and females. Our results from the RFR machine learning algorithm suggest that adolescents who meet the international CRF and BMI criterion-referenced standards have a high probability of getting a higher academic achievement score than those who do not meet the standards (unfit, overweight, or obesity). Among the factors thought to impact primary school students' academic performance, the VIMP ranking produced by the RFR algorithm identified CRF as the most significant. However, the predictive capability of the algorithm was modest. It is important to highlight that the association between academic achievement and CRF, as revealed by the RFR, is not linear. Attaining a criterion-referenced standard level of fitness is correlated with an increased likelihood of achieving higher academic scores. Similarly to our results, machine learning models such as random forest, support vector machine, and K-nearest neighbor demonstrated predictive power for academic

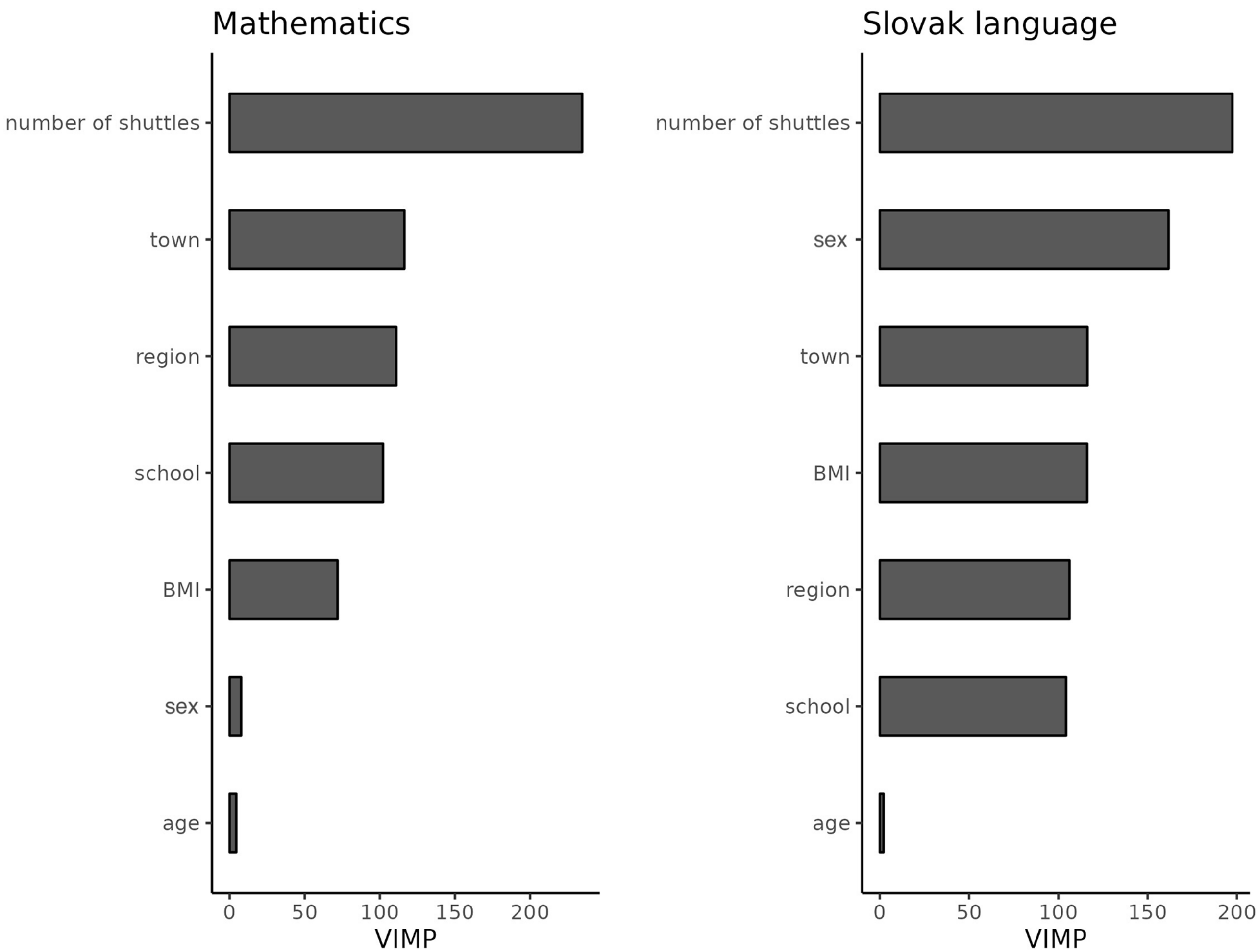

Fig. 1 Variable Importance (VIMP) plot for Mathematics (left panel) and Slovak language (right panel), derived from their respective Random Forest Regression (RFR) models. In each panel, the predictors (independent variables) are displayed along the y-axis, ranked according to their importance in predicting the outcome variable. The importance of each predictor is quantified using the VIMP metric, which is shown on the x-axis. Higher VIMP values indicate greater importance in the predictive model

performance in relation to the physical fitness of primary school students [21].

To be certain of our results, sedentary behaviors and factors increasing body fat and lowering CRF were previously negatively associated with academic achievement as assessed from school reports [20, 40]. It was shown that to predict academic performance, there is an interdependent association, and additional adjustments, e.g., CRF, need to be addressed [19]. Upon examining the joint relationship between CRF and BMI, it was found in this study that the chances of achieving the greatest level of academic achievement rose by 165% in mathematics and 484% in Slovak language for boys who were fit and of normal weight compared to reference (unfit boys with obesity). From another perspective, being both unfit and either with obesity or overweight was associated with lower chances of excelling academically in our population. Notably, unfit boys with obesity and unfit overweight girls had significantly lower odds of achieving higher academic performance in Slovak language and mathematics compared to their fit and normal-weight peers. We must admit that higher odds for having better academic achievement was not significant when fit and of normal weight girls were compared to unfit girls with obesity. A possible rationale for this observation could be the lower percentage of girls with obesity in our cohort (5.1. %). Additionally, we observed higher academic performance in Slovak language among girls compared to boys (Table 1). This finding aligns with the results of a meta-analysis, which indicates that the female advantage is most pronounced in language courses and less significant in math courses [41]. Furthermore, the VIMP plot for Slovak language, derived from the RFR model in this study, identified sex as the second most significant predictor of student academic performance. Our findings suggest that the combination of fitness and BMI components could be a predictor of higher academic achievement, and it also confirmed the previous findings for

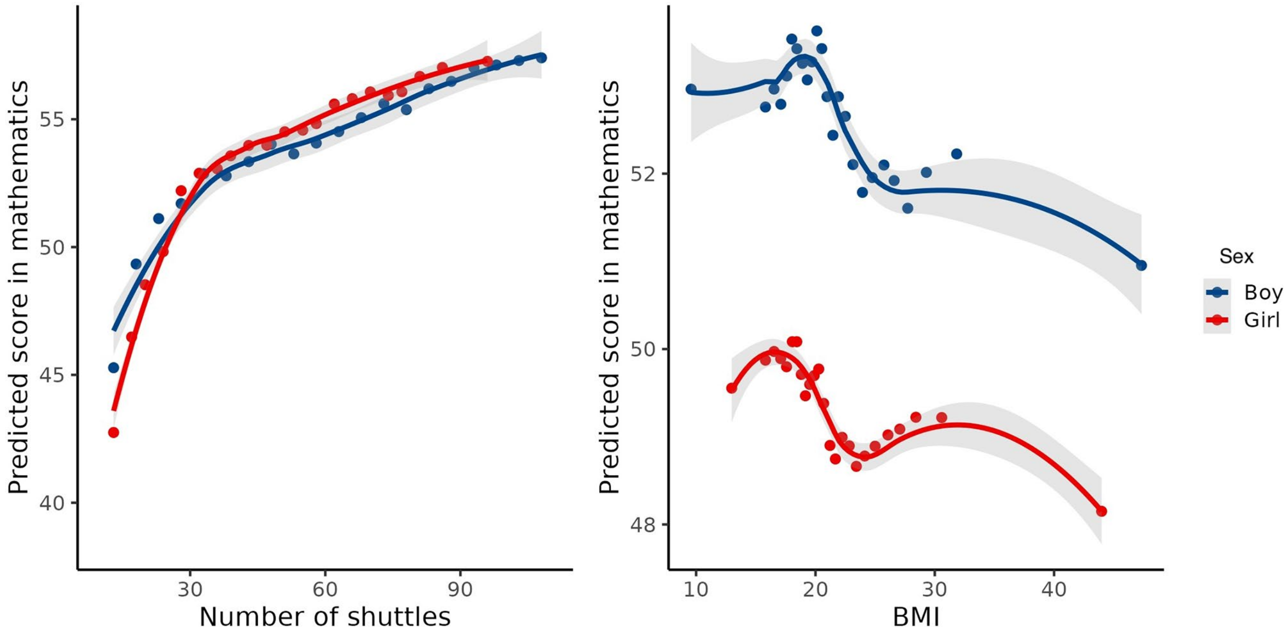

Fig. 2 Partial dependence plots illustrating the relationship between the predicted academic achievement scores in Mathematics (y-axis) and two key predictors: the number of rounds completed in a 20-meter shuttle run (left panel) and Body Mass Index (BMI) (right panel). In each plot, the x-axis represents the range of values for the respective predictor, while the y-axis shows the corresponding predicted values of academic achievement based on the Random Forest Regression (RFR) model

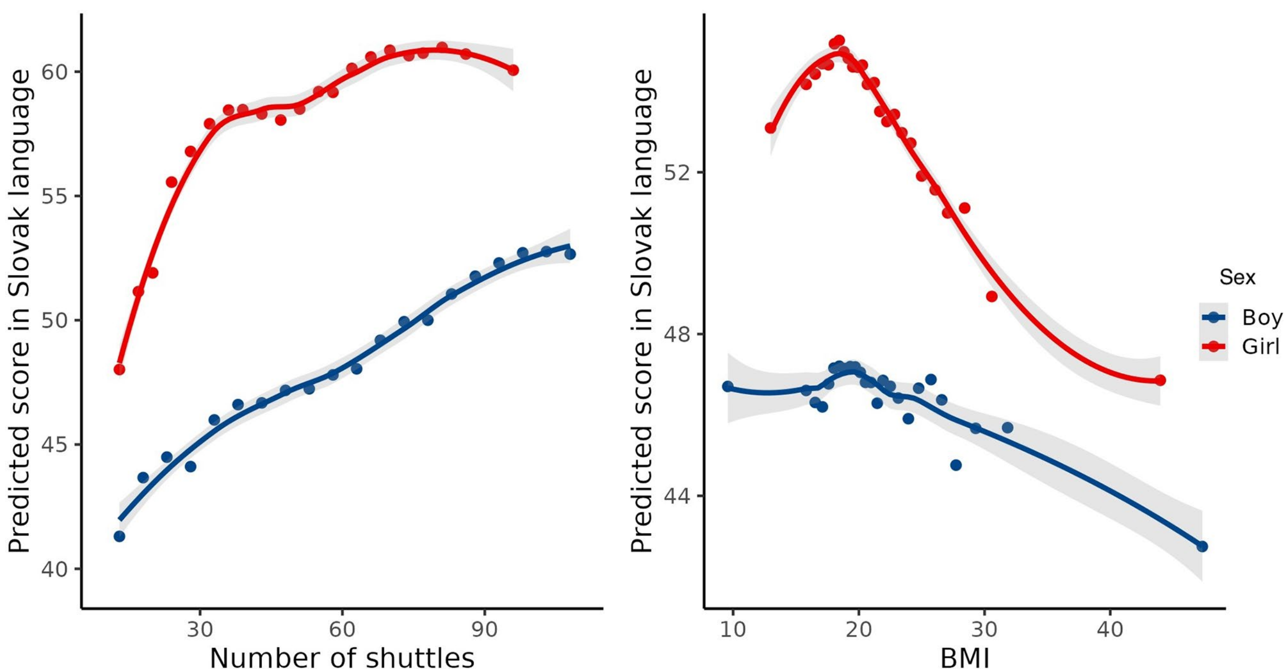

Fig. 3 Partial dependence plots illustrating the relationship between the predicted academic achievement scores in Slovak language (y-axis) and two key predictors: the number of rounds completed in a 20-meter shuttle run (left panel) and Body Mass Index (BMI) (right panel). In each plot, the x-axis represents the range of values for the respective predictor, while the y-axis shows the corresponding predicted values of academic achievement based on the Random Forest Regression (RFR) model

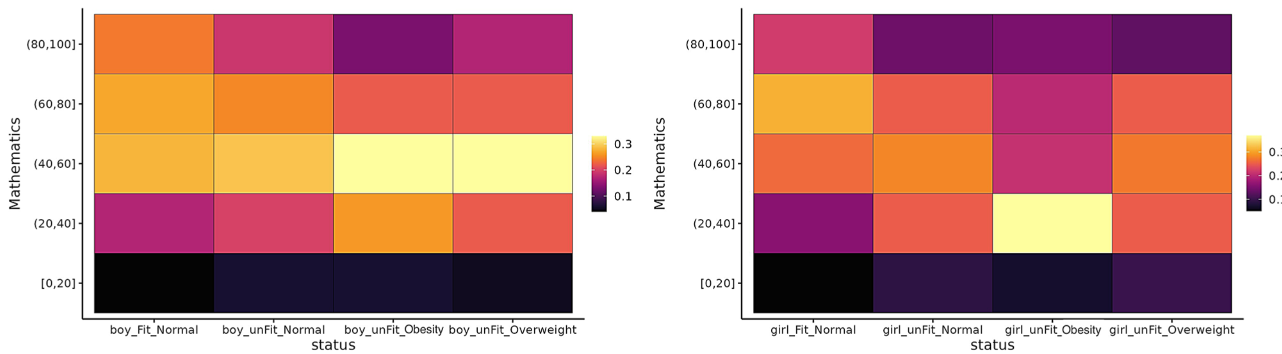

Fig. 4 Heatmap of the contingency table, represented as a mosaic plot, visualizes the relationship between academic achievement scores in Mathematics and categories of physical fitness and Body Mass Index (BMI) among boys and girls. In this plot, the rows correspond to different academic achievement score ranges, while the columns represent distinct fitness and BMI classes. The plot is color-coded to reflect the frequency distribution within each category combination. The sum of each column is normalized to 1, indicating that the values within each column represent proportions rather than absolute counts

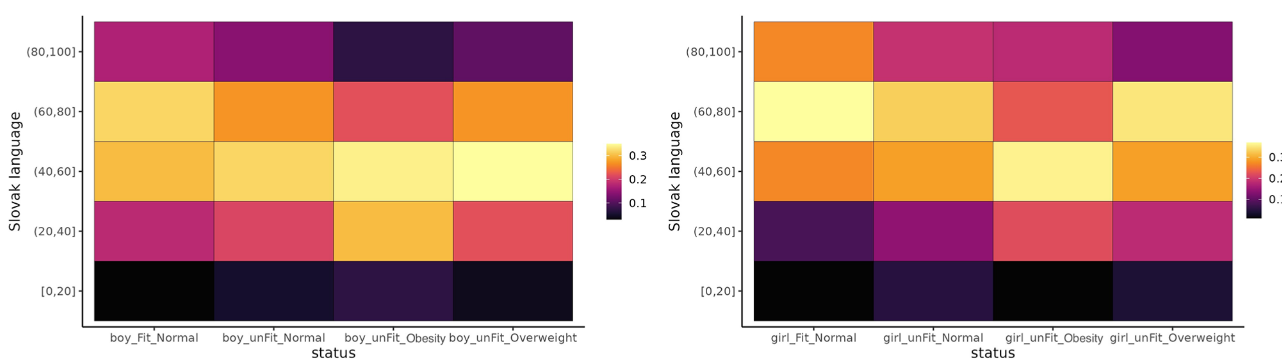

Fig. 5 Heatmap of the contingency table, represented as a mosaic plot, visualizes the relationship between academic achievement scores in Slovak language and categories of physical fitness and Body Mass Index (BMI) among boys and girls. In this plot, the rows correspond to different academic achievement score ranges, while the columns represent distinct fitness and BMI classes. The plot is color-coded to reflect the frequency distribution within each category combination. The sum of each column is normalized to 1, indicating that the values within each column represent proportions rather than absolute counts

the combined effects of weight status and CRF [42]. It remains unanswered, however, whether a single CRF factor could independently, based on impaired weight status, predict better academic performance. When analyzing the CRF factor adjusted for BMI, we reported low number of fit and subjects with obesity (0.7% of boys and 0.4% of girls).

It is an interesting possibility, though, to validate the reversible impact of BMI and CRF on academic achievement in a large student sample using a prospective study design. The results of a longitudinal study design showed that students who increased CRF achieved better school marks compared with those who were unfit at both the beginning and end of the intervention [17]. The other study on finish students (9–5 years old) reported that changes in CRF were positively associated with changes in academic achievement during repeated spring assessments [43]. Interestingly, data collected from a single public district showed that the less-fit students improved in national mathematics percentile rankings more than lower academic performers when comparing changes between spring and fall assessments [44]. Noteworthy, the positive association was observed independently from CRF between weight improvements and academic performance after a 2-year follow-up [45].

The association between weight status, physical fitness, and academic success is still not clearly explained. Several studies have shown that children and adolescents with poor physical fitness and impaired weight status (overweight or obesity) are at risk of impaired brain health [10, 46]. A range of structural brain changes, such as alterations in cortical gray matter thickness and the integrity of white matter tracts, have been observed in connection with CRF. These changes may be linked to the effects of CRF on angiogenesis, neurogenesis, and neuroplasticity through increased levels of brain-derived neurotrophic factor [47]. Furthermore, higher CRF and motor skills in children up to 13 years of age were associated with more efficient cognitive processing at the neuroelectric level, greater hippocampal and basal ganglia volumes, and better inhibitory control in tasks requiring rigorous attention allocation. The study on twenty-four healthy 8- to

Table 2 Multivariate multinomial logistic regression predicting level of academic achievement

	Slovak (mother language)			
	1; OR (95% CI)	**2; OR (95% CI)**	**3; OR (95% CI)**	**4; OR (95% CI)**
boy_Fit_Normal	1.46 (0.82–2.61)	2.09 (1.18–3.70) **	3.47 (1.93–6.24) ***	5.84 (2.92–11.67) ***
boy_Fit_Obesity	> 100 000 (0.00 – Infinity)	> 100 000 (0.00 – Infinity)	> 100 000 (0.00 – Infinity)	> 100 000 (0.00 – Infinity)
boy_Fit_Overweight	2.35 (0.65–8.52)	3.66 (1.04–12.94) *	6.67 (1.88–23.61) **	8.95 (2.32–34.51) ***
boy_unFit_Normal	0.96 (0.55–1.65)	1.28 (0.75–2.19)	1.70 (0.97–2.97)	2.90 (1.49–5.67) **
boy_unFit_Overweight	1.44 (0.69–3.02)	2.05 (0.99–4.23)*	2.41 (1.15–5.08) *	3.18 (1.35–7.50) **
girl_Fit_Normal	0.40 (0.08–1.85)	0.83 (0.18–3.78)	1.73 (0.37–7.97)	1.69 (0.36–7.91)
girl_Fit_Obesity	> 100 000 (0.00 – Infinity)	0.31 (0.02–3.92)	0.19 (0.01–2.90)	0.17 (0.01–2.78)
girl_Fit_Overweight	0.22 (0.03–1.87)	0.63 (0.08–4.74)	1.34 (0.18–10.11)	1.18 (0.15–9.14)
girl_unFit_Normal	0.21 (0.05–0.89) *	0.25 (0.06–1.07)	0.45 (0.10–1.92)	0.33 (0.08–1.44)
girl_unFit_Overweight	0.32 (0.07–1.49)	0.31 (0.07–1.45)	0.58 (0.12–2.69)	0.28 (0.06–1.36)
	Mathematics			
	1; OR (95% CI)	**2; OR (95% CI)**	**3; OR (95% CI)**	**4; OR (95% CI)**
boy_Fit_Normal	0.97 (0.53–1.75)	1.27 (0.71–2.27)	1.73 (0.95–3.15)	2.65 (1.41– 4.99) **
boy_Fit_Obesity	1.16 (0.13–10.55)	1.07 (0.12–9.49)	1.31 (0.14–12.00)	3.19 (0.36–28.07)
boy_Fit_Overweight	0.83 (0.34–2.05)	0.77 (0.32–1.88)	1.23 (0.50–3.00)	1.83 (0.72–4.61)
boy_unFit_Normal	0.75 (0.42–1.33)	0.83 (0.47–1.46)	1.05 (0.58–1.87)	1.41 (0.76–2.62)
boy_unFit_Overweight	0.99 (0.48–2.03)	1.14 (0.57–2.29)	1.12 (0.54–2.31)	1.50 (0.70–3.21)
girl_Fit_Normal	0.58 (0.27–1.26)	1.62 (0.72–3.64)	2.04 (0.90–4.61)	1.84 (0.79–4.28)
girl_Fit_Obesity	0.73 (0.07–7.39)	0.63 (0.05–7.90)	1.64 (0.16–16.23)	0.41 (0.02–7.45)
girl_Fit_Overweight	0.98 (0.27–3.55)	2.47 (0.68–8.95)	2.38 (0.65–8.73)	1.76 (0.45–6.81)
girl_unFit_Normal	0.48 (0.23–1.01)*	0.94 (0.43–2.05)	0.92 (0.42–2.02)	0.65 (0.28–1.47)
girl_unFit_Overweight	0.46 (0.20–1.03)	0.85 (0.36–1.98)	0.88 (0.37–2.07)	0.59 (0.24–1.45)

Academic achievement is a five-level ordinal variable: 0 [0,20]; 1 (20,40]; 2 (40,60]; 3 (60,80]; and 4 (80,100]. Based on the model (Unfit_Obesity as reference), the Odds Ratios (OR) were computed together with their 95% confidence intervals and p-values for the null hypothesis that the population OR is 1. * $p<0.05$; ** $p<0.01$; *** $p<0.001$

10-year-old children revealed differences in regional gray and white matter development in the brain and differences in white matter microstructures between normal-weight and healthy children with obesity [48]. Although the amount of research on the subject is limited, brain structure impairment in pediatric obesity is associated with poor executive function and attention [49]. To confirm the importance of brain health, results showed that gray matter volume in the bilateral hippocampal formation and the right inferior frontal gyrus is associated with a higher school-based mathematics score [50].

This is an observational study. The usual caveats for drawing conclusions from observational studies apply. Causal claims cannot be made. The set of predictors studied had a poor goodness of fit for academic achievement scores. Since the other predictors (grade for the subject from the last school year, IQ, socioeconomic status of either participants or schools, etc.) are not included in the predictor set, and this is an observational study, there is no guarantee that the character of the association of the subject score and fitness (increasing one) would be present were the key predictors available. The use of the 20 m shuttle run in this study can be viewed as both a strength and a limitation. While it facilitates the inclusion of a large population, it provides only an estimate of an individual's CRF, which can be more accurately measured using direct maximal tests, such as cardiopulmonary exercise tests. However, the reliability and validity of the 20 m shuttle run for assessing CRF in adolescents aged 12–15 years have been well established in previous research [51]. For the purpose of the analyses, state-based, criterion-referenced competency tests were used to assess the academic performance of 6 530 ninth-grade adolescents (15%) from all 44 936 students tested in the country on the same day in mathematics and Slovak language.

Our study highlighted the importance of CRF in predicting academic achievement among ninth-grade students, suggesting that improving physical fitness could enhance academic outcomes. Implementing regular physical activity in schools may benefit both health and academic success. Longitudinal studies are needed to explore how changes in fitness over time impact academic performance. Future research should also examine the effects of such interventions across different age groups and populations, as well as interactions with cognitive function and socio-economic status.

Conclusion

This study adds substantial evidence from a larger cohort, demonstrating that cardiorespiratory fitness and weight status among adolescents are associated

Table 3 Multivariate multinomial logistic regression predicting level of academic achievement

	Slovak (mother language)			
	1; OR (95% CI)	**2; OR (95% CI)**	**3; OR (95% CI)**	**4; OR (95% CI)**
boy_Fit_Obesity	> 100 000 (0.00 – Infinity)	> 100 000 (0.00 – Infinity)	> 100 000 (0.00 – Infinity)	> 100 000 (0.00 – Infinity)
boy_Fit_Overweight	1.61 (0.46–5.60)	1.75 (0.52–5.93)	1.92 (0.57–6.47)	1.53 (0.44–5.38)
boy_unFit_Normal	0.66 (0.42–1.02)	0.61 (0.40–0.94)*	0.49 (0.32–0.75)***	0.50 (0.32–0.78)**
boy_unFit_Obesity	0.69 (0.38–1.22)	0.48 (0.27–0.85)**	0.29 (0.16–0.52)***	0.17 (0.09–0.34)***
boy_unFit_Overweight	0.99 (0.51–1.92)	0.98 (0.51–1.87)	0.70 (0.36–1.34)	0.55 (0.27–1.10)
girl_Fit_Obesity	> 100 000 (0.00 – Infinity)	0.37 (0.04–3.28)	0.11 (0.01–1.18)	0.10 (0.01–1.17)
girl_Fit_Overweight	0.55 (0.10–3.01)	0.76 (0.16–3.52)	0.77 (0.17–3.55)	0.70 (0.15–3.27)
girl_unFit_Normal	0.52 (0.27–0.98)*	0.30 (0.17–0.55)***	0.26 (0.14–0.47)***	0.19 (0.11–0.36)***
girl_unFit_Obesity	2.53 (0.54–11.81)	1.21 (0.26–5.49)	0.58 (0.13–2.67)	0.59 (0.13–2.77)
girl_unFit_Overweight	0.80 (0.36–1.80)	0.38 (0.17–0.83)**	0.33 (0.15–0.72)**	0.17 (0.08–0.38)***
	Mathematics			
	1; OR (95% CI)	**2; OR (95% CI)**	**3; OR (95% CI)**	**4; OR (95% CI)**
boy_Fit_Obesity	1.20 (0.14–10.50)	0.85 (0.10–7.20)	0.76 (0.09–6.64)	1.20 (0.14–10.05)
boy_Fit_Overweight	0.86 (0.38–1.92)	0.61 (0.28–1.34)	0.71 (0.32–1.55)	0.69 (0.31–1.53)
boy_unFit_Normal	0.77 (0.52–1.15)	0.66 (0.45–0.97)*	0.60 (0.41–0.89)**	0.53 (0.36–0.79)**
boy_unfit_Obesity	1.04 (0.57–1.88)	0.79 (0.44–1.41)	0.58 (0.32–1.05)	0.38 (0.20–0.71)**
boy_unFit_Overweight	1.03 (0.57–1.84)	0.90 (0.51–1.58)	0.65 (0.36–1.16)	0.57 (0.31–1.03)
girl_Fit_Obesity	1.26 (0.14–11.63)	0.39 (0.03–4.43)	0.80 (0.09–7.13)	0.22 (0.01–3.69)
girl_Fit_Overweight	1.69 (0.56–5.15)	1.53 (0.51–4.52)	1.17 (0.39–3.49)	0.95 (0.30–2.99)
girl_unFit_Normal	0.83 (0.57–1.21)	0.58 (0.40–0.84)**	0.45 (0.31–0.65)***	0.35 (0.24–0.51)***
girl_unfit_Obesity	1.72 (0.79–3.75)	0.62 (0.28–1.39)	0.49 (0.22–1.11)	0.54 (0.23–1.26)
girl_unFit_Overweight	0.79 (0.47–1.30)	0.52 (0.32–0.86)**	0.43 (0.26–0.71)***	0.32 (0.18–0.55)***

Academic achievement is a five-level ordinal variable: 0 [0,20]; 1 (20,40]; 2 (40,60]; 3 (60,80]; and 4 (80,100]. Based on the model (Fit_Normal as reference), the Odds Ratios (OR) were computed together with their 95% confidence intervals and p-values for the null hypothesis that the population OR is 1. * $p<0.05$; ** $p<0.01$; *** $p<0.001$

with performance on state-based, criterion-referenced academic competency tests. Cardiorespiratory fitness emerged as a significant predictor, with fit and normal-weight boys having higher odds of achieving better academic outcomes. However, the modest predictive power of the model indicates that additional factors likely influence academic performance and should be considered in future research.

Abbreviations

BMI	Body mass index
BwO	Boys with obesity
CRF	Cardiorespiratory fitness
GwO	Girls with Obesity
OLOV	Slovak Olympic and Sports Committee
OOB	Out-of-Bag
OR	Odds Ratios
VIMP	Variable IMPortance

Acknowledgements
The authors are grateful to all the subjects for their participation in this study, as well as to the Ministry of Education, Research, Development and Youth of the Slovak Republic - Program 026: National Sports Development Program in Slovakia; Subprogramme 026 01: Sport for All, School and University Sports.

Author contributions
VB, VN, and MG contributed equally to this work. VB, VN, and MG designed the project and contributed to the research questions. VB wrote the original manuscript and interpreted the findings. VN and MG reviewed the manuscript, conducted all statistical analysis, and interpreted the findings. LN contributed to the methodology and edited the manuscript. MŠ and KŽ contributed to the methodology and data collection. All the authors approved the final version of the manuscript.

Funding
This study was supported by the Slovak Research under Grant No. APVV-22-0047 and by the Development Agency, under Grant No. VEGA 1/0260/21.

Data availability
Results of all analyses are included in this published article. The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval
The study received approval from the Ethic Committee of the Faculty of Physical Education and Sport at the Comenius University of Bratislava (No. 06/2024), National Institute of Education and Youth in Slovakia, Slovak Olympic and Sports Committee, and the principals of each of the included schools.

Consent to participate
All participants were fully informed about the objectives of the study, and informed written consent was obtained from their legal guardians.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Biological and Medical Science, Faculty of Physical Education and Sport, Comenius University in Bratislava, Bratislava 814 69, Slovakia
[2]Neurological Clinic, Jessenius Faculty of Medicine in Martin, Comenius University in Bratislava, Martin 036 01, Slovakia

[3]Biomedical Center, Institute of Clinical and Translational Research, Slovak Academy of Sciences, Bratislava 845 05, Slovakia
[4]Slovak Olympic and Sports Committee, Bratislava 831 04, Slovakia
[5]Department of Didactics of Mathematics and Science Subjects, Faculty of Education, Comenius University in Bratislava, Bratislava 811 08, Slovakia
[6]Biomedical Center Martin, Jessenius Faculty of Medicine in Martin, Comenius University in Bratislava, Martin 036 01, Slovakia

Received: 11 April 2024 / Accepted: 23 December 2024
Published online: 09 January 2025

References

1. Volpato LA, Costa JC, Lopes WA, et al. Time reallocations from Sedentary Behavior to Physical Activity and Cardiovascular Risk factors in children and adolescents: a systematic review. J Phys Act Health. 2023;20:1084–91. https://doi.org/10.1123/jpah.2022-0471.
2. Mello JB, Pedretti A, García-Hermoso A, et al. Exercise in school Physical Education increase bone mineral content and density: systematic review and meta-analysis. Eur J Sport Sci. 2022;22:1618–29. https://doi.org/10.1080/17461391.2021.1960426.
3. García-Hermoso A, Ramírez-Vélez R, Ramírez-Campillo R, et al. Concurrent aerobic plus resistance exercise versus aerobic exercise alone to improve health outcomes in paediatric obesity: a systematic review and meta-analysis. Br J Sports Med. 2018;52:161–6. https://doi.org/10.1136/bjsports-2016-096605.
4. Marson EC, Delevatti RS, Prado AKG, et al. Effects of aerobic, resistance, and combined exercise training on insulin resistance markers in overweight or obese children and adolescents: a systematic review and meta-analysis. Prev Med (Baltim). 2016;93:211–8. https://doi.org/10.1016/j.ypmed.2016.10.020.
5. Cao Y, Zhu L, Liu J. Effects of aerobic exercise on obese children with metabolic syndrome: a systematic review and meta-analysis. J Pediatr Endocrinol Metab. 2021;34:1069–79. https://doi.org/10.1515/jpem-2021-0295.
6. Rodriguez-Ayllon M, Cadenas-Sánchez C, Estévez-López F, et al. Role of physical activity and sedentary behavior in the Mental Health of Preschoolers, children and adolescents: a systematic review and Meta-analysis. Sports Med. 2019;49:1383–410. https://doi.org/10.1007/s40279-019-01099-5.
7. Philippot A, Dubois V, Lambrechts K, et al. Impact of physical exercise on depression and anxiety in adolescent inpatients: a randomized controlled trial. J Affect Disord. 2022;301:145–53. https://doi.org/10.1016/j.jad.2022.01.011.
8. Ekeland E, Heian F, Hagen KB, et al. Exercise to improve self-esteem in children and young people. Cochrane Database Syst Reviews. 2004. https://doi.org/10.1002/14651858.CD003683.pub2.
9. van Woudenberg TJ, Bevelander KE, Burk WJ, Buijzen M. The reciprocal effects of physical activity and happiness in adolescents. Int J Behav Nutr Phys Activity. 2020;17:147. https://doi.org/10.1186/s12966-020-01058-8.
10. Haapala EA, Lubans DR, Jaakkola T, et al. Which indices of cardiorespiratory fitness are more strongly associated with brain health in children with overweight/obesity? Scand J Med Sci Sports. 2024;34. https://doi.org/10.1111/sms.14549.
11. Esteban-Cornejo I, Stillman CM, Rodriguez-Ayllon M, et al. Physical fitness, hippocampal functional connectivity and academic performance in children with overweight/obesity: the ActiveBrains project. Brain Behav Immun. 2021;91:284–95. https://doi.org/10.1016/j.bbi.2020.10.006.
12. Van Dusen DP, Kelder SH, Kohl HW, et al. Associations of Physical Fitness and Academic Performance among Schoolchildren*. J Sch Health. 2011;81:733–40. https://doi.org/10.1111/j.1746-1561.2011.00652.x.
13. Martínez-Vizcaíno V, Garrido-Miguel M, Redondo-Tébar A et al. (2021) The Fat but Fit Paradigm from a children's Health-Related Quality of Life Perspective. Childhood Obesity chi.2021.0041. https://doi.org/10.1089/chi.2021.0041
14. Esteban-Cornejo I, Cadenas-Sanchez C, Contreras-Rodriguez O, et al. A whole brain volumetric approach in overweight/obese children: examining the association with different physical fitness components and academic performance. ActiveBrains Project Neuroimage. 2017;159:346–54. https://doi.org/10.1016/j.neuroimage.2017.08.011.
15. García-Hermoso A, Esteban-Cornejo I, Olloquequi J, Ramírez-Vélez R. Cardiorespiratory Fitness and muscular strength as mediators of the influence of Fatness on Academic Achievement. J Pediatr. 2017;187:127–e1333. https://doi.org/10.1016/j.jpeds.2017.04.037.
16. Martínez-López EJ, Grao-Cruces A, De la Torre-Cruz MJ, Ruiz-Ariza A. Associations between physical fitness and academic performance in teenagers. South Afr J Res Sport Phys Educ Recreation. 2019;41:63–75.
17. Sardinha LB, Marques A, Minderico C, et al. Longitudinal relationship between Cardiorespiratory Fitness and Academic Achievement. Med Sci Sports Exerc. 2016;48:839–44. https://doi.org/10.1249/MSS.0000000000000830.
18. Saevarsson E, Svansdottir E, Arngrimsson S, et al. Different cardiorespiratory fitness expressions based on the maximal cycle ergometer test show no effect on the relation of cardiorespiratory fitness to the academic achievement of nine-year-olds. PLoS ONE. 2018;13:e0200643. https://doi.org/10.1371/journal.pone.0200643.
19. Cadenas-Sanchez C, Migueles JH, Esteban-Cornejo I, et al. Fitness, physical activity and academic achievement in overweight/obese children. J Sports Sci. 2020;38:731–40. https://doi.org/10.1080/02640414.2020.1729516.
20. Sánchez-Miguel PA, Molina-López J, Vaquero-Solís M, Tapia-Serrano MA. Sedentary behaviours and their relationship with academic performance in adolescents: a mediation analysis. J Sports Sci. 2022;40:2570–7. https://doi.org/10.1080/02640414.2023.2174731.
21. Xu K, Sun Z. Predicting academic performance associated with physical fitness of primary school students using machine learning methods. Complement Ther Clin Pract. 2023;51:101736. https://doi.org/10.1016/j.ctcp.2023.101736.
22. Sun Z, Yuan Y, Xiong X, et al. Predicting academic achievement from the collaborative influences of executive function, physical fitness, and demographic factors among primary school students in China: ensemble learning methods. BMC Public Health. 2024;24:274. https://doi.org/10.1186/s12889-024-17769-7.
23. Slovenský olympijský a športový výbor Olympijský. odznak všestrannosti. https://www.olympic.sk/olov. Accessed 15 Mar 2024.
24. Harriss D, Atkinson G. Update – ethical standards in Sport and Exercise Science Research. Int J Sports Med. 2011;32:819–21. https://doi.org/10.1055/s-0031-1287829.
25. Ministerstvo školstva výskumu. vývoja a mládeže S republiky Národný inštitút vzdelávania a mládeže. https://www2.nucem.sk/. Accessed 15 Mar 2024.
26. Council of Europe. Eurofit: handbook for the eurofit tests of physical fitness. Rome: Council of Europe; 1988.
27. Tomkinson GR, Carver KD, Atkinson F, et al. European normative values for physical fitness in children and adolescents aged 9–17 years: results from 2 779 165 eurofit performances representing 30 countries. Br J Sports Med. 2018;52:1445–56. https://doi.org/10.1136/bjsports-2017-098253.
28. Léger LA, Mercier D, Gadoury C, Lambert J. The multistage 20 metre shuttle run test for aerobic fitness. J Sports Sci. 1988;6:93–101. https://doi.org/10.1080/02640418808729800.
29. Ruiz JR, Cavero-Redondo I, Ortega FB, et al. Cardiorespiratory fitness cut points to avoid cardiovascular disease risk in children and adolescents; what level of fitness should raise a red flag? A systematic review and meta-analysis. Br J Sports Med. 2016;50:1451–8. https://doi.org/10.1136/bjsports-2015-095903.
30. Cole TJ, Lobstein T. Extended international (< scp > IOTF) body mass index cut-offs for thinness, overweight and obesity. Pediatr Obes. 2012;7:284–94. https://doi.org/10.1111/j.2047-6310.2012.00064.x.
31. Wickham HF. (2023) dplyr: A Grammar of Data Manipulation. In: R package version 1.1.4. https://CRAN.R-project.org/package=dplyr. Accessed 16 Mar 2024.
32. Wickham H. ggplot2: elegant graphics for data analysis. New York: Springer-; 2016.
33. Sjoberg DD, Whiting K, Curry M, et al. Reproducible Summary tables with the Gtsummary Package. R J. 2021;13:570. https://doi.org/10.32614/RJ-2021-053.
34. R Core Team. R: a Language and Environment for StatisticalComputing. Vienna, Austria: R Foundation for Statistical Computing; 2021.
35. Ishwaran Hermant KU. Random survival forests for R. RNews. 2007;7:25–31.
36. Liaw AWM. Classification and regression byrandomForest. R News. 2002;2:18–22.
37. Ishwaran H, Kogalur UB, Blackstone EH, Lauer MS. Random survival forests. Ann Appl Stat. 2008. https://doi.org/10.1214/08-AOAS169. 2:.
38. Ishwaran Hemant KU. (2023) Fast Unified Random Forests forSurvival, Regression, and Classification (RF-SRC). In: R package version3.2.3. https://cran.r-project.org/package=randomForestSRC. Accessed 16 Mar 2024.
39. Ehrlinger J. (2022) ggRandomForests: Visually Exploring Random Forests. In: R package version 2.2.1. https://cran.r-project.org/package=ggRandomForests. Accessed 16 Mar 2024.

40. Howie EK, Joosten J, Harris CJ, Straker LM. Associations between meeting sleep, physical activity or screen time behaviour guidelines and academic performance in Australian school children. BMC Public Health. 2020;20:520. https://doi.org/10.1186/s12889-020-08620-w.
41. Voyer D, Voyer SD. Gender differences in scholastic achievement: a meta-analysis. Psychol Bull. 2014;140:1174–204. https://doi.org/10.1037/a0036620.
42. Sardinha LB, Marques A, Martins S, et al. Fitness, fatness, and academic performance in seventh-grade elementary school students. BMC Pediatr. 2014;14:176. https://doi.org/10.1186/1471-2431-14-176.
43. Syväoja HJ, Kankaanpää A, Joensuu L, et al. The Longitudinal associations of Fitness and Motor skills with Academic Achievement. Med Sci Sports Exerc. 2019;51:2050–7. https://doi.org/10.1249/MSS.0000000000002031.
44. Bartee RT, Heelan KA, Dority BL. Longitudinal evaluation of Aerobic Fitness and Academic Achievement among Schoolchildren. J Sch Health. 2018;88:644–50. https://doi.org/10.1111/josh.12666.
45. Mcloughlin GM, Bai Y, Welk GJ. Longitudinal associations between Physical Fitness and Academic Achievement in Youth. Med Sci Sports Exerc. 2020;52:616–22. https://doi.org/10.1249/MSS.0000000000002159.
46. Likhitweerawong N, Louthrenoo O, Boonchooduang N, et al. Bidirectional prediction between weight status and executive function in children and adolescents: a systematic review and meta-analysis of longitudinal studies. Obes Rev. 2022;23. https://doi.org/10.1111/obr.13458.
47. Raghuveer G, Hartz J, Lubans DR, et al. Cardiorespiratory Fitness in Youth: an important marker of Health: A Scientific Statement from the American Heart Association. Circulation. 2020;142. https://doi.org/10.1161/CIR.0000000000000866.
48. Ou X, Andres A, Pivik RT, et al. Brain gray and white matter differences in healthy normal weight and obese children. J Magn Reson Imaging. 2015;42:1205–13. https://doi.org/10.1002/jmri.24912.
49. Sadler JR, Thapaliya G, Ranganath K, et al. Paediatric obesity and metabolic syndrome associations with cognition and the brain in youth: current evidence and future directions. Pediatr Obes. 2023;18. https://doi.org/10.1111/ijpo.13042.
50. Wilkey ED, Cutting LE, Price GR. Neuroanatomical correlates of performance in a state-wide test of math achievement. Dev Sci. 2018;21. https://doi.org/10.1111/desc.12545.
51. Liu NY-S, Plowman SA, Looney MA. The reliability and validity of the 20-Meter shuttle test in American students 12 to 15 Years Old. Res Q Exerc Sport. 1992;63:360–5. https://doi.org/10.1080/02701367.1992.10608757.

Publisher's note