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A LOW HAMSTRING/QUADRICEPS RATIO MAY INCREASE THE RISK OF KNEE INJURY IN INACTIVE YOUNG WOMEN: CROSS SECTIONAL STUDY

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Abstract This study aimed to evaluate the isokinetic hamstring/quadriceps (H/Q) performance in male and female individuals with different physical activity levels and to examine the interaction between gender and activity level. A total of 84 volunteers (42 males and 42 females) with varying physical activity levels (inactive, minimally active, active) participated in the study. Based on the International Physical Activity Questionnaire Short Form (IPAQ-SF) scores, participants were categorized into three activity groups by gender (n=12–15 per group). Isokinetic muscle strength measurements were performed at angular velocities of 60°/s and 180°/s. Both gender and physical activity level had significant effects on quadriceps and hamstring muscle strength ($p < 0.001$). A significant interaction between gender and activity level was observed ($p < 0.01$). For the H/Q ratio, only gender showed a significant effect ($p < 0.01$). Inactive females had notably lower H/Q ratios than males ($p < 0.01$, Cohen's $d > 1.3$). A similar but less pronounced gender difference was also observed in active individuals. The gender difference in H/Q ratio is more pronounced among individuals with low physical activity levels. These findings suggest that inactive females may be at greater risk for knee injuries compared to males.

Key words: h/q ratio, isokinetic measurement, risk of knee injury, inactivite

Introduction

The stability of the muscles of the knee (quadriceps and hamstrings) is one of the parameters that are utilised in the assessment of injuries to the lower extremity. In particular, the evidence suggests that a lower hamstring strength in comparison to quadriceps strength (H/Q ratio) may serve as a potential mechanism that increases the

risk of injury to the lower extremities (Knapik et al., 1991; Myer et al., 2004). This torque ratio indicates the strength imbalance between the agonist and antagonist muscle groups surrounding the knee joint (Baltzopoulos & Brodie, 1989; Kellis & Baltzopoulos, 1995). The determination of the H/Q ratio can be achieved through the utilisation of concentric, eccentric and isometric contraction types, angular velocities (60°/s and 180°/s) and torque types (peak or angle-specific torque) within the isokinetic dynamometer measurement system (Kellis, 1998). The majority of studies have indicated that the peak torque ratio is the concentric hamstring-quadriceps peak torque ratio (Hcon/Qcon) of the knee muscles at a speed of 60°/s (Coombs & Garbutt, 2002). In relevant reviews, it seems to be generally accepted that the reference value ratio for this conventional peak torque H/Q ratio at the slow speed of isokinetic measurement is 0.60 (Coombs & Garbutt, 2002; Croisier et al., 2008; Hewett et al., 2008; Kellis et al., 2023). For example, it has been proposed that a minimum Hcon/Qcon ratio of 0.60 at an angular velocity of (60°/s) should be used as a basis for detecting muscle imbalances and preventing injury (6,7). It has also been suggested that a concentric H/Q ratio of less than 0.55 (Con 60/Con 60) is associated with an elevated risk of injury (Croisier et al., 2008).

It is well established that the strength profiles of the hamstring and quadriceps muscles exhibit significant disparities between males and females during and following the process of puberty (Hewett et al., 2004). Women with lower H/Q peak torque ratios may be at higher risk of knee injury (Knapik et al., 1991). Knapik et al. (1991), established that a lower H/Q ratio, as determined by high-speed isokinetic parameters, was associated with a higher incidence of anterior cruciate ligament (ACL) injury in female collegiate athletes.

Insufficient hamstring torque relative to quadriceps torque has been demonstrated to impair the control of coronal and sagittal plane knee movements in female athletes, thereby increasing knee joint loading and predisposing them to a greater injury risk than their male counterparts (Kellis & Baltzopoulos, 1995; Markolf et al., 1995).

In the literature searched, the H/Q ratio showed significant differences between genders, depending on sports activity, isokinetic test speed, and number of study participants (Hewett Hewett et al., 2008). However, these differences in the H/Q ratio have not been well reported in the young population at different speeds by sex according to certain physical activity levels. Therefore, in this study, we aimed to compare H/Q ratios according to different activity levels in young men and women according to physical activity score.

Methods

The study has been approved by Balıkesir University Health Sciences Non-Interventional Research Ethics Committee on October 12, 2021 (No: 2021/16) and all participants have signed an informed consent form.

The Study Procedure and Participants

Study data were collected on separate days. First, participants' physical activity levels were determined using the self-administered International Physical Activity Questionnaire-Short Form (IPAQ-SF) questionnaire (Lee et al., 2011). Then, the physical composition of the participants were measured, and right leg isokinetic knee muscle strength tests were performed. Forty-two men and 42 women, totalling eighty-four people, participated in this study. All volunteers had no musculoskeletal or neurological injuries or disabilities or use any anti-inflammatory drugs or any treatments during the research period.

At the first visit, participants were given a week before the test to familiarize themselves with the isokinetic testing protocol. Isokinetic test measurements were performed on the right leg at similar times of the day (± 2 h) for all and one researcher performed all measurements.

Assessment of the Physical Activity Level Using IPAQ-SF

The participants physical activity level was determined by Turkish version of IPAQ-SF (Saglam et al., 2010). The physical activity levels of the participants in the last 7 days were assessed in accordance with the scale. This scale consists of seven questions. It assesses the duration of sitting, walking, moderate and vigorous activity. The walking, moderate and vigorous activity scores are summed to give a total score. The final scores of the IPAQ-SF are reported in units of MET minutes-week⁻¹. This calculating protocol for walking=(3.3× walking minutes × walking days); moderate activity=(4.0× moderate activity minutes × moderate activity days); and vigorous activity=(8.0× vigorous activity minutes × vigorous activity days). Based on the total PA score, participants are classified as “Active, Minimally Active, and Inactive person.” The sitting score is calculated separately, it indicates sedentary behaviour (Saglam et al., 2010; Craig et al., 2003).

Isokinetic Test Evaluation

The Isokinetic test, concentric/concentric active mode knee flexion and extension strength of the participants were evaluated by ISOMED 2000 (D.& R. Ferstl GmbH, Hemau, Germany). Before the test, participants were informed about the evaluation process with visual feedback. All participants were verbally motivated for maximum effort. Participants were allowed to hold the handles on the edge of the seat and asked how to stop the test in case of an emergency. Knee, hip, and waist positions were automatically adjusted by software to position the hips at the correct angle. The upper part of the body, shoulders, hips, and upper leg were fixed with a belt to stabilise them. The distal part of the lower leg articulating arm is attached to the lateral malleolus of the ankle. The swivel axis in the knee is positioned with the lateral femoral condyle of the knee joint at 90° knee flexion. The range of motion of the knee was adjusted between 0 and 90° with mechanical limits. Also, the effect of gravity correction was calculated before the test. The test protocol was performed at two different angular speeds, from slow to fast (60°/s and 180°/s) with flexion/extension and concentric/concentric mode. Before the actual test, three submaximal extension/flexion trials were performed to warm up and familiarise with the speed and resistance. Participants actual test performed at the 60°/s 6 repetitions and 20 repetitions at the 180°/s angular velocity of knee flexion/extension. All isokinetic muscle strength parameters were analysed at the end of the test.

Statistical Analysis

The analysis of the data was carried out using the SPSS software package (version 30). Descriptive data are expressed as numbers, percentages, and in the form of mean and standard deviation. Normality of data distribution was evaluated using Shapiro-Wilk test. The effects of gender and physical activity on isokinetic parameters (Hamstring PT, Quadriceps PT and H/Q PT Ratio) were evaluated by two-way analysis of variance (ANOVA). When a significant two-factor interaction or main effect was observed, Tukey's HSD was applied as a post hoc test. A priori power analysis was performed using G*Power software (version 3.1) to determine the required sample size for the two-way ANOVA design (3 activity levels × 2 gender=6 groups). Assuming a large effect size (Cohen's $f=0.40$), an alpha level of 0.05 and a power of 0.80, the analysis indicated that a total of 52 participants would be sufficient to detect statistically significant differences. This corresponds to a minimum of 9 participants per group. Accordingly,

the study was designed with three physical activity groups of 12 to 15 participants each. Variables between genders were compared using an independent t-test (Student's t-test). The significance level was determined as $\alpha=0.05$.

Results

In Table 1, participants were categorised as inactive, minimally active, and active according to IPAQ-SF scores in men and women. The age, weight, and BMI of all participants were not significantly different according to activity level by gender ($p>0.05$), whereas the height of the active group was significantly higher than the height of the other groups ($p<0.05$) (Table 1).

Table 1. Classification of groups according to international physical activity questionnaire-short form scores in women and men

Activity level	Gender	n	Age (y)			Height (cm)			Weight (kg)			IPAQ-SF score		
			Min.	Max	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Inactive	W	15	20	23	21.40	154	175	164	45	75	55.54	00	594	214.6
	M	12	20	28	22.75	167	183	176.3	60	115	79.70	00	594	162.0
Minimally Active	W	12	20	23	20.66	157	180	168.6	49	80	62.65	780	2772	1557.7
	M	15	20	25	21.50	167	186	175.1	58	93	75.40	676	2950	1902.4
Active	W	15	18	23	20.93	157	178	167.0	48	77	58.40	3012	7572	5574.7
	M	15	20	28	22.13	171	200	184.1	68	109	85.66	3177	6657	4555.8

W=Women, M= Men, n=number; IPAQ-SF=International Physical Activity Questionnaire–Short Form.

Table 2 shows the mean $\pm$ SD values of isokinetic muscle performance variables according to the participants' gender and activity level.

Table 2. Mean $\pm$ SD Values of Isokinetic Muscle Performance Variables According to Gender and Activity Level.

Degree & PT	^a Inactive (n=27)		^b Minimally Active (n=27)		^c Active (n=30)	
	Women (n=15)	Men (n=12)	Women (n=12)	Men (n=15)	Women (n=15)	Men (n=15)
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
60°/s						
Q	112.40 $\pm$ 15.03	185.41 $\pm$ 35.76	147 $\pm$ 31.12	197.50 $\pm$ 33.03	141 $\pm$ 22.17	252.20 $\pm$ 46.01
H	55.13 $\pm$ 7.59	111.58 $\pm$ 22	81.33 $\pm$ 22.01	118.28 $\pm$ 24.02	82.93 $\pm$ 15.40	163.33 $\pm$ 27.58
H/Q Ratio	0.49 $\pm$ 0.08	0.60 $\pm$ 0.09	0.55 $\pm$ 0.11	0.59 $\pm$ 0.07	0.58 $\pm$ 0.06	0.65 $\pm$ 0.11
180°/s						
Q	91 $\pm$ 14.35	150.66 $\pm$ 40.81	121.58 $\pm$ 21.6	165.92 $\pm$ 33.81	121.46 $\pm$ 19.36	222.20 $\pm$ 30.01
H	47.53 $\pm$ 9.24	98.58 $\pm$ 19.84	68 $\pm$ 17.77	102.35 $\pm$ 21.53	72.40 $\pm$ 14.80	139.66 $\pm$ 28.03
H/Q Ratio	0.52 $\pm$ 0.10	0.67 $\pm$ 0.12	0.55 $\pm$ 0.13	0.61 $\pm$ 0.09	0.59 $\pm$ 0.09	0.63 $\pm$ 0.13

Q=Quadriceps, H= Hamstring, Mean $\pm$ SD, mean $\pm$ standard deviation; PT, peak torque (Nm); H/Q Ratio, hamstring/quadriceps ratio

According to the Two-Way ANOVA results (Table 3), at an angular velocity of 60°/s, quadriceps strength was significantly affected by gender ($F=123.180$, $p=0.001$), activity level ($F=15.758$, $p<0.001$), and their interaction ($F=6.489$, $p=0.002$). Similarly, hamstring strength was significantly influenced by gender ($F=161.177$, $p<0.001$), activity level ($F=26.545$, $p<0.001$), and the interaction between them ($F=7.736$, $p<0.001$). For the H/Q ratio, gender ($F=14.548$, $p<0.001$) and activity level ($F=4.487$, $p<0.001$) had significant effects, while the interaction effect was not significant ($F=0.930$, $p=0.399$).

Table 3. Two-Way ANOVA Results of Gender, Activity Level and Interaction on Isokinetic Muscle Performance Variables.

Angular Velocity & Isokinetic Muscle Strength Variables		Gender		Activity Group		Activity Level * Gender Interaction	
		F	p	F	p	F	p
60°/s	Quadriceps	123.180	<0.001**	15.758	<0.001**	6.489	0.002**
	Hamstring	161.177	<0.001**	26.545	<0.001**	7.736	<0.001**
	H/Q Ratio	14.548	<0.001**	4.487	<0.001**	0.930	0.399
180°/s	Quadriceps	124.715	<0.001**	24.122	<0.001**	7.851	<0.001**
	Hamstring	140.772	<0.001**	20.976	0.001**	4.979	0.009**
	H/Q Ratio	10.038	0.002**	0.411	0.664	1.726	0.185

PT, peak torque (Nm); H/Q Ratio, hamstring/quadriceps ratio

* The degree of significance was set at $p<0.05$; **= $p<0.001$.

At 180°/s, quadriceps strength was again significantly affected by gender ($F=124.715$, $p<0.001$), activity level ($F=24.122$, $p<0.001$), and their interaction ($F=7.851$, $p<0.001$). The same pattern was observed for hamstring strength (gender: $F=140.772$, $p<0.001$; activity: $F=20.976$, $p<0.001$; interaction: $F=4.979$, $p=0.009$). However, for the H/Q ratio at this velocity, only gender had a significant effect ($F=10.038$, $p=0.002$), while activity level ($F=0.411$, $p=0.664$) and the interaction ($F=1.726$, $p=0.185$) were not significant.

Table 4. Independent samples t-test results of PT H/Q ratios by gender

Degree & Activity Level	PT H/Q Ratio		<i>t</i>	<i>P</i> -value	Cohen d
	Women	Men			
	Mean±SD	Mean±SD			
60°/s					
Inactive	0.49±0.08 (n=15)	0.60±0.09 (n=12)	-3.392	0.002**	-1.314
Minimally Active	0.55±0.11 (n=12)	0.59±0.07 (n=15)	-1.211	0.238	-0.476
Active	0.58±0.06 (n=15)	0.65±0.11 (n=15)	-2.132	0.042*	-0.778
180°/s					
Inactive	0.52±0.10 (n=15)	0.67±0.12 (n=12)	-3.405	0.002**	-1.319
Minimally Active	0.55±0.13 (n=12)	0.61±0.09 (n=15)	-1.250	0.223	-0.492
Active	0.59±0.09 (n=15)	0.63±0.13 (n=15)	-0.887	0.191	-0.324

Mean±SD, mean±standard deviation; PT, peak torque (Nm); H/Q Ratio, hamstring/quadriceps ratio

* The degree of significance was set at $p<0.05$. **= $p<0.01$.

As shown in Table 4, at 60°/s, inactive females had a significantly lower H/Q ratio (0.49 ± 0.08) than inactive males (0.60 ± 0.09 ; $t = -3.392$, $p = 0.002$, Cohen's $d = -1.314$). A similar gender difference was observed in active participants (females: 0.58 ± 0.06 , males: 0.65 ± 0.11 ; $t = -2.132$, $p = 0.042$, Cohen's $d = -0.778$). No significant gender difference was found in the minimally active group ($p = 0.238$). At 180°/s, inactive females again had a significantly lower H/Q ratio (0.52 ± 0.10) than males (0.67 ± 0.12 ; $t = -3.405$, $p = 0.002$, Cohen's $d = -1.319$). No significant gender differences were observed in the minimally or active groups ($p = 0.223$ and $p = 0.191$, respectively).

Discussion

In this study, the H/Q ratio was analyzed according to physical activity level and gender. The most striking finding of the study was that at low angular velocity (60°/s), the PT H/Q ratio (0.49) was lower in inactive women compared to activity level. In addition, in men, the H/Q ratio did not differ significantly at low and high speeds according to activity level. When evaluated on the basis of gender, inactive women had a lower H/Q ratio than inactive men at both angular velocities; when the activity level increased, a gender difference was observed only at low angular velocity. Inactivity reduced the H/Q ratio in both men and women, but the risk of knee injury may be significantly increased in women compared to men.

In this study, the mean H/Q ratio for inactive women (0.49) was lower than for inactive men (0.60). This result seems to be consistent with the results of a meta-analysis of twenty-two studies in the literature. This meta-analysis included 1145 men and 423 women. Isokinetic test speeds ranged from 30°/s to 360°/s and the mean H/Q ratio over all test speeds was 51.9% (Hewett et al., 2008). These meta-analyses also showed that there was a significant increase in H/Q ratio as speed increased, but there was no relationship between H/Q ratio and test speed in women. In men, the H/Q ratio increased significantly with speed. In addition, it was determined that the H/Q ratio of men was statistically significantly higher than that of women (Hewett et al., 2004). However, in our study, a significant gender difference was found among inactive participants at 60°/s. This suggests that especially inactivity may affect the H/Q ratio between genders.

In this study, it was also observed that PT H/Q ratio showed gender-related differences in individuals with high physical activity level according to IPAQ-SF scores, and active males had higher values in slow speed ($p < .05$) compared to active females. In previous studies by Holm & Vøllestad (2008), it was shown that there were significant gender differences in terms of H/Q ratio and static balance in children aged 7, 8, 9, 10 and 12 years, and that the hamstring muscle strength of boys was higher than that of girls at all ages. In adolescents and adults, sedentary lifestyle, physical activity and type of sport may affect the H/Q ratio. Indeed, no significant difference was found in the strength ratio between the anterior and posterior thigh muscles between active men and women with similar activity levels (Bojsen-Møller et al., 2007; Kong & Burns, 2010). In a study by Kong & Burns (2010), no difference was found between isokinetic and isometric H/Q ratios at any angular velocity (60°/s, 180°/s, 330°/s) between physically active adult men and women. In addition, it was reported that gender differences in isokinetic H/Q ratio were generally observed in different sports activities and it was stated that women could not increase their hamstring muscle strength as much as the amount of quadriceps torque unlike men (Hewett et al., 2008). In Myer's study, no gender difference was found in H/Q ratios at slow angular velocities (Myer et al., 2004).

In another study, no difference was found between men and women with the same training level in isometric and functional isokinetic eccentric H/Q ratios performed at speeds of 60°/s and 180°/s at different knee flexion positions (40°, 50°, 60°, 70°, 80°) (Pellicer-Chenoll et al., 2017). In another study, angularly specific H/Q ratios

of soccer players were compared with recreationally active individuals and no difference was found between the groups at any speed (Evangelidis et al., 2015). However, in our study, a gender difference was observed between active men and women at low angular velocity. This difference may be related to hamstring and quadriceps peak torque (PT) values, which may vary depending on sport-specific activity levels and training type.

This shows that the H/Q ratio is affected by inactivity and activity level. The results of this study suggest that knee problems may be more common in women than in men. According to related studies, the lowest ratios between the mean values of H/Q at slow speeds (30°/s and 60°/s) in women were reported as 0.41, 0.46, 0.47 and 0.48, respectively (Aagaard et al., 1997; Griffin et al., 1993; Richards, 1981; Westing & Seger, 1989). These existing findings have been analyzed; Aagaard et al. (1997) studied elite female sailors (n=8), Westing & Seger (1989) studied twenty women but did not provide clear information about their training history. Griffin et al. (1993) studied fifty untrained women between the ages of 21–67, but did not analyze the effect of age. Our findings regarding H/Q ratio are similar to these studies. In addition, for example, in our findings, the difference in quadriceps peak torque (PT) between active men and women was 36%, while the difference in hamstring PT reached 98%. Among inactive subjects, these differences were 65% for quadriceps and nearly 100% for hamstrings. Also, in our study, the inactivity level of women was clearly determined by IPAQ-SF score and young women (18–30 years) were included in the study. In addition, according to the physical activity score, inactive women spent a greater proportion of the day sitting compared to men (Female=8 hours; Male=5 hours).

In conclusion, in this study, we found a gender difference in H/Q ratios. This difference is affected by inactivity and sport-specific activity types. We think that this effect is due to hamstring peak torque values. Notably, the disparity in hamstring strength was greater than that in quadriceps strength, indicating that females have comparatively weaker hamstring muscles than males.

Conclusion

In conclusion, our findings show that inactive young women have a lower H/Q ratio than inactive men at both velocities. This indicates that inactivate higher knee injury risk of the women than men. However, according to the IPAQ-SF score, we found that at 4 METs and above, there was a significant gender difference, with males demonstrating higher values of the PT H/Q ratio compared to females. In terms of velocity, our results confirm the H/Q ratio did not differ according to activity level at high speed (180°/s).

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APPLICATION AND PRACTICAL RELEVANCE OF VERTICAL FORCE-VELOCITY PROFILING FOR OPTIMIZING PERFORMANCE IN TEAM SPORTS: A SYSTEMATIC REVIEW

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Abstract Vertical force–velocity (F–V) profiling is widely used to assess athletes' neuromuscular capabilities; however, its transfer to sport-specific performance and the effectiveness of individualized interventions remain debated. This systematic review examined the application and efficacy of vertical F–V profiling for optimizing explosive actions such as sprinting, jumping, and change-of-direction performance in team-sport athletes.

Following PRISMA guidelines, a systematic search was conducted across Scopus, Web of Science, and SpringerLink for studies published between January 2020 and December 2025. Thirteen studies met the inclusion criteria (team-sport athletes aged ≥17 years, vertical F–V assessment through loaded jumps, and sport-related performance outcomes) and were included in the qualitative synthesis.

The results indicate that maximum power (P_{max}) is strongly associated with jump performance, whereas its relationship with sprint ability appears more variable and may be influenced by sex and biomechanical specificity. Individualized interventions targeting F–V imbalance generally improved P_{max} and jump performance, but transfer to sprinting was limited and inconsistent across studies. Methodological heterogeneity, particularly in test standardization and the distinction between vertical and horizontal force production, was a key factor affecting outcomes.

Overall, vertical F–V profiling appears useful for optimizing jump performance but shows limited predictive value for sprinting and change-of-direction tasks due to vector specificity. Future research should integrate horizontal profiling and longer intervention periods to better address team-sport demands.

Key words: force–velocity profile; neuromuscular performance; vertical jump; individualized training; team sports

Introduction

In modern team sports, the ability to generate explosive power is a key determinant of athletic performance (Türkarslan & Deliceoglu, 2024). Decisive actions such as sprinting, jumping, and changing direction depend on the neuromuscular system's ability to generate high levels of force and movement velocity in a short time frame (Morin & Samozino, 2016). In this context, characterizing the force–velocity (F–V) profile has become a fundamental approach in sports science (Samozino et al., 2008). This approach provides a framework for assessing athletes' individual mechanical qualities and for prescribing targeted training interventions (Samozino et al., 2012). The vertical F–V profile is particularly valuable in practice for talent identification, monitoring neuromuscular development, and guiding individualized training strategies in team-sport athletes. Analysis of the F–V profile, as measured through loaded jump tests, quantifies the linear relationship between force and velocity (Garcia-Ramos et al., 2019). This approach enables the identification of key variables such as theoretical maximal force (F_0), theoretical maximal velocity (V_0), and maximal power (P_{max}) (Morin et al., 2019). This analysis has also been considered useful for identifying mechanical imbalances and guiding individualized training interventions in athletic populations (Bobbert et al., 2023).

Notwithstanding the burgeoning interest in F–V profiling, there are still significant gaps in the literature. Numerous studies have explored the relationship between the F–V profile and vertical jump performance (Baena-Raya et al., 2022; Ramirez-Campillo et al., 2015), but the transfer of these findings to sprint performance and field-based actions remains less clear, and conclusions are often contradictory (Ettema, 2024). For instance, a robust correlation between vertical F–V profile variables and sprint speed has been demonstrated in certain studies (Jiménez-Reyes et al., 2018), while other research has been unable to substantiate this association or to demonstrate adequate external validity (Lindberg et al., 2021; Wolte et al., 2024). Furthermore, the effectiveness of individualized training protocols based on the F–V profile to correct specific deficits (strength deficit vs. velocity deficit) has not yet been firmly established, particularly for specific populations such as female athletes or young talents in various disciplines (Solberg et al., 2025). To date, there has been a paucity of critical and integrative syntheses of the results of these studies, which could clarify the conditions of application, optimal methodologies, and limitations of this approach.

The primary aim of this systematic review was to evaluate the relevance and practical application of the vertical force–velocity profile and its key variables (F_0 , V_0 , P_{max} , F–V slope, FV_{imb} , and DSI) in explaining and optimizing explosive performance in team sports, including sprinting, jumping, and change-of-direction tasks. A secondary aim was to compare the methodologies and measurement tools used across studies and to identify the most effective

individualized training strategies derived from vertical F–V profiling. It was hypothesized that individualized training based on the vertical F–V profile would improve key neuromuscular qualities (F_0 , V_0 , and P_{max}) and selected explosive performance outcomes in team-sport athletes. It was also hypothesized that the relationship between vertical F–V variables and athletic performance would be influenced by biomechanical task specificity.

Materials and Methods

Study Design

This review was conducted following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement Page et al. (2021).

Eligibility Criteria

The PICO framework was used to define the following review question: “To what extent does the application of a training intervention based on the vertical force–velocity profile improve explosive performance (sprinting, jumping, and change-of-direction performance) in team-sport athletes?” This framework was also used to guide study eligibility.

Table 1. PICO Search Strategy

P	I	C	O
Male and female team-sport athletes. ≥17 years old	Individualized strength training using the vertical force-velocity profile	Comparison between groups (force vs velocity deficits. different performance levels. pre vs post-intervention)	Primary outcomes: Changes in explosive performance metrics (sprint time, jump height, change-of-direction performance). Secondary outcomes: Changes in mechanical variables of the vertical F–V profile (F_0 , V_0 , P_{max}).

Inclusion Criteria

This review included observational studies (cross-sectional and cohort studies), quasi-experimental studies, and experimental studies that met the following criteria: (i) The study implemented a training intervention or assessment protocol based on the evaluation of the vertical force–velocity profile, as determined through the simple field method proposed by Samozino et al., (2008, 2010) or similar loaded jump protocols (e.g., squat jump or countermovement jump performed with varying external loads). Only vertical F–V profiling methods were included to maintain biomechanical specificity relevant to jumping and sprinting tasks. (ii) Participants were healthy and physically active men or women aged 17 years or older, competing in team sports at any level (elite, amateur, or recreational). (iii) The study reported at least one primary outcome related to sport performance, such as sprinting, jumping, or change-of-direction performance. Studies that additionally reported changes in F–V profile mechanical variables (e.g., F_0 , V_0 , P_{max}) were also included.

Exclusion Criteria

Studies were excluded based on the following criteria:

1. Studies focusing on adults with health problems that prevented sports participation (e.g., osteomuscular pathology, recent surgery, or contusion) or clinical populations.

2. Studies that did not utilize a method to assess the vertical force-velocity profile (e.g., studies using only isometric tests or horizontal sprint profiling without a vertical jump component).
3. Studies that only reported changes in F–V mechanical variables without reporting any functional performance outcomes.
4. Validation studies, literature reviews, systematic reviews, brief reviews, meta-analyses, letters to the editor, comments, and conference abstracts.

Information source

Scopus, Web of Science, and SpringerLink were selected for the literature search.

Search Strategy

A systematic search was conducted across Scopus, Web of Science, and SpringerLink to identify studies investigating the vertical force–velocity profile and its relationship with sport-performance outcomes. The initial search was conducted on April 15, 2024, and was subsequently updated in December 2025 to include newly published and early-access studies. The search covered articles published between January 2020 and December 2025.

The search strategy was as follows: (“The search syntax was adapted to the indexing rules of each database. The core search terms were: (“force–velocity profile” OR “force velocity profiling” OR “vertical force–velocity profile” OR “jump force–velocity profile”) AND (“vertical jump” OR “neuromuscular performance” OR sprint OR “change of direction” OR “team sport” OR “team sports”).

In addition, the reference lists of all included studies were manually screened to identify any further relevant articles.

Data Extraction

The data extraction and analysis process was executed in accordance with a rigorous methodology, ensuring consistent and comprehensive interpretation of the results from the included studies. A standardized grid was employed to systematically collect pertinent information, including the first author name, year of publication, study design and sample size (N), the study population (age, sex, and sporting level), the key parameters of the Force-Velocity profile (F_0 , V_0 , P_{max} , and FV slope) as well as any reported associations between F–V variables and sport-performance outcomes.

Risk of Bias Assessment

The methodological quality of the included studies was assessed using the National Heart, Lung, and Blood Institute (NHLBI) Study Quality Assessment Tools. The specific checklist was selected according to each study design: the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies, the Quality Assessment Tool for Controlled Intervention Studies, or the Quality Assessment Tool for Before-After Studies With No Control Group. Two reviewers (S.K. and K.E.M.) independently assessed each study. Disagreements were resolved through discussion and consensus. Items were rated as •Yes,• •No,• •Cannot determine,• •Not reported,• or •Not applicable. Overall quality judgments were based on the reviewers• evaluation of the potential risk of bias rather than solely on a numerical score.

Study Characteristics and Main Findings

The initial search yielded a total of 965 records from the selected academic databases: Scopus ($n=37$), Web of Science ($n=640$), and SpringerLink ($n=288$). After the removal of duplicate records ($n=428$), 537 unique records remained. In addition, three records were identified through a targeted search for 2025 early-access articles, resulting in a total of 540 records screened. During the screening process, 283 records were excluded based on title and 227 after abstract review. The remaining 30 reports were assessed for eligibility in full text, of which 17 were excluded for not meeting the inclusion criteria. Ultimately, 13 studies were included in the qualitative synthesis. The complete study selection process is presented in Figure 1.

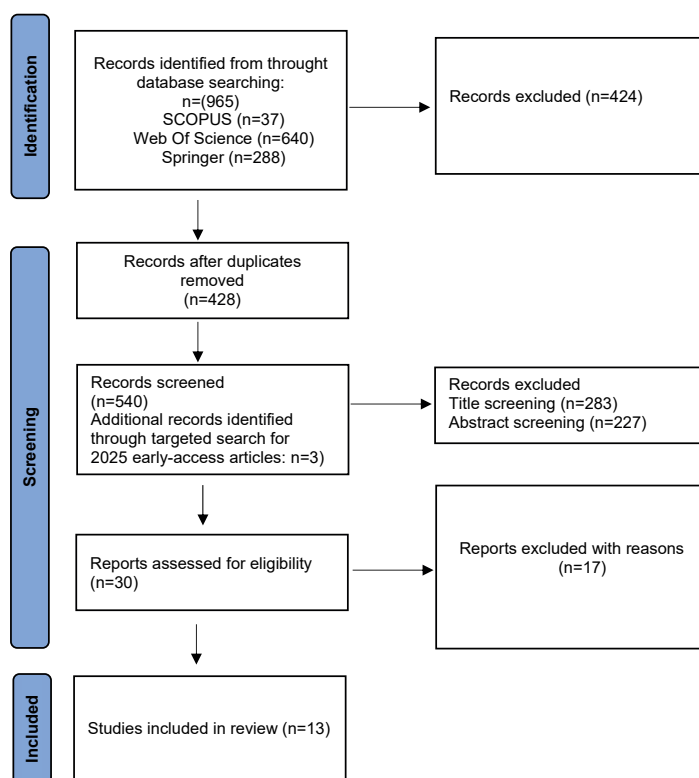


Fig. 1. PRISMA 2020 flow diagram illustrating the study selection process for the systematic review

The included studies were grouped into three main categories according to study design and research purpose: (1) observational studies that described force–velocity (F–V) profiles in specific populations (Conceição et al., 2025; Hicks et al., 2023; Pérez-Ifrán et al., 2024; Qin et al., 2025); (2) correlational studies that assessed associations between F–V profile parameters and specific sport-performance metrics (Manson et al., 2021; Pleša et al., 2021, 2024; Spudić et al., 2024); and (3) experimental studies that evaluated the effects of training interventions on F–V profile parameters and physical performance (Conceição, 2024; Ishihara et al., 2024; Koźlenia et al., 2025; Lindberg et al., 2021; Nishioka & Okada, 2022).

Methodological Quality of Included Studies

The results of the methodological quality assessment are summarized in Table 5. The methodological quality of the included studies varied across study designs. Most studies satisfied several key criteria, including clearly defined research objectives, adequately described populations, appropriate intervention or exposure protocols, and valid outcome measures. However, recurrent methodological limitations included the absence of sample-size justification, limited assessor blinding, insufficient control of potential confounding variables, and incomplete reporting of participant recruitment and retention. These limitations should be considered when interpreting the overall findings of the review.

The following tables summarize the characteristics of the studies included in this systematic review, detailing the programs and outcomes observed.

Table 2. Characterization of vertical force-velocity (F-V) profiles in different athletic populations

Author (Year)	Participants (N, Sex, Age)	Athletic Level	F-V Protocol	F ₀ (N/kg)	V ₀ (m s ⁻¹)	Pmax (W/kg)	F-V slope / FVimb	Key Findings
Hicks et al. (2023)	16-M (8-AT, 8-Df)/ 24.8±7.3	Professional (Field Hockey)	CMJ with 3 loads (0%, 25%, 50% BM)	M: 40.16±3.70 F: 34.01±4.60	M: 3.20±0.21 F: 2.79±0.45	M: 32.28±4.31 F: 23.45±3.03	M: -12.52±1.15 F: -12.15±1.64	Significant sex differences. Pmax correlated with jump height (r=0.68 males, r=-0.71 females).
	17-F (9-AT, 8-Df)/ 22.3± 4.2							
Pérez-Ifrán et al. (2024)	10 M (18.9±0.3)	Professional (Rugby)	Loaded SJ (progressive loads)	29.5±5.3	3.81±0.97	27.3±4.4	-8.6±4.0	Pmax strongly correlated with SJ height (r=0.76). High prevalence of velocity deficit in youth players.
Conceição et al. (2025)	38 M (17.1±0.9)	Professional (Soccer)	Loaded CMJ (0, 30, 50, 70% BM)	D1 : 33.58±3.85 D2 : 32.27±3.45 1.08 (p > 0.05)	D1 : 3.18±0.50 D2 : 3.96±1.14 * 2.88 (p > 0.05)	D1 : 26.95±4.17 D2 : 31.54±6.45 * 2.67 (p < 0.05)	D1 : -83.05±20.34 D2 : -62.94±21.28	1st division players had more balanced profiles. Forwards more balanced than midfielders. 76% of players exhibited a force deficit. No differences in jump height.
Qin et al (2025)	SG 10-M/ 22.9±2.1	Professional (resistance- trained)	Loaded SJ (progressive loads)	Stronger group: SJ70: 2.627±296 SJ90: 2.820±261 SJ110: 3.141±501	Stronger group: SJ70: 3.54±0.69 SJ90: 3.33±0.58 SJ110: 3.23±1.31	Stronger group: SJ70: 2.292±318 SJ90: 2.325±330 SJ110: 2.421±653	Stronger group: SJ70: 782±241 SJ90: 883±241 SJ110: 1142±526	Significant between-group differences in F ₀ , V ₀ , and Pmax (p<0.05). Supports F-V profiling for talent identification
	WG 11-M/ 22.9±2.3							
				Weaker group: SJ70: 2.461±308 SJ90: 2.615±308 SJ110: 2.806±557	Weaker group: SJ70: 2.70±0.46 SJ90: 2.75±0.54 SJ110: 2.71±0.62	Weaker group: SJ70: 1.648±303 SJ90: 1.782±325 SJ110: 1.885±396	Weaker group: SJ70: 950±268 SJ90: 1000±310 SJ110: 1125±545	

As summarized in Table 2, observational studies identified several relevant characteristics of force–velocity (F–V) profiles in team-sport athletes. Hicks et al., (2023) reported clear sex-related differences, with male athletes showing higher theoretical force (F_0), theoretical velocity (V_0), and maximal power (Pmax) values than female athletes. Pérez-Ifrán et al., (2024) described a high prevalence of force deficits in under-20 rugby players, emphasizing the importance of individualized mechanical profiling in youth populations. Similarly, Conceição et al., (2025) showed that first-division soccer players presented more balanced F–V profiles than second-division players, suggesting that profile balance may be associated with competitive level.

Table 3. Correlational Studies Relationships between F–V variables and specific performance metrics

Author (Year)	Participants	F–V Variables Measured	Performance Tests	Significant Correlations
Manson et al. (2021)	39 F (24.3±4.7)	F_0 . V_0 . Pmax. FVimb	Sprint (ACC. MSS). CMJ	Pmax ↔ ACC ($r=-0.44$) / CMJ ↔ MSS ($r=-0.67$) / Weaker links between vertical F–V profile and sprint performance in female athletes.
Pleša et al. (2021)	37 M (21.8±3.9)	F_0 . V_0 . Pmax (CMJ)	25m Sprint. T-test. Jump	Pmax ↔ 25m Sprint ($r=-0.93$) / Pmax ↔ T-test ($r=-0.58$) / Sprint-derived F–V metrics were strong predictors of jumping performance.
Pleša et al. (2024)	19 M. 9 F (25.2±3.9)	F_0 . V_0 . Pmax. Slope (SJ & CMJ)	Dynamic Strength Index (DSI)	DSI90 ↔ Pmax ($r=0.550.69$) / DSI30 ↔ V_0 ($r=0.43-0.44$) / DSI proposed as a practical alternative to F–V profiling.
Spudić et al. (2024)	326-M / 17 143-F / 17.4	F_0 . V_0 . Pmax (CMJ)	(CMJ. CoD90 and CoD180) and FvP	No significant correlations were found between the F–V variables from flywheel squats and performance in the CMJ or CoD tests.

Table 3 summarizes correlational studies examining the relationships between F–V variables and sport-performance outcomes. Pleša et al. (2024) reported a substantial association between the dynamic strength index (DSI) and the F–V profile, suggesting that DSI may represent a pragmatic alternative for performance assessment. Manson et al. (2021) and Pleša et al. (2021) reported significant relationships between maximal power (Pmax) and sprint-related performance, although Manson et al. (2021) highlighted weaker associations in female athletes. In contrast, Spudić et al. (2024) found no significant correlations between flywheel-derived F–V variables and jump or change-of-direction performance, highlighting the methodological specificity of assessment tools.

Table 4. Interventional Studies Effects of individualized training based on F–V profil

Author (Year)	Participants	Duration	Intervention Type	Group / Profile Targeted	Key Outcomes
Lindberg et al. (2021)	40 M (20±4)	10 weeks	Individualized training (Force. Optimal. Velocity)	Force-deficient → Balanced → Velocity-deficient	Pmax: +7.8% (Balanced). -2.0% (Velocity). Training towards optimal profile showed greatest power gains.
Nishioka & Okada (2022)	10 M (21.9±1.8)	Acute Protocol	Post-Activation Performance Enhancement (PAPE)	Bilateral Eccentric-Concentric (BEP) vs. Horizontal Resistance (HRP)	Pmax significantly increased in BEP group (p=0.009). highlighting protocol specificity.
Ishihara et al. (2024)	82 M (20.7±1.5)	6 weeks	Deficit-specific training (Force vs. Velocity)	Velocity-deficit: Pmax +4.0% / Force-deficit: Pmax +7.3%	Targeted interventions effectively improved Pmax in the respective deficit groups.
Conceição et al. (2024)	38 M (17.1±0.9)	6 weeks	Individualized training	Correction of F–V imbalance	Significant increase in Pmax from Day 1 to Day 2 (p<0.05) following intervention.
Koźlenia et al. (2025)	25 M (~24 years)	Acute Protocol	PAPE (Force- vs. Velocity-dominant)	PAPE-F (Force) vs. PAPE-V (Velocity)	Pmax increased in PAPE-F group (r=0.63. p=0.03). Supports specific potentiation protocols.

As demonstrated in Table 4, research conducted by Lindberg et al. (2021) and Ishihara (2024) indicates that targeted training programmes are efficacious in correcting F–V imbalances and optimising maximum power (Pmax). These results suggest potential value in training programmes tailored to athletes' specific requirements, though the evidence remains mixed. Furthermore, research on post-activation potentiation (PAPE) protocols, such as that conducted by Nishioka & Okada, (2022) and Koźlenia et al., (2025), reveals that utilising an F–V profile-based approach can also result in substantial performance enhancements.

Table 5. Risk of bias assessment of included studies

Author & Year	Study Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Quality Rating
Observational Cross-Sectional Studies																
Manson et al. (2021)	Observational	Yes	Yes	NA	Yes	NR	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	9
Pleša et al. (2021)	Observational	Yes	Yes	NA	Yes	NR	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	9
Hicks et al. (2023)	Observational	Yes	Yes	NA	Yes	NR	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	9
Pleša et al. (2024)	Observational	Yes	Yes	NA	Yes	NR	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	9
Pérez-Ifrán et al. (2024)	Observational	Yes	Yes	NA	Yes	NR	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	9
Spudić et al. (2024)	Observational	Yes	Yes	NA	Yes	Yes	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	10
Conceição et al. (2025)	Observational	Yes	Yes	NA	Yes	Yes	Yes	NA	Yes	Yes	NA	Yes	No	Yes	Yes	10
Randomized Controlled Trials (RCT)																
RCT – 3 Parallel Groups																
Lindberg et al. (2021)	RCT – 3 Parallel Groups	Yes	Yes	NR	NR	NR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
RCT – Crossover																
Nishoka & Okada (2022)	RCT – Crossover	Yes	Yes	NR	NR	NR	Yes	Yes	Yes	Yes	Yes	Yes	NR	Yes	Yes	10
RCT – Parallel Groups																
Kozłenia et al. (2025)	RCT – Parallel Groups	Yes	Yes	NR	NR	NR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
Non-Randomized Intervention Studies (Quasi-Experimental)																
Intervention – No Control Group																
Ishihara et al. (2024)	Intervention – No Control Group	Yes	NR	NR	NR	NR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Quasi-Experimental																
Conceição et al. (2024)	Quasi-Experimental	Yes	Yes	Yes	Yes	NR	Yes	Yes	No	Yes	Yes	Yes	Yes	-	-	11
Quasi-Experimental																
Qin et al. (2025)	Quasi-Experimental	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	-	-	11

Observational, Cohort, and Cross-Sectional Studies: 1. Clear description of the study objective; 2. Study population clearly specified and defined; 3. ≥50% participation rate of eligible individuals; 4. Uniformly applied and specified selection criteria; 5. Sample size justification provided; 6. Exposure measured before the outcome; 7. Sufficient time frame to expect exposure-outcome association; 8. Different levels of exposure examined; 9. Clearly defined, valid, and reliable exposure measure; 10. Exposure assessed more than once over time; 11. Clear definition of outcome measures; 12. Outcome assessors blinded to participants' exposure status; 13. Loss to follow-up after baseline less than 20%; 14. Adjustment for potential confounding variables.

Randomized Controlled Trials (RCTs): 1. Study described as randomized; 2. Adequate randomization method reported; 3. Concealment of treatment allocation; 4. Participants blinded; 5. Outcome assessors blinded to group assignments; 6. Groups similar at baseline; 7. Overall dropout rate <20%; 8. Differential dropout rate between groups <15%; 9. High adherence to assigned protocols; 10. External interventions avoided or similar between groups; 11. Use of reliable measurement tools; 12. Sample size justification provided; 13. Outcomes or subgroups clearly specified; 14. Analysis performed by intention-to-treat.

Quasi-Experimental Studies: 1. Clear description of the study objective; 2. Eligibility criteria clearly specified and defined; 3. Participants representative of the target population; 4. Eligible participants included consistently; 5. Sufficient sample size to ensure adequate statistical power; 6. Clear description of the intervention; 7. Outcome measures clearly defined and reliable; 8. Outcome assessors blinded to participants' status; 9. Overall dropout rate <20%; 10. Appropriate statistical analysis for pre- vs. post-intervention comparisons; 11. Multiple outcome measurements over time; 12. Group-level effects reported in statistical analysis.

Discussion

Force-velocity (F-V) profile analysis has become an integral component of contemporary performance assessment and physical training in team sports such as soccer, rugby, and basketball (Baena-Raya et al., 2022). This discussion is based on the synthesis of 13 studies included in the present systematic review and aims to critically interpret the principal findings regarding the evaluation and practical application of the vertical F-V profile in team-sport athletes.

The majority of studies conducted on the subject (Conceição, 2024; Hicks et al., 2023; Koźlenia et al., 2025; Manson et al., 2021; Pleša et al., 2024) converge to indicate that the key variables of the vertical F-V profile (theoretical maximum force F_0 , theoretical maximum velocity V_0 , maximum power P_{max} , and slope of the F-V relationship) are relevant indicators of neuromuscular qualities (Samozino et al., 2012). P_{max} has been shown to be a reliable predictor of vertical jump performance (Manson et al., 2021; Pérez-Ifrán et al., 2024). Research has demonstrated a substantial correlation between P_{max} and vertical jump height, thereby validating its role as a reliable metric for evaluating athletic capability (Pérez-Ifrán et al., 2024). These results are consistent with the research of Jiménez-Reyes et al., (2022), which highlights the importance of power as a predictor of explosive performance in various team sports. However, its role becomes more complex when the subject is sprinting (Cross et al., 2017). A significant point of convergence is the pervasive observation of a strength deficit in young athletes (Conceição et al., 2025; Pérez-Ifrán et al., 2024). These findings suggest that more than 75% of young soccer players may present an imbalanced profile oriented toward velocity, with a similarly high prevalence also reported among rugby players.

The evidence regarding training efficacy presents notable inconsistencies. While research by Conceição (2024) and Ishihara (2024) reports improvements following individualized training, it is important to balance these positive findings against contradictory evidence. Lindberg et al., (2021) found no significant advantage of F-V profile-based individualization over non-individualized training, suggesting that the benefits may not be as consistent as sometimes presumed. This discrepancy raises important questions regarding the relative importance of correcting F-V imbalance versus increasing overall power output (Solberg et al., 2025). It is important to note that the duration of the interventions and the population studied could be explanatory factors (Jiménez-Reyes et al., 2014).

In recent research on athletic performance, a recurring question concerns the specificity of F-V profiles in various sports, particularly those involving repetitive actions such as football and rugby. Research has indicated that, in order to enhance performance and mitigate the risk of injury, a training programme that concurrently incorporates vertical (e.g. squats, jumps, plyometric exercises) and horizontal (e.g. sled towing, assisted sprints) exercises is imperative (Falces-Prieto et al., 2021). The findings of this review, which focused exclusively on the vertical profile, indicate a limited transfer to sprinting and change-of-direction performance, consistent with the principle of task- and vector-specificity. This lack of robust transfer is consistent with the principle of specificity and with emerging literature suggesting that horizontal locomotion actions may be better predicted by specific horizontal F-V profiles (Hicks et al., 2023; Pleša et al., 2021). This observation remains speculative within the context of our findings, as the horizontal profile was outside the scope of this systematic review. Therefore, the key conclusion from our analysis is that the vertical F-V profile is a task-specific tool.

Future research should integrate concurrent assessment of vertical and horizontal profiles to clarify their respective contributions to overall sports performance (Jiménez-Reyes et al., 2018). A notable observation from the study by Pleša et al., (2021) is that sprint variables demonstrated a significant predictive capacity for running

jump performance. This particular finding, while intriguing, originates from a single study and warrants replication in broader and more varied athletic populations. It does not overturn the general principle of vector specificity, which is strongly supported by the body of evidence synthesized in this review, but it suggests that the interactions between vertical and horizontal qualities may be complex and merit further investigation. Moreover, the study by Spudić et al., (2024) draws attention to a further significant discrepancy. The findings of this study demonstrate an absence of a substantial correlation between F–V variables derived from a test utilizing an inertial device (flywheel) and performance in vertical jump (CMJ) or change of direction. The lack of correlation observed by Spudić et al., (2024) between flywheel-derived F–V variables and functional performance highlights the methodological specificity of assessment tools. The absence of significant relationships suggests that F–V variables obtained from flywheel squats may not adequately capture the neuromuscular qualities required for jumping and change-of-direction tasks. This finding reinforces the importance of selecting assessment methods that closely match the target performance outcomes.

An important aspect of the present discussion concerns the testing protocols and measurement tools used to derive the vertical F–V profile. Qin et al. (2025) examined squat jumps performed from starting knee angles of 70°, 90°, and 110°. Their findings suggest that standardizing the push-off distance to the value corresponding to a 90° knee angle may reduce variability and improve comparability between participants. The objective of this approach is to reduce variability and enhance the reliability of the simplified method developed by Samozino et al., (2013). Concurrently, the study by Pleša et al., (2024) proposes that the Dynamic Strength Index (DSI) might serve as a valid and safe substitute for the F–V profile in training guidance. However, the study by Conceição et al., (2025) demonstrates that jump height, considered in isolation, is not sufficient to detect F–V imbalances a finding also supported by Bobbert et al., (2023). Indeed, the assessment of these imbalances necessitates a more rigorous approach, particularly through multiple load tests, in order to obtain a comprehensive characterization of physical abilities.

While the exact mechanisms underlying these observations were not directly investigated in the included studies, several theoretical frameworks may help interpret these findings. The disparities between the results obtained in different studies can be attributed to several factors. A thorough examination of the study population illuminates the most salient aspects of this dynamic. As demonstrated in the study by Hicks et al., (2023), responses to a training protocol vary according to performance level (elite vs. amateur), age (youth athletes vs. adults), and gender, highlighting the importance of tailoring vertical F–V interventions to individual characteristics. It is important to note that training protocols vary in terms of duration (between six and ten weeks), volume, and intensity. Seasonal timing may also influence neuromuscular adaptations, as suggested by previous longitudinal studies in team-sport athletes (Hostrup et al., 2019; Jiménez-Reyes et al., 2017). Furthermore, it should be noted that performance tests may vary, which can lead to potentially contradictory results. For instance, an enhancement in CMJ does not necessarily signify progression in sprinting (Ishihara, 2024), thereby reinforcing the relative independence of vertical and horizontal force–velocity (F–V) profiles.

The hypothesis that training specificity is more pronounced for jumping than sprinting finds support in fundamental biomechanical differences between movement vectors. Vertical jumping primarily involves concentric knee extension with minimal horizontal displacement, making it highly responsive to vertical F–V profile optimization. In contrast, sprinting requires efficient force application in a horizontal direction, engaging different muscle groups and neural coordination patterns (Fernández-Galván et al., 2021). This explains why interventions based on vertical

profiling show clearer effects on jump performance compared to sprint outcomes. The scientific literature reports a fundamental distinction between vertical and horizontal F–V profiles (Hicks et al., 2023; Pleša et al., 2021). The research team Pleša et al., (2021) has demonstrated that jumping performance is directly correlated with the vertical profile. Conversely, sprinting and change-of-direction performance are predominantly influenced by horizontal qualities. The findings of this analysis demonstrate that interventions grounded in the vertical F–V profile, encompassing exercises analogous to those employed in the assessment test (bar jumps), provide a more direct application and more unambiguous results.

The findings of this review suggest that F–V profiling shows promise for individualising physical training regimens, particularly for vertical jump performance, though the evidence for its efficacy across all performance domains is not uniform. These findings have clear practical value for coaches and practitioners, offering actionable guidance for optimising training strategies in young and elite athletes. Coaches may consider prioritising the development of maximum strength, given the prevalence of detected strength deficits in young players (Faigenbaum & Myer, 2010), while recognizing that the optimal training approach may vary between individuals. This should encourage the incorporation of heavy strength training (>70% 1RM) into annual planning (Androulakis-Korakakis et al., 2020). Furthermore, it is imperative to personalise training by taking into account the independence of profiles, both vertically and horizontally. Moreover, the assessment of eccentric power can provide a valuable addition to the analysis of essential abilities in deceleration and change of direction manoeuvres.

Limitations and Methodological Considerations

This review synthesizes current evidence on force-velocity profiling, but several limitations must be acknowledged. Although this review primarily targeted studies published between 2020 and 2025, some recently indexed or early-access publications may still have been missed despite the updated search strategy. Second, the focus exclusively on the vertical force-velocity profile, while justified by methodological standardization, means the review cannot fully address the critical interplay between vertical and horizontal force production. Furthermore, the findings must be interpreted considering the methodological characteristics of the included studies. The quality assessment revealed a generally high standard; however, common limitations such as the frequent absence of participant blinding in interventions and occasional lack of sample size justification should be acknowledged. These factors may introduce potential for performance bias and limit the generalizability of some results.

Conclusion

This systematic review shows that the practical usefulness of vertical force–velocity profiling depends largely on the specificity of the motor task being assessed. The synthesized evidence supports its usefulness for optimizing vertical jump performance, an area in which personalised vertical F–V profiling can inform tailored training interventions to systematically enhance power output. However, its application to sprinting and change-of-direction performance remains limited, underscoring the task-specific nature of vertical F–V profiling.

In practice, these results suggest that vertical profiling should be routinely complemented by horizontal assessments to guide training decisions. Future research should integrate these two dimensions through longitudinal studies to validate multidirectional approaches to individualisation, particularly among women and at different levels of competition.

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ASSESSING THE IMPACT OF ASSISTS IN OFFENSIVE EFFICIENCY AND GAME OUTCOMES IN EUROLEAGUE BASKETBALL

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Key words: basketball, assists, efficiency, EuroLeague, data analysis

Abstract: Assists in basketball are considered a key metric of team play and offensive efficiency. The purpose of the study was to examine how assist performance influences team offensive efficiency and game outcomes in the EuroLeague. Data from 224 games of the 2024-2025 EuroLeague regular season were analyzed, including game context, basic and advanced assist metrics, and shooting and performance efficiency metrics. The Mann-Whitney U test measured the differences in these variables between the winning and losing teams, and Spearman's rank-order correlation assessed the strength and direction of associations between assist-related variables, offensive efficiency, and game results. The findings showed that the winning teams recorded significantly higher assist-related metrics ($p < .001$) and higher efficiency ($p < .001$) compared to the losing teams. The Spearman analysis revealed a strong positive correlation between assist-related metrics and offensive efficiency ($p < .001$). A weaker association was observed between assist-related metrics and game outcome ($p < .05$). The assist-to-turnover ratio emerged as a key factor contributing to offensive output and, to a lesser extent, to winning outcomes in elite-level basketball. Data-driven analysis helps optimize team coordination, identify patterns, and promote a culture of effective ball movement, which is vital in elite basketball.

Introduction

As a multidimensional and dynamic team sport, basketball has advanced considerably, with teams increasingly employing offensive and defensive systems that emphasize spacing, tempo control, greater reliance on three-point shots, off-ball movement, and decision-making under pressure (Foteinakis & Pavlidou, 2024; Zajac et al., 2023; Stamiris et al., 2020; Kinrade et al., 2015). Performance analysis has also developed significantly, allowing recording, analysis, and evaluation of individual and team performance (Foteinakis et al., 2024; Gomez-Ruano et al., 2020; Sarlis & Tjortjis, 2020; Zuccolotto et al., 2017). This progression goes beyond traditional scoring metrics, incorporating advanced box-score and tracking data to better quantify team success and strategies (Turner & Franks, 2021).

Statistical analysis in basketball has traditionally focused on scoring ability, with point-related metrics being primary in evaluating team performance. Although traditional and advanced statistics such as points per game, field goal percentage, and offensive rating are still relevant, they do not fully capture how game-related statistics influence team success (Goldsberry, 2012). Research in basketball analytics shows that it is more important to consider multiple factors beyond just scoring variables when measuring team performance (Turner & Franks, 2021). Among the numerous variables affecting basketball performance, assists (AST) have been an important indicator of team play and offensive efficiency (Skinner, 2010). An AST is a pass that directly leads to a scored basket (Melnick, 2001), highlighting not only a team's ability to create scoring opportunities but also the collaborative nature of the game. In the EuroLeague, where top teams and players from Europe compete, understanding how AST impacts overall performance is essential (Kubatko et al., 2007).

The role of AST in basketball has garnered significant interest among researchers and analysts, and smooth ball movement is widely regarded as a key factor in winning games (Supola et al., 2022). Early studies focused on the basic statistical contributions of AST, often linking them to team success (Karipidis, Fotinakis et al., 2001; Melnick, 2001). Oliver (2004) introduced the "assist percentage", which measures the proportion of team plays resulting in an AST, underscoring its importance in analyzing offensive efficiency. Kubatko et al. (2007) also developed the "Player Efficiency Rating", where AST is a major component, emphasizing its relevance to team success and offensive efficiency.

Recent research has further explored how AST influences offensive efficiency, highlighting its importance in elite team performance. Analyses of team play during the Paris Olympics showed that high-scoring teams relied heavily on assists, while lower-scoring teams mainly relied on individual actions, which limited the overall impact of AST (Wang et al., 2025). In NBA and NCAA games, teams with the highest number of assists and secondary assists (a pass that leads to an assist) were more successful and could generate more and higher-quality shots, while winning teams demonstrated significantly higher numbers of passes per possession, confirming that increased ball circulation is positively associated with offensive effectiveness (Karamousalidis et al., 2025; Supola et al., 2022; Stančin & Jović, 2018). Additionally, teams with many ASTs tend to demonstrate better decision-making, improved ball movement, offensive fluidity, and efficiency, characteristics more common among winning teams (Garcia et al., 2013; Sampaio et al., 2010). Supporting these findings, the “expected points added” framework in basketball enables quantifying each action, such as AST, in terms of its contribution to the overall team score, offering a more detailed view of AST value (Cervone et al., 2016). In the EuroLeague, AST was identified as playing a pivotal role with a significant impact on game outcome (Mikolajec et al., 2021). Moreover, Özmen (2016) demonstrated that higher-performing teams have substantially more ASTs, especially in more competitive stages. Conversely, Çene (2018) reported that ASTs did not significantly influence close, balanced, or unbalanced games within the league.

Despite advances in basketball metrics, the influence of AST-related data on offensive efficiency and game results remains underexplored, particularly given the diverse playing styles of the EuroLeague, from fast-paced transition plays to structured half-court sets. Using a dataset that includes both traditional and advanced statistics, such as AST, assist-to-turnover ratio, assisted points ratio, and assists ratio, this research aims to better understand how ASTs support team success. The study explores key questions, such as the link between AST and offensive efficiency and which advanced metrics best capture the AST value compared to traditional stats. The results will deepen insights into the role of AST in team success and identify emerging strategic trends throughout the league, providing practical guidance to coaches and analysts to boost performance, refine offensive tactics, and promote player development, emphasizing the crucial role of AST in top-tier European basketball. The purpose of this study was to examine how AST performance influences team offensive efficiency and game outcomes in the EuroLeague. Specifically, it seeks to analyze the relationship between AST metrics and team success, evaluate AST’s impact on offensive efficiency, and connect traditional statistics with advanced performance measures. It was hypothesized that higher assist-related metrics would be positively associated with greater offensive efficiency and that winning teams would demonstrate higher assist-related values than losing teams. Additionally, advanced assist metrics would better explain team performance compared to traditional statistics.

Methods

Sample

The study utilized game data from the official box scores of the first 25 rounds of the EuroLeague regular season 2024–2025, which are available on the open-access official EuroLeague website (<https://www.euroleaguebasketball.net/en/euroleague/stats/>). The sample included data from 18 EuroLeague teams, with each team playing 25 games, except for two teams that played 24 games due to flu cases, which led to the postponement of their game according to EuroLeague regulations. The total number of games analyzed in this study was 224. Because EuroLeague game-related statistics are publicly available, approval from the Institutional Review Board was not required for this project (Navalta et al., 2019).

Variables and Procedure

The dataset contained two observations per game, one for each team, totaling 448 observations from 224 games. It included variables such as game context (Win/Loss and WIN%), basic assist metrics like AST count and assist-to-turnover ratio (AST/TO), shooting efficiency metrics such as eFG%, and advanced performance measures like offensive rating (OFFRTG). Additionally, composite metrics such as AST Ratio and Assisted Points Ratio (APR) were calculated to provide a more detailed view of the impact of assists. APR shows the percentage of points from assisted shots relative to the total points scored by the team in each game. Its strength lies in being unaffected by factors such as game pace, allowing for comparisons across teams with different tempos. It remains consistent whether a game is high or low scoring, serving as an objective indicator of team cooperation. All variable definitions are provided in Table 1.

Table 1. Definition of the examined variables.

Metric	Definition
Win/Lose	The team won or lost the game
Win Percentage (WIN%)	The percentage of games played that a team has won
Assists (AST)	The number of assists (passes that lead directly to a made basket)
Assists Ratio (AST Ratio)	The number of assists made by the team per 100 possessions
Assists to Turnover Ratio (AST/TO)	The number of assists for a team compared to the number of turnovers
Assisted Points Ratio (APR)	Measures the percentage of points coming from assisted shots among total points for each team in each game. The metric was calculated using the formula: $APR = \{(ASTED_2FG \times 2 + ASTED_3FG \times 3 + ASTED_FT) / PTS\} \times 100$
Effective Field Goal (eFG%)	A pace-independent measure of overall shooting efficiency by accounting for the added value of three-point field goals. The metric is calculated as: $eFG = (FGM + 0.5 \times 3PM) / FGA$. This formula incorporates two and three-point field goals into a single measure, offering a comprehensive assessment of a team's shooting effectiveness
Offensive Rating (OFF RTG)	It captures the ability of a team to score each time they get the ball and estimates the points made by a team based on 100 possessions. The formula is as follows: $OFF\ RTG = PTS / POSS \times 100$

Statistical analysis

No missing values were observed, and the data were retained without transformations. Summary statistics (mean and standard deviation, $M \pm SD$) were calculated for all variables to provide an overview of the dataset. The Shapiro-Wilk test assessed the normality assumption and indicated a non-normal distribution for the examined variables. The Mann-Whitney U test was used to evaluate differences in the examined variables between the winning and losing teams. The rank biserial correlation (r) measured the effect size between assist-related parameters and game outcomes ($r < .30$ = small effect, r between .30 and .50 = medium effect, $r > .50$ = large effect, Cohen, 1988). In addition, Spearman's rank-order correlation analyzed the strength and direction of associations between assist-related variables and offensive efficiency. To prevent multicollinearity, a multiple regression analysis was performed and covariates with Variance Inflation Factors (VIF) > 5 were flagged as potentially redundant and removed from the analysis (Akinwande et al., 2015). The correlation incorporated five variables and the WIN%. All statistical analyses were conducted with JASP (version 0.19, University of Amsterdam, The Netherlands). Statistical significance was set at $p < .05$.

Results

The Mann-Whitney U test revealed significant differences between winning and losing teams in multiple indicators of offensive performance related to AST (Table 2).

Table 2. Comparison of Performance Variables Between Winning and Losing Teams

Variable	Winning Teams (M $\pm$ SD)	Losing Teams (M $\pm$ SD)	U	p	r
Assists	19.53 $\pm$ 4.39	17.085 $\pm$ 3.83	17.085	<.001	.32
Assist Ratio (%)	23.6 $\pm$ 5.40	20.6 $\pm$ 4.80	17.006	<.001	.32
Assisted Points Ratio (%)	50.46 $\pm$ 9.30	48.66 $\pm$ 10.00	22.487	.057	.10
Assist/Turnover Ratio	1.86 $\pm$ 0.93	1.41 $\pm$ 0.49	16.321.50	<.001	.35
eFG%	58.6 $\pm$ 7.20	51.7 $\pm$ 7.00	12.142.50	<.001	.52
Offensive Rating	123.4 $\pm$ 11.38	108.53 $\pm$ 11.20	8.605	<.001	.66

Note. M=mean; SD=standard deviation; U=Mann-Whitney U statistic; r=rank-biserial correlation.

The winning teams recorded significantly more AST ($U=17.085$, $p<.001$), with a medium effect size ($r=.32$). Similarly, the AST/TO Ratio was significantly higher in winning teams compared to losing teams ($U=16.321.50$, $p<.001$, $r=.35$), indicating more efficient ball management. Additionally, the AST Ratio was significantly higher for winning teams than for losing teams ($U=17.006$, $p<.001$, $r=.32$), while APR marginally did not show a statistically significant difference between winning and losing teams ($p=.057$).

Performance-based metrics further distinguished the two groups. The winning teams had significantly higher eFG% than losing teams, with a large effect size ($U=12.142.50$, $p<.001$, $r=.52$). Additionally, OFFRTG was significantly better among winning teams ($U=8.605$, $p<.001$), indicating a large effect size ($r=.66$).

Spearman's rank-order correlation analysis was also performed to examine the relationships between assist-related variables, offensive performance metrics, and winning outcomes in EuroLeague games (Figure 1). The analysis showed a strong positive correlation between AST/TO and OFFRTG ($\rho=.565$, $p<.001$), indicating that teams with higher assists relative to turnovers tend to perform better offensively. Similarly, the AST Ratio was positively associated with OFFRTG ($\rho=.495$, $p<.001$), as was the APR ($\rho=.129$, $p<.01$). Regarding the association of eFG% and assist-related metrics, AST Ratio exhibited a strong correlation ($\rho=.602$, $p<.001$), while AST/TO and APR demonstrated a moderate positive relationship with eFG% ($\rho=.315$ and $\rho=.291$, $p<.001$, respectively).

Furthermore, eFG% showed a very strong positive correlation with OFFRTG ($\rho=.794$, $p<.001$), confirming that shooting efficiency plays a significant role in a team's scoring ability. Concerning winning outcomes, OFFRTG displayed a moderate positive correlation with WIN% ($\rho=.227$, $p<.001$), indicating its important role in differentiating successful teams. Although AST/TO and the AST Ratio were positively correlated with WIN% ($\rho=.177$, $p<.001$ and $\rho=.094$, $p<.05$, respectively), these associations were weaker (Figure 1).

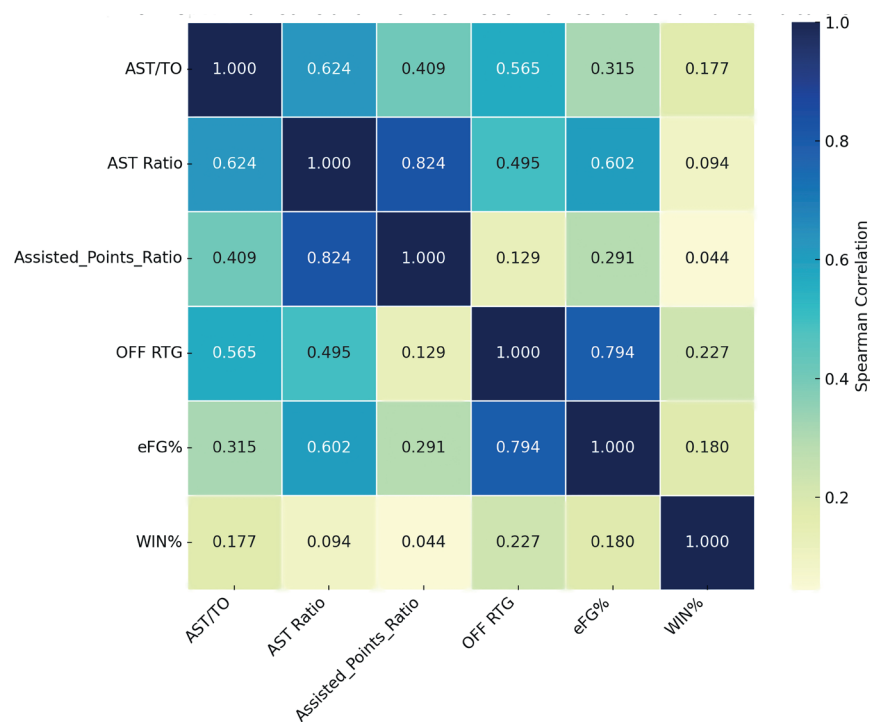


Figure 1. Spearman correlation matrix showing the relationships between assist-related metrics and performance indicators in EuroLeague games.

Discussion

This study examined how assist-related metrics contribute to offensive efficiency and distinguish between winning and losing teams in EuroLeague basketball. The findings strongly indicate that advanced statistics related to ASTs, rather than just the number of ASTs, are more reliable predictors of offensive success and competitive outcomes, supporting the growing view in performance analysis that suggests predicting outcomes in elite basketball relies more on metrics adjusted by possession than on simple statistics.

In support of earlier research on the importance of playmaking in elite basketball (Liang et al., 2025; Plakias et al., 2024; Turner & Franks, 2021), winning teams showed significantly higher values in AST and AST/TO Ratio compared to losing teams. The moderate effect sizes observed for AST and the AST Ratio, with a stronger effect for AST/TO, emphasize that creating scoring opportunities is key, but doing so while minimizing turnovers is equally vital. This supports the idea that efficient playmaking, indicated by the AST/TO balance, is a more meaningful measure of team quality than total assists alone (Plakias et al., 2024). More assists generally lead to more field goals made, while fewer turnovers lead to more field goals attempted and fewer points lost from turnovers. This aligns with emerging evidence suggesting that isolated AST metrics can be misleading without considering context-specific factors such as turnover risk, shot selection, and possession quality (Skinner, 2010).

Although the APR did not reach statistical significance between winning and losing teams ($p=.057$), it was close to the traditional threshold, indicating a possible trend toward higher values among winning teams. This nearly significant result suggests that the proportion of points generated through assists may influence offensive effectiveness, though its impact appears less consistent than other assist-related metrics, such as AST/TO or AST Ratio. One reason could be that APR reflects the outcome of assisted scoring rather than the efficiency of ball movement, making it more affected by contextual factors like shooting accuracy, shot selection, and offensive structure. Additionally, the medium effect size suggests that while assisted scoring is relevant, it may not alone distinguish team success at the elite level. These findings highlight the need for further research on APR alongside other performance indicators and larger samples to better understand its role in offensive performance.

The results also confirmed the crucial role of offensive efficiency in winning games. eFG% and OFFRTG were notably higher among winning teams, indicating a strong effect size. These results align with previous research (McKim et al., 2023; Mandić et al., 2019), which identified eFG% and OFFRTG as key performance indicators. These metrics were closely linked, suggesting that accurate and high-value shot selection, especially from three-point range, is essential for effective scoring (Foteinakis & Pavlidou, 2024; Gkotsis, 2024; Çene, 2018). EuroLeague teams prioritize good ball movement and creating open shot opportunities to improve overall shot quality and offensive efficiency, with offensive possessions characterized by patience and precision, often taking shots later in the shot clock (Karamousalidis et al., 2025). This aligns with the findings of Foteinakis, Pavlidou, and Stavropoulos (2024), who reported that EuroLeague offenses are typically built on structured, team-oriented strategies that favor collective execution over individual shot creation, resulting in higher scoring efficiency, a process directly reflected in the elevated AST metrics of winning teams in this study.

Although both AST/TO and AST Ratio showed positive correlations with WIN%, these relationships were weaker than the correlation of OFFRTG with WIN%. Although correlation does not imply causation, this pattern emphasizes that AST efficiency helps enable broader offensive success rather than directly determining game outcomes. These findings support earlier research (Cabarkapa et al., 2024; Özmen, 2016; Ziv et al., 2010), indicating that efficient passing and fewer turnovers lead to more effective offenses, which in turn increase the chances of winning. However, the weaker links between AST metrics and WIN% highlight the complexity of predicting victory, as it also depends on defensive and game context factors not examined here.

From a practical point of view, these findings highlight the strategic importance of improving assist efficiency through tactical design, such as optimizing spacing, shot opportunities, and decision-making under pressure. Coaches can benefit from fostering a team culture that emphasizes effective ball movement, which has been proven essential, especially in critical game situations (Foteinakis & Pavlidou, 2024). Additionally, we recommend using AST/TO as the most influential metric to assess the value of ball movement. Employing the AST/TO ratio provides a more accurate reflection than simply counting assists or points created per game because some teams prioritize offense while others focus on defense, making comparisons across different play styles potentially misleading. While this study provides significant information, it does not account for contextual factors such as player roles, opponent strength, shot quality, and defensive coverages. Furthermore, the current analysis focuses solely on regular-season data, which may restrict generalizability to playoff or high-pressure contexts where tactical behaviors may differ. Extending the research to playoff games could potentially offer deeper insights into assist-related metrics under increased pressure. Future research could also explore AST-related metrics across various play types (pick-and-

roll, isolation, etc.) or during clutch moments. Additionally, integrating players' position tracking data could lead to a better understanding of assist creation and conversion efficiency.

Conclusions

Exploring AST metrics in EuroLeague basketball revealed significant findings that impact offensive efficiency and game outcomes. Particularly, the AST/TO ratio appeared as a key contributor to offensive output and, to a lesser extent, to winning outcomes in elite-level basketball. The winning teams demonstrated a more effective assist distribution, thereby enhancing offensive efficiency and illustrating the critical role of teamwork in achieving game success. The observed differences in the AST/TO ratio and assist efficiency between winning and losing teams suggest that traditional measures, such as the raw number of assists, are no longer sufficient to explain performance outcomes. Modern basketball analytics is therefore moving toward efficiency-driven indicators, which provide a more accurate reflection of team effectiveness and decision-making in elite competition. Meanwhile, offensive efficiency, as represented by eFG% and OFFRTG, remained the most important factor linked to successful outcomes. Data-driven analyses can guide coaches in optimizing team collaborations and identifying assist patterns, resulting in strategic adjustments during the season. These findings can help coaches and team analysts develop strong coaching strategies, highlighting the importance of communication and disciplined tactical execution, which are essential factors for enhancing performance in elite basketball environments.

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ANALYSIS OF BODY COMPOSITION IN SCHOOL-AGED CHILDREN AS AN INDICATOR OF OBESITY RISK AND A CHALLENGE FOR HEALTH PROMOTION

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Abstract Background. Overweight and obesity among school-aged children are an increasing global public health problem, leading to serious health, social, and economic consequences. Early diagnosis and identification of children at risk are essential for preventive strategies. Since BMI has limitations in assessing body composition, bioelectrical impedance analysis (BIA) is increasingly applied.

Aim. The aim of the study was to analyze body composition parameters in 10–11 year-old children with emphasis on gender differences.

Material and methods. The study involved 254 primary school students from the Świętokrzyskie region. Body composition was measured using the Tanita MC-780 device, assessing body weight, height, BMI, body fat percentage, muscle mass, basal metabolic rate (BMR), impedance, and phase angle.

Results. Among 10-year-old children, boys showed significantly higher fat-free mass, muscle mass, and bone mass than girls. In the group of 11-year-olds, girls demonstrated significantly higher fat-free mass, muscle mass, and bone mass than boys. No significant sex differences were observed in BMI, body fat percentage, or phase angle. Strong positive correlations were found between body mass and BMI and between muscle mass and fat-free mass in both sexes.

Conclusions. The results confirm sex-based differences in body composition. Early identification of abnormal values can support targeted preventive and educational interventions.

Key words: body composition, obesity, overweight, health, prevention

Introduction

Childhood obesity is currently one of the most serious health challenges worldwide, recognized by the World Health Organization (WHO) as the epidemic of the 21st century. According to WHO data from 2023, over 340 million

children and adolescents aged 5–19 years were overweight or obese, and this problem affects nearly all countries regardless of their economic development level (WHO, 2023a). In Poland, according to the latest data from the Institute of Mother and Child, overweight and obesity affect over 30% of boys and 20% of girls of school age (Instytut Matki i Dziecka, 2022).

The health consequences of obesity in childhood are multidimensional. They include both direct threats such as hypertension, insulin resistance, and lipid disorders, as well as long-term consequences in adulthood, including an increased risk of type 2 diabetes, cardiovascular diseases, and metabolic syndrome (Styne et al., 2017; Simmonds et al., 2016). Moreover, childhood obesity is often associated with lowered self-esteem, depression, and social relationship disorders (Griffiths et al., 2010).

The traditional tool for assessing nutritional status and obesity risk is the Body Mass Index (BMI); however, it has limitations, especially in children undergoing growth. BMI does not account for body composition and does not distinguish between fat mass and muscle mass, which may lead to misclassification, particularly among physically active children or those in rapid growth phases (Javed et al., 2015). Therefore, in recent years, increasing attention has been paid to body composition assessment as a more accurate tool for identifying health risks (McCarthy et al., 2006; Maffei et al., 2008; Ashwell et al., 2005; Wells & Fewtrell, 2006).

Studying body composition in children aged 10–11, who are at the onset of puberty, holds particular diagnostic and preventive significance. This period involves intensive hormonal and growth changes that may affect metabolic processes and health behaviors established for life (Reilly et al., 2011).

In the context of child and adolescent health, health promotion should include multi-level activities combining health education, environmental support, and public policy. According to the WHO Bangkok Charter, health promotion is “the process of enabling people to increase control over and improve their health” (WHO, 2019). This specifically involves shaping pro-health dietary habits, promoting daily physical activity, and reducing sedentary behavior, including screen time (WHO, 2005; Guthold et al., 2020). Schools play an important role as educational and developmental environments where effective preventive and health programs can be implemented. WHO and UNESCO emphasize that schools should be “Health-Promoting Schools,” integrating physical, mental, and social health content (WHO, UNESCO, UNICEF, 2021).

Despite the availability of such programs, their effectiveness is sometimes limited due to a lack of systematic monitoring and insufficient involvement of families and local communities. Meanwhile, early body composition and nutritional status assessment can serve as a starting point for individualizing educational and motivational interventions, enhancing their effectiveness (Żegleń & Koziol-Kozakowska, 2018). The hypothesis is that sex-related differences in body composition are already present in prepubertal children and can be detected using bioelectrical impedance analysis, providing more detailed insight than BMI alone. The combination of diagnostic tools (e.g., body composition analysis) with promotional and educational activities appears crucial for building healthy habits and preventing the childhood obesity epidemic.

The aim of this study was a detailed analysis of body composition and evaluation of obesity risk indicators in children aged 10–11 attending primary schools in the Świętokrzyskie Voivodeship. The paper also presents implementation recommendations for promoting health among school-aged children to prevent overweight and obesity risk.

Material and methods

The study was conducted at the Posturology Laboratory of the Collegium Medicum, Jan Kochanowski University in Kielce. The measurements were performed once, after obtaining written consent from the parent or guardian of each participant. All research procedures were carried out in accordance with the Declaration of Helsinki of 1964 and with the approval of the Bioethics Committee of Jan Kochanowski University in Kielce (Resolution No. 37/2018).

Participants

A total of 254 children from the Świętokrzyskie Voivodeship participated in the study, including 123 girls (48.43%) and 131 boys (51.57%). The selection of participants was mixed, following predefined inclusion criteria for each group. The study included children aged 10 and 11 years. The larger group consisted of 10-year-olds ($n=134$; 52.76%), of whom 69 (51.49%) were girls and 65 (48.51%) were boys. The 11-year-old group consisted of 120 children (47.24%), including 54 (45%) girls and 66 (55%) boys. Inclusion criteria covered children aged 10–11 attending primary schools in the region, who voluntarily agreed to participate and whose parents or legal guardians provided consent. Children with chronic diseases or metabolic disorders potentially affecting body composition, such as diabetes or hormonal imbalances, were excluded. Participants who did not consent to measurements or withdrew from the study were also excluded, as well as those with contraindications for bioelectrical impedance measurement (e.g., pacemaker or other electronic implants). Incomplete or unreliable measurement data were excluded from the analysis. These criteria ensured a reliable and representative study sample necessary for a thorough health assessment and for formulating recommendations on health promotion and obesity prevention among school-aged children.

Instruments

The assessment of body composition was conducted using the objective method of bioelectrical impedance with the Tanita MC-780 device. Bioelectrical impedance is a rapid and non-invasive method for evaluating body composition, based on measuring the electrical resistance of tissues. The Tanita MC-780 device employs advanced algorithms and multifrequency impedance analysis to accurately estimate muscle mass, fat mass, water content, and bone mass. Recent publications emphasize improvements in measurement precision due to technological advancements and highlight its wide application in clinical studies, population health monitoring, and preventive programs. Body composition analysis was performed using the Tanita MC-780 analyzer, which provides a full body composition profile in approximately 20 seconds. The device measures the following parameters: Body Mass (BM), expressed in kilograms; Basal Metabolic Rate (BMR), indicating the minimum amount of energy required for proper functioning of the body at rest; Fat Percent (FP%), the percentage of body fat; Fat Mass (FMkg), the absolute mass of fat tissue; Fat Free Mass (FFMkg), which includes muscle mass, internal organs, and bones, representing the most metabolically active component of the body; Total Body Water (TBW); Predicted Muscle Mass (PMM), which includes skeletal and smooth muscles; Impedance (IMP), the measure of electrical resistance of tissues used in body composition calculations, where water-rich tissues (e.g., muscles) conduct electrical current more easily than fat tissue. Additionally, the device measures Body Mass Index (BMI), a standard parameter for assessing body weight, expressed in kg/m^2 ; Visceral Fat Level (VFATL), indicating fat located deep in the abdominal cavity; Bone

Mass (BONEM); Extracellular Water (ECW) and Intracellular Water (ICW). The Phase Angle (PA) is also analyzed, which reflects the overall health status and quality of tissue and cellular functions, as well as the nutritional status of the body. The phase angle is calculated based on electrical resistance and reactance; low values may indicate physical exhaustion, malnutrition, or chronic diseases (Lima et al., 2022).

Measurements were performed under standardized conditions. Participants were assessed in light clothing and barefoot. They were instructed to avoid vigorous physical activity before the examination and to maintain normal hydration status. All measurements were performed according to the manufacturer's recommendations.

Statistical analysis

For statistical analysis, descriptive methods were applied, including calculation of arithmetic means ($\bar{x}$), standard deviations (SD), and coefficients of variation (CV) for individual body composition parameters. Pearson's correlation coefficient (r) was used to assess the strength and direction of relationships between anthropometric variables. Furthermore, to compare the significance of differences between correlation coefficients in girls and boys, the Fisher's Z-transformation test was applied, enabling statistical evaluation of differences between correlations. To address intergroup variability, Student's t-test for independent samples was used to compare body composition parameters between girls and boys.

Results

Table 1 presents the mean values and variability of basic body composition parameters in 10-year-old children, differentiated by sex. The average height of boys (139.97 cm) was slightly higher than that of girls (138.52 cm), with a low coefficient of variation (around 6%), indicating a narrow range of measurements in both groups. Body mass and body mass index (BMI) were comparable between sexes, but showed a high coefficient of variation (around 27% for mass), reflecting significant individual differences. Basal metabolic rate (BMR) was higher in boys, correlating with their greater fat-free mass. The percentage and mass of fat tissue were slightly higher in girls, whereas fat-free mass, muscle mass, and bone mass were significantly higher in boys, consistent with typical sex differences at this age. Bioimpedance parameters such as electrical impedance and phase angle indicated similar muscle quality and hydration status in both groups. The analysis of variability distribution highlights substantial individual differences in the examined parameters, which is important for assessing obesity risk and planning preventive interventions.

Table 1. Descriptive parameters of variables in the group of 10-year-old children

Variable	Girls			Boys		
	($\bar{x}$)	(S)	(V%)	($\bar{x}$)	(S)	(V%)
Height [cm]	138.52	9.02	6.51	139.97	8.59	6.14
Mass [kg]	36.36	9.75	26.83	37.58	10.27	27.32
BMI	18.85	3.92	20.78	18.91	3.74	19.76
BMR [kJ]	5199.41	767.71	14.77	5538.52	599.45	10.82
BMR [kcal]	1255.54	170.17	13.55	1324.32	138.80	10.48
Fat tissue [%]	23.26	4.91	21.12	22.54	6.84	30.37
Fat tissue mass [kg]	8.89	4.01	45.15	8.79	4.74	53.92
Fat-free mass (FFM) [kg]	27.46	6.46	23.54	28.83	6.02	20.86
Muscle mass (PMM) [kg]	25.69	5.99	23.30	27.34	5.67	20.74

	Girls			Boys		
Bone mass [kg]	1.43	0.30	21.29	1.56	0.28	18.02
Total body water (TBW) [kg]	20.26	4.65	22.97	20.97	5.86	27.94
Water content [%]	55.71	3.53	6.33	56.69	4.34	7.66
Impedance [Ohm]	689.41	76.93	11.16	688.94	67.84	9.85
Phase angle [°]	5.22	0.45	8.58	5.31	0.67	12.60

Source: Author's own elaboration. Abbreviations: ($\bar{x}$) – mean; (S) – standard deviation; (V%) – coefficient of variation.

A comparative analysis of body composition parameters in 11-year-old children (Table 2) showed similar mean values of height and body mass between girls and boys, with girls presenting slightly higher body mass (42.40 kg vs. 40.49 kg) and BMI (20.78 vs. 19.34 kg/m²). Basal metabolic rate (BMR), expressed both in kJ and kcal, was comparable between sexes. The percentage and mass of body fat were slightly higher in girls, which is consistent with physiological developmental differences observed at this age. In addition, girls demonstrated higher values of fat-free mass (FFM), predicted muscle mass (PMM), bone mass, and total body water (TBW) expressed in kilograms. Boys, however, showed slightly lower variability in several body composition parameters, suggesting a more homogeneous pattern of somatic development. The percentage of body water was also higher in girls (57.77%) than in boys (55.53%), although variability remained moderate in both groups. Electrical impedance values were higher in boys, whereas phase angle values were comparable between sexes. The greatest variability was observed for fat mass expressed in kilograms, indicating substantial individual differences in adiposity among the examined children.

Overall, the results demonstrate sex-related differences in body composition at the age of 11 years and emphasize the importance of comprehensive body composition assessment in obesity prevention and health promotion programs targeting school-aged children.

Table 2. Descriptive parameters of variables in the group of 11-year-old children

	Girls			Boys		
Variable	($\bar{x}$)	(S)	(V%)	($\bar{x}$)	(S)	(V%)
Height [cm]	142.00	9.25	6.39	143.46	9.17	6.39
Mass [kg]	42.40	12.77	29.24	40.49	11.84	29.24
BMI	20.78	4.90	23.58	19.34	4.05	20.92
BMR [kJ]	5517.83	821.86	14.89	5605.36	695.72	12.41
BMR [kcal]	1316.83	186.74	14.19	1317.79	225.19	17.09
Fat tissue [%]	24.20	7.77	32.11	23.05	7.17	31.10
Fat tissue mass [kg]	10.63	6.90	64.89	10.09	6.01	59.57
Fat-free mass (FFM) [kg]	31.77	7.39	23.27	29.66	6.53	22.01
Muscle mass (PMM) [kg]	30.08	6.94	23.07	28.40	6.29	22.14
Bone mass [kg]	1.70	0.33	19.53	1.61	0.31	18.98
Total body water (TBW) [kg]	23.42	5.55	23.71	21.75	5.88	27.03
Water content [%]	57.77	7.02	12.14	55.53	6.27	11.28
Impedance [Ohm]	694.50	92.02	13.24	735.80	81.08	11.02
Phase angle [°]	5.30	0.54	10.19	5.28	0.48	9.03

Source: Author's own elaboration. Abbreviations: ($\bar{x}$) – mean; (S) – standard deviation; (V%) – coefficient of variation.

Table 3 presents a comparison of Pearson correlation coefficients (r) for selected pairs of anthropometric variables in girls and boys aged 10 and 11 years, along with an assessment of the significance of differences between these correlations using Fisher's Z test. This comparison was made both for body mass vs. BMI and muscle mass (PMM) vs. fat-free mass (FFM). Very high positive correlations were observed in both sexes, regardless of the age group. Correlation coefficients ranged from $r=0.88$ to $r=0.97$, indicating a strong relationship between the analyzed parameters.

The Fisher's Z test analysis showed no significant differences in correlation strength between girls and boys – all p -values were significantly greater than the 0.05 threshold. This means that the relationships between body mass and BMI, as well as between muscle mass and fat-free mass, are comparable between sexes in both age groups studied. These results confirm the stability of the relationships among basic body composition indicators in the studied population and support their use in assessing the risk of overweight and obesity in children.

Table 3. Comparison of correlation strength for selected pairs of anthropometric and body composition variables in girls and boys aged 10 and 11 years, with significance testing using Fisher's Z statistic

Age	Variable Pair	Girls (r)	Boys (r)	Fisher's Z	p -value
10	Body mass [kg] / BMI	0.92	0.90	0.31	0.75
	Muscle mass PMM / FFM	0.97	0.94	1.12	0.26
11	Body mass [kg] / BMI	0.89	0.88	0.14	0.89
	Muscle mass PMM / FFM	0.95	0.96	-0.41	0.68

Source: Author's own elaboration. Abbreviations: r – Pearson's correlation coefficient; Z – Fisher's Z transformation; p -value – probability value

Table 4. Comparison of body composition parameters between girls and boys aged 10 and 11 years using Student's t-test

Variable	Age	Girls ($\bar{x} \pm SD$)	Boys ($\bar{x} \pm SD$)	t-value	p -value
Height [cm]	10	138.52 $\pm$ 9.02	139.97 $\pm$ 8.59	-0.95	0.34
Body mass [kg]	10	36.36 $\pm$ 9.75	37.58 $\pm$ 10.27	-0.71	0.47
BMI [kg/m ²]	10	18.85 $\pm$ 3.92	18.91 $\pm$ 3.74	-0.08	0.93
Fat tissue [%]	10	23.26 $\pm$ 4.91	22.54 $\pm$ 6.84	0.69	0.49
Fat-free mass (FFM) [kg]	10	27.46 $\pm$ 6.46	28.83 $\pm$ 6.02	-2.11	0.036
Muscle mass (PMM) [kg]	10	25.69 $\pm$ 5.99	27.34 $\pm$ 5.67	-2.28	0.024
Bone mass [kg]	10	1.43 $\pm$ 0.30	1.56 $\pm$ 0.28	-2.17	0.031
Phase angle [°]	10	5.22 $\pm$ 0.45	5.31 $\pm$ 0.67	-0.88	0.37
Height [cm]	11	142.00 $\pm$ 9.25	143.46 $\pm$ 9.17	-0.91	0.36
Body mass [kg]	11	42.40 $\pm$ 12.77	40.49 $\pm$ 11.84	1.02	0.31
BMI [kg/m ²]	11	20.78 $\pm$ 4.90	19.34 $\pm$ 4.05	1.89	0.06
Fat tissue [%]	11	24.20 $\pm$ 7.77	23.05 $\pm$ 7.17	1.01	0.31
Fat-free mass (FFM) [kg]	11	31.77 $\pm$ 7.39	29.66 $\pm$ 6.53	2.45	0.015
Muscle mass (PMM) [kg]	11	30.08 $\pm$ 6.94	28.40 $\pm$ 6.29	2.18	0.031
Bone mass [kg]	11	1.70 $\pm$ 0.33	1.61 $\pm$ 0.31	2.01	0.046
Phase angle [°]	11	5.30 $\pm$ 0.54	5.28 $\pm$ 0.48	0.22	0.82

Source: Author's own elaboration. Abbreviations: $\bar{x} \pm SD$; SD – standard deviation; $\bar{x}$ – mean; t-value – t-test statistic; p -value (statistical significance at $p < 0.05$).

Discussion

The results presented in this analysis indicate very strong positive relationships between selected pairs of anthropometric and body composition variables in both girls and boys aged 10 and 11 years. The highest correlation coefficients were observed between muscle mass (PMM) and fat-free mass (FFM), with values of r ranging from 0.94 to 0.97. This level of concordance confirms the dominant role of muscle mass within the FFM structure in the population of children in late childhood.

Strong correlations were also found between body mass and BMI ($r=0.88-0.92$), confirming their high interdependence. However, as noted by Ortega et al., BMI does not differentiate the quality of body mass, especially the ratio between fat and muscle tissue, which can lead to misinterpretations of nutritional status, particularly in children with increased muscle mass. Although BIA provides more detailed insight than BMI, its accuracy may be influenced by hydration status and pubertal stage, which should be considered when interpreting pediatric data. Thus, the results of this analysis emphasize the need to use more complex measures of body composition, such as bioelectrical impedance analysis, for assessing obesity risk during developmental age (Ortega et al., 2022).

The analysis of differences in correlation strength between girls and boys, conducted using Fisher's Z statistic, showed no statistically significant discrepancies (all p -values >0.05). This indicates that the nature of the relationships between the analyzed pairs of variables is similar in both sexes, which may suggest comparable developmental processes in body composition components during this period of life. At the same time, the results align with international pediatric studies conducted in European populations, which describe typical sex-related differences in body composition. The present study demonstrated sex-related differences in body composition; however, the pattern varied according to age. Among 10-year-old children, boys exhibited significantly higher fat-free mass, muscle mass, and bone mass. In contrast, among 11-year-olds, girls presented significantly higher values of these parameters. These findings may reflect differences in the timing of biological maturation, as girls typically enter pubertal development earlier than boys. Therefore, body composition assessment should be interpreted not only according to chronological age but also considering developmental stage.

Regular monitoring of indicators such as PMM, FFM, fat mass, and body water content allows for a more precise assessment of metabolic risk and can serve as a starting point for educational activities and school programs promoting physical activity and healthy eating habits (Janssen & LeBlanc., 2021; WHO, 2023b).

In summary, the conducted body composition analysis of children aged 10–11 years indicates significant changes that fit into the global rise of childhood obesity, confirmed by numerous studies in recent years. Our observations, especially regarding higher BMI and increased fat percentage among the examined children, align with current epidemiological trends described by Wang and Lim, who confirmed the increasing obesity rate in school-aged children worldwide (Wang & Lim 2012).

Moreover, studies by Sahoo et al. indicate that early adolescence is a critical period for interventions preventing obesity development, and precise monitoring of body composition can significantly improve early detection of children at risk of excessive fat gain (Sahoo et al., 2015).

Furthermore, recent studies indicate that BMI alone is insufficient for precise identification of children at obesity risk. As stressed by authors from the European Childhood Obesity Group (ECOG) in their 2022 recommendations, incorporating body composition, including fat percentage and muscle mass, is crucial to better tailor preventive and therapeutic strategies (ECOG, 2022). Our own results fit within this framework, showing individual differences in body composition that do not always correlate linearly with BMI values.

In light of these data, the present analysis confirms the necessity of introducing comprehensive body composition assessments in routine pediatric examinations and highlights the need for health education targeted at families, promoting physical activity and healthy eating habits from early childhood (Barlow, 2007). Increasing emphasis on childhood obesity prevention is also evident in global WHO strategies (2023c), which underline the need for multidimensional interventions involving school, family, and community environments (WHO, 2023c).

For effective health promotion among children aged 10–11 years, it is recommended to implement regular monitoring of health parameters, including annual BMI measurements and detailed body composition assessment, such as muscle and fat mass. To ensure the reliability and accuracy of these measurements, training of school personnel—such as nurses and physical education teachers in measurement techniques and result interpretation is essential. Concurrently, education of children and their parents through workshops and meetings highlighting the importance of proper nutrition and regular physical activity is crucial. Educational materials like brochures, posters, and short videos should clearly explain the significance of the balance between muscle and fat mass for health and proper development. Promotional activities should be systematically monitored and evaluated through data collection and trend analysis regarding body composition and health indicators in children. Regular assessment of intervention effectiveness will enable optimization and adaptation to population needs, increasing the efficiency of health promotion and obesity prevention programs.

Despite the practical value of this study, several limitations should be acknowledged. First, the study sample included children from only one region, which may limit the generalizability of the findings to the entire pediatric population in Poland. Second, the cross-sectional design does not allow for causal inference regarding obesity development. Third, the analysis did not include levels of physical activity, dietary habits, or socioeconomic factors, which may significantly influence body composition. Moreover, although bioelectrical impedance analysis is a practical and non-invasive method, its accuracy may be affected by hydration status and diurnal biological variability.

Regular physical activity remains a key component of obesity prevention in school-aged children. According to WHO recommendations, children and adolescents aged 5–17 years should engage in at least 60 minutes of moderate-to-vigorous physical activity daily. Insufficient physical activity and sedentary behavior significantly increase the risk of excessive fat accumulation and metabolic disorders. Therefore, body composition monitoring should be combined with physical activity promotion programs and health education implemented in the school environment (WHO, 2019).

The obtained results support the study hypothesis, confirming that sex-related differences in body composition are already observable in children aged 10–11 years. Bioelectrical impedance analysis provided more detailed information than BMI alone and allowed identification of differences in fat-free mass, muscle mass, and fat tissue distribution that may be relevant for obesity prevention and health promotion strategies.

Conclusions

1. Significant sex-related differences in body composition were observed among children aged 10–11 years.
2. Girls demonstrated a higher percentage of body fat, whereas differences in muscle mass, fat-free mass, and bone mass varied according to age.
3. Strong correlations indicate that these indicators may be useful components of obesity risk assessment.

4. Bioelectrical impedance analysis provides valuable information beyond BMI and may improve early identification of children at increased risk of overweight and obesity.
5. Regular monitoring of body composition should be incorporated into school-based health promotion and obesity prevention programs.
6. Future studies should include larger and more diverse populations and consider physical activity, dietary habits, and socioeconomic determinants of health.

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POSTURE IN RELANTION TO BMI AMONG 10-YEAR-OLD PRIMARY SCHOOL PUPILS

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Abstract We are currently seeing an increase in poor posture and body weight. The aim of the study was to determine the relationship between proper posture and the Body Mass Index (BMI) among pupils in primary education. We applied ex post facto research. The study sample consisted of a total of n=559 pupils. We compared the groups of boys (n=127) and girls (n=138) from 2015 with the group of boys (n=143) and girls (n=151) studied in 2025 from 26 primary schools in the regions of Western and Central Slovakia. When assessing the overall posture in relation to the BMI of primary school girls in selected regions of Slovakia in 2015 and 2025, we found a significant increase in the BMI of 0.52, as well as a deterioration in overall posture by an average of 1.5 points. Among primary school boys from selected regions of Slovakia tested in 2025, we found a significant increase in the BMI of 0.88 compared to boys tested in 2015. These findings indicate that an elevated BMI negatively impacts overall posture in both boys and girls in primary schools in selected regions of Slovakia.

Key words: primary school, posture, BMI, musculoskeletal health, child development

Introduction

In Slovakia, over the past two decades, there has been an increasing trend in illnesses and health disorders among the school population. Bendíková (2020) points out an unfavourable situation in the area of postural health in the school population.

However, there is little longitudinal evidence showing how these trends have evolved over the past decade in Central European countries. The period 2015–2025 is particularly important, as it includes major changes in society, from the increase in the use of digital devices to the COVID-19 pandemic (2020–2021) which have significantly influenced children's physical activity levels and sedentary behaviours (Neville et al., 2022; Pfefferbaum, & Van Horn, 2022; Faust et al., 2024).

The school environment can pose a health risk for some pupils. Reduced physical activity due to sedentary behaviour and carrying school bags increase the risk of poor posture, a higher BMI, and rising obesity among pupils (Kabatová et al., 2012; Rozim et al., 2022; Hojker et al., 2023).

Correct posture in pupils depends on the spine, the body's axis that bends, rotates, and stretches. Its elementary function is precisely the support and holding of the body (Kabatová et al., 2012; Repko, 2017).

Spinal deformities have various forms and causes. They belong to groups of diseases that are often associated with a primary condition. Pupils in primary schools often avoid physical education classes (Arufe-Giráldez et al., 2022; Shimon, 2025). The absence of physically active role models among parents contributes to a large proportion of pupils having poor posture accompanied by pain. Up to 85% of cases of poor posture in youth in Slovakia are idiopathic scoliosis (Vojtaššák, 2000; Prieto-González et al., 2021).

Many postural problems begin during periods of growth and physical development (Bendíková, 2016; Desouzart, & Figueiras, 2023).

The biomechanical relationship between increased BMI and poor posture is well established: excess abdominal adipose tissue shifts the centre of gravity anteriorly, requiring compensatory postural adjustments in the kinetic chain (Calcaterra et al., 2022). In growing children, these compensatory mechanisms can become stable patterns, which can lead to structural changes in the developing musculoskeletal system over time.

Similarly, obesity represents a significant global health problem today. From a biological perspective, it is a metabolic disease with an excess of adipose tissue in the body, assessed according to the child's age, height, and sex.

In obese pupils, excessive fat mass leads to a reduction in coordination abilities and a decline in health-related fitness. Their ability to perform physical activity decreases (Cvejic, & Ostojic, 2018; Chen et al., 2018). Scientific studies in this area show that up to 80% of obese children become obese adults (Zhu, & Yin, 2023; Ng et al., 2024).

Despite the growing evidence on the relationship between obesity and posture, few studies have simultaneously examined the temporal trends of both indicators within the same population. This study addresses this gap by comparing BMI and postural quality in primary school children in Slovakia over a 10-year period (2015–2025).

Beyond its scientific relevance, the study is highly valuable for education and public health. Monitoring posture and BMI in schools provides key information for adapting physical education programs and identifying pupils at risk. For teachers, especially in physical education, the findings can guide interventions to prevent postural imbalances and promote an active lifestyle. At the public health level, understanding long-term trends in children's posture and weight supports preventive strategies, reduces musculoskeletal risks, and helps curb rising obesity rates among youth.

We hypothesized that: (1) BMI would be significantly higher in 2025 compared to 2015, (2) postural quality would be significantly lower in 2025, and (3) higher BMI would be correlated with poorer posture in both periods, with stronger associations in the obesity category.

The aim of the study was to expand knowledge about posture depending on the BMI in the school population of younger school-aged boys and girls. We compared the results of research on primary education pupils in 2015 and 2025. Highlights:

- Higher BMI is associated with poorer posture in 10-year-old pupils.
- Posture quality declined between 2015 and 2025 in Slovak primary schools.
- BMI increased significantly in both boys and girls over the 10-year period.
- Excess weight negatively affects musculoskeletal alignment in children.
- Findings highlight the need for school-based preventive interventions.

Material and Methods

Participants

The monitored sample consisted of a total of $n=559$ pupils. We compared groups of boys ($n=127$) and girls ($n=138$) diagnosed in 2015 with a group of boys ($n=143$) and girls ($n=151$) diagnosed in 2025 from 26 primary schools in the western and central regions of Slovakia.

Ethical Approval. This study was approved by the Ethics Committee of University CU (Decision No. CZ 03113/2025 RE, 04. September 2025).

The research and measurements were conducted in accordance with ethical principles of the Declaration of Helsinki as well as GDPR. All the participants, including school officials, teachers, parents and pupils, signed a consent to voluntarily participate in the research. This implies that the study only involved schools and pupils representative of the general population. Participants were not exempt from physical and sports education at school. Pupils with special educational needs, as defined by the Schools Act (No. 245/2008 Coll. in Slovakia), were excluded from the study. Furthermore, the sample only included pupils for whom complete data were available in accordance with the methodology section.

The average age of the research sample of boys and girls in 2015 was 10.49 ± 0.63 and 10.62 ± 0.51 years, respectively, and the average age of the research sample of boys and girls in 2025 was 10.64 ± 0.59 and 10.69 ± 0.56 years, respectively. The basic characteristics of the sample of boys and girls are presented in Tables 1 and 2.

Table 1. Basic Characteristics of the Sample of Boys from Selected Primary Schools in Western and Central Slovakia in 2015 and 2025

Sample	S.ch.	Posture [points]	BMI [index]	Height [cm]	Weight [kg]
Boys (2015)	n	127	127	127	127
	x	12.45	21.38	143.51	44.04
	SD	6.14	9.24	11.21	14.31
Boys (2025)	n	143	143	143	143
	x	14.65	22.26	148.02	48.78
	SD	7.41	8.61	10.74	16.74

Note. n – sample size, x – arithmetic mean, SD – standard deviation

Table 2. Basic Characteristics of the Sample of Girls from Selected Primary Schools in Western and Central Slovakia in 2015 and 2025

Sample	S.ch.	Posture [points]	BMI [index]	Height [cm]	Weight [kg]
Girls (2015)	n	138	138	138	138
	x	13.97	20.85	142.29	42.21
	SD	5.94	8.86	10.12	15.12
Girls (2025)	n	151	151	151	151
	x	15.47	21.37	148.23	46.96
	SD	7.05	9.41	11.94	16.13

Note. n – sample size, x – arithmetic mean, SD – standard deviation

Procedures

We applied an ex post facto research design. When comparing the average height (Tables 1 and 2) of the pupil research sample in 2015 (Boys=143.51cm; Girls=142.29 cm) and the pupil research sample in 2025 (Boys=148.02 cm; Girls=148.23 cm), we recorded an increase in average height of 4.51 cm (3.04%) for boys and 5.94 cm (4.01%) for girls.

When comparing the average weight of the pupil research sample in 2015 (Boys=44.04 kg; Girls=42.21 kg) and the pupil research sample in 2025 (Boys=48.78 kg; Girls=46.96 kg), we recorded an increase in average weight of 4.74 kg (9.71%) for boys and 4.75 kg (10.11%) for girls.

Comparing the average Body Mass Index of the pupil research sample in 2015 (Boys=21.38 index; Girls=20.85 index) and the pupil research sample in 2025 (Boys=22.26 index; Girls=21.37 index), we recorded an increase in the average Body Mass Index of 0.88 index (3.95 %) for boys and an increase of 0.52 index (2.43 %) for girls.

When comparing the average values of correct posture of the pupil research sample in 2015 (Boys=12.45 points; Girls=13.97 points) and the pupil research sample in 2025 (Boys=14.65 points; Girls=15.47 points), we recorded a deterioration in the average values of correct posture of 2.20 points (15.01 %) for boys and 1.50 points (9.69 %) for girls.

The main indicators we monitored in the research (correct posture and BMI) were compared with the values given for correct posture (Šeráková, 2006) and the BMI values divided into four bands (Tables 3 and 4). To assess the level of somatic indicators and the BMI of boys and girls, we used norms for the 10-year-old population of children in Slovakia (Ševčíková et al., 2004).

Table 3. Norms for Posture Assessment (Šeráková, 2006) and BMI for 10-year-old Girls in Slovakia

Posture (Šeráková, 2006)	Norm (posture)	Band	Norm (BMI)	BMI (Ševčíková et al., 2004)
5 points	Perfect posture	1st band	Underweight	≤2.7
6–10 points	Good posture	2st band	Ideal weight	12.8–17.2
11–15 points	Poor posture	3st band	Overweight	17.3–19.0
16–20 points	Incorrect posture	4st band	Obesity	19.1≥

Table 4. Norms for Posture Assessment (Šeráková, 2006) and BMI for 10-year-old Boys in Slovakia

Posture (Šeráková, 2006)	Norm (posture)	Band	Norm (BMI)	BMI (Ševčíková et al., 2004)
5 points	Perfect posture	1st band	Underweight	≤12.9
6–10 points	Good posture	2st band	Ideal weight	13.0–17.1
11–15 points	Poor posture	3st band	Overweight	17.2–19.0
16–20 points	Incorrect posture	4st band	Obesity	19.1≥

To assess the values of correct posture, we applied the standardized method according to Thomas – Klein modified by Mayer (Šeráková, 2006). The evaluation of the individual areas was expressed as the sum of points, each area being evaluated by points 1, 2, 3, and 4 according to the current level of body posture. We assessed the qualitative level of posture based on the points achieved: I. Correct body posture (5 points), II. Good (almost correct) body posture (6–10 points), III. Bad body posture (11–15 points), IV. Incorrect body posture (16–20 points).

The assessment of the musculoskeletal system was carried out in cooperation with a physiotherapist, who has more than 25 years of experience.

Data Analysis

For the verification of the obtained data, we used standardized measurement and testing methods applicable to school practice. In the processing and evaluation of the obtained data, we used basic methods of exploratory analysis: (n) frequency, (x) arithmetic mean, (s) standard deviation, (min.). In terms of normality of data distribution, the Kolmogorov-Smirnov test was used. The differences between the groups were evaluated using basic statistical methods and the statistical methods of Kruskal-Wallis H-test and Mann-Whitney U-test ($p < 0.05$)*. The effect size was evaluated as follows: Effect size r : $r = 0.10$ (small effect), $r = 0.30$ (medium effect), $r = 0.50$ (large effect). We formulated the findings and conclusions based on a logically sound evaluation of the obtained results. The statistical analyses were performed using MS Excel 2016, IBM SPSS 22, and JASP 0.16.4.0 software.

Results

When evaluating changes in posture, depending on the Body Mass Index (BMI) in primary education pupils from selected primary schools in Slovakia in 2015 and 2025, we divided the pupil samples into four bands based on the average BMI values.

We compared the correct posture of girls from selected primary schools in Slovakia in 2015 and the average Body Mass Index values (Table 5).

Table 5. Posture Assessment and BMI of Girls (2015) from Selected Primary Schools in Western and Central Slovakia

Girls 2015 (n=138)								
Zone	1st band (n=10)		2st band (n=14)		3st band (n=65)		4st band (n=49)	
Sample	Posture	BMI	Posture	BMI	Posture	BMI	Posture	BMI
S.ch.								
x	5.0	12.2	9.4	16.5	14.7	18.4	18.9	24.5
SD	-	4.57	3.54	5.28	5.34	6.37	6.49	8.58
test	p>0.05		p<0.05*		p<0.05*		p<0.05*	

Note. Posture [points], BMI - Body mass index, n – sample size, x – arithmetic mean, SD – standard deviation

Band 1 (underweight) included 10 girls (7.24 %) with an average BMI (M=12.2 index; SD=4.57) and an average correct posture score of (M=5.0 points). Band 2 (ideal weight) included 14 girls (10.14 %) with average BMI values (M=16.5 index; SD=5.28) and their average correct posture score was (M=9.4 points; SD=3.54), which were statistically significant at the 0.05 significance level ($r=0.619$ – large effect). Band 3 (overweight) included 65 girls (47.12 %) with average BMI values (M=18.4 index; SD=6.37) and their average correct posture score was (M=14.7 points; SD=5.34), which were statistically significant at the 0.05 significance level ($r=0.300$ – medium effect).

Band 4 (obesity) included 49 girls (35.50 %) with average BMI values (M=24.5 index; SD=8.58) and their average correct posture score was (M=18.9 points; SD=6.49), which were statistically significant at the 0.05 significance level ($r=0.345$ – medium effect).

In 2025, we repeatedly evaluated the correct posture of girls from selected primary schools in Slovakia and the average BMI values (Table 6).

Table 6. Posture Assessment and BMI of Girls (2025) from Selected Primary Schools in Western and Central Slovakia

Girls 2025 (n=151)								
Zone	1st band (n=7)		2st band (n=19)		3st band (n=67)		4st band (n=58)	
Sample	Posture	BMI	Posture	BMI	Posture	BMI	Posture	BMI
S.ch.								
x	5.0	12.6	9.9	17.0	14.6	18.9	19.4	25.7
SD	-	5.49	4.23	6.24	4.21	4.42	5.28	9.53
test	p>0.05		p<0.05*		p<0.05*		p<0.05*	

Note. Posture [points], BMI - Body mass index, n – sample size, x – arithmetic mean, SD – standard deviation

Band 1 (underweight) included only 7 girls (4.51 %) with an average BMI (M=12.6 index; SD=5.49) and an average correct posture score of (M=5.0 points). Band 2 (ideal weight) included 19 girls (12.58 %) with average BMI values (M=17.0 index; SD=6.24) and their average correct posture score was (M=9.9 points; SD=4.23), which were statistically significant at the 0.05 significance level ($r=0.554$ – large effect). Band 3 (overweight) included 67 girls (44.60 %) with average BMI values (M=18.9 index; SD=4.42) and their average correct posture score was (M=14.6 points; SD=4.21), which were statistically significant at the 0.05 significance level ($r=0.445$ – medium effect). Band 4 (obesity) included 58 girls (38.31 %) with average BMI values (M=25.7 index; SD=9.53) and their average

correct posture score was ($M=9.4$ points; $SD=5.28$), which were statistically significant at the 0.05 significance level ($r=0.378$ – medium effect).

We also compared the correct posture of boys in selected primary schools in Slovakia in 2015 and the average Body Mass Index values (Table 7). Band 1 (underweight) included 11 boys (8.66 %) with an average BMI ($M=12.8$ index; $SD=4.57$) and an average correct posture score of ($M=5.0$ points). Band 2 (ideal weight) included 16 boys (12.60 %) with average BMI values ($M=16.1$ index; $SD=6.68$) and their average correct posture score was ($M=9.4$ points; $SD=5.54$), which were statistically significant at the 0.05 significance level ($r=0.479$ - medium effect). Band 3 (overweight) included 49 boys (38.59 %) with average BMI values ($M=18.2$ index; $SD=6.87$) and their average correct posture score was ($M=14.7$ points; $SD=6.51$), which were statistically significant at the 0.05 significance level ($r=0.252$ - small effect). Band 4 (obesity) included 51 boys (40.15 %) with average BMI values ($M=22.4$ index; $SD=5.78$) and their average correct posture score was ($M=18.9$ points; $SD=5.40$), which were statistically significant at the 0.05 significance level ($r=0.346$ - medium effect).

Table 7. Posture Assessment and BMI of Boys (2015) from Selected Primary Schools in Western and Central Slovakia

Boys 2015 (n = 127)								
Zone	1st band (n = 11)		2nd band (n = 16)		3rd band (n = 49)		4th band (n = 51)	
Sample	Posture	BMI	Posture	BMI	Posture	BMI	Posture	BMI
S.ch.								
x	5.0	12.8	9.4	16.1	14.7	18.2	18.9	22.4
SD	-	4.57	5.54	6.68	6.51	6.87	5.40	5.78
test	p > 0.05		p < 0.05*		p < 0.05*		p < 0.05*	

Note. Posture [points], BMI – Body mass index, n – sample size, x – arithmetic mean, SD – standard deviation

In 2025, we repeatedly assessed the average values of correct posture in selected primary schools in Slovakia and the average BMI values for boys (Table 8). Band 1 (underweight) included only 7 boys (4.89 %) with an average BMI ($M=12.9$ index; $SD=5.28$), and the average correct posture score was ($M=5.0$ points). Band 2 (ideal weight) included 22 boys (15.38 %) with average BMI values ($M=18.7$ index; $SD=6.24$) and their average correct posture score was ($M=9.9$ points; $SD=5.13$), which were statistically significant at the 0.05 significance level ($r=0.610$ – large effect). Band 3 (overweight) included 52 boys (36.36 %) with average BMI values ($M=18.9$ index; $SD=5.41$) and their average correct posture score was ($M=14.8$ points; $SD=4.21$), which were statistically significant at the 0.05 significance level ($r=0.389$ – medium effect). Band 4 (obesity) included 62 boys (43.37 %) with average BMI values ($M=24.1$ index; $SD=7.51$) and their average correct posture score was ($M=19.2$ points; $SD=5.28$), which were statistically significant at the 0.05 significance level ($r=0.353$ – medium effect).

Table 8. Posture Assessment and BMI of Boys (2025) from Selected Primary Schools in Western and Central Slovakia

Boys 2025 (n = 143)								
Zone Sample S.ch.	1st band (n = 7)		2st band (n = 22)		3st band (n = 52)		4st band (n = 62)	
	Posture	BMI	Posture	BMI	Posture	BMI	Posture	BMI
x	5.0	12.9	9.9	18.7	14.8	18.9	19.2	24.1
SD	-	5.28	5.13	6.24	4.21	5.41	5.28	7.51
test	p > 0.05		p < 0.05*		p < 0.05*		p < 0.05*	

Note. Posture [points], BMI – Body mass index, n – sample size, x – arithmetic mean, s – standard deviation

Discussion

Our study highlights a significant degradation of both body mass index (BMI) and posture quality in 10-year-old Slovak children between 2015 and 2025. The increase in BMI (0.88 in boys and 0.52 in girls), together with the trend of increasing postural deficiencies (2.20 points in boys and 1.50 points in girls), suggests the cumulative influence of several interdependent factors: the intensification of sedentary behaviours associated with the use of various types of screens, the reduction of physical activity during the period of restrictions imposed by the COVID-19 pandemic (2020–2021), as well as the maintenance of unfavourable lifestyle behaviours after its end.

The more pronounced impact observed in boys, compared to girls, can be attributed to gender-specific differences in participation in physical activities and in the stage of biological development (Lombardo et al., 2024; Delas-Kalinski et al., 2025). At the age of 10, most boys have not yet entered puberty, while some girls are already in this process, which can generate different patterns of physical activity and distinct postural adaptations. Comparable trends have been reported in other Central and Eastern European countries, where rising overweight prevalence has been accompanied by a deterioration in postural parameters. Studies from Poland, Hungary, and Serbia show similar patterns, suggesting that the situation observed in Slovakia reflects a broader regional trend influenced by shared lifestyle and environmental changes (Grabara, 2014; Jakab et al., 2018; Halasi et al., 2018).

By comparing the average differences in the body mass index in 2015 and 2025, we observed the highest increase in the average body mass index in boys in 2025 in the second band by 2.6 (index) (13.90 %) and in the fourth band by 1.7 (index) (7.05 %) among primary school boys and girls from the western and central regions of Slovakia. In girls in 2025, we also recorded an increase in the average body mass index in the fourth band by 1.2 (index) (4.66 %) and in the second band by 0.5 (index) (2.94 %). We observed a deterioration in the average values of correct posture in boys in 2025 compared to 2015 in the second band by 0.5 points (5.05 %) and in the fourth band by 0.3 points (1.56). In girls in 2025, we recorded a deterioration in the average posture values compared to 2015 in the fourth band by 1.2 points (6.18%) and in the second band by 0.5 points (5.05 %).

By evaluating the results of the average BMI values depending on the average correct posture values of boys and girls from primary schools in the western and central regions of Slovakia, we state a significant dependence of the increased body mass index and correct posture in boys and also in girls in 2015 and in 2025.

Similar significant associations between the BMI and correct posture are stated in the studies by authors (Gajewska, et al., 2015; Faik et al., 2017; Marsigliante et al., 2023).

Limitations

Several limitations should be acknowledged. First, the cross-sectional design prevents causal inference; we cannot definitively determine whether increased BMI causes poor posture or vice versa. Second, our sample was limited to Western and Central Slovakia, which may limit generalizability to the entire country or to other regions in Central Europe. Third, we did not measure important confounders, including physical activity levels (accelerometry), screen time, socioeconomic status, pubertal maturation (Tanner stages), or family history of obesity/postural problems. Finally, our 2025 data may reflect the effects of the COVID-19 pandemic that are not representative of typical secular trends; longitudinal follow-up is needed to determine whether the observed changes persist or reverse in a relevant way post-pandemic.

Conclusions

Based on the results of our study focused on the assessment of BMI and correct posture in boys and girls from primary schools in the western and central regions of Slovakia in 2015 and 2025, we conclude that with an increased body mass index, the posture values of pupils are significantly worsened at the 5 % ($p < 0.05$) level of statistical significance.

We also consider the fact that in 2015, only 19.24 % boys and girls had perfect and good posture (Level 1 and Level 2), and as many as 80.76 % boys and girls had poor and incorrect posture (Level 3 and Level 4) as a serious finding. In 2025, 18.71 % boys and girls had perfect and good posture (Level 1 and Level 2), and as many as 81.29 % boys and girls had poor and incorrect posture (Level 3 and Level 4).

Based on our findings, we consider the current state of the increase in the BMI depending on incorrect posture in boys and girls in primary schools from the western and central regions of Slovakia from 2015 to 2025 to be unsatisfactory and health-threatening. These facts need to be further addressed, and systemic preventive measures need to be sought.

Appropriate preventive intervention is needed to ensure healthy growth and prevent comorbidities in childhood and adulthood.

A suitable solution may be to limit pupils' sedentary behaviour by including physical education classes in the curriculum every day, with the aim of reducing the unfavourable occurrence of overweight and obesity in pupils during their school attendance (Trecroci et al., 2021).

Practical Implications

Pedagogical diagnostics in the school environment is the primary factor that can point to changes in the area of health-oriented fitness as the basis of a pupil's health. The above findings point to the importance of monitoring the above factors from a preventive perspective and supporting the health of pupils.

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EFFECTS OF THE FITKIDS PROGRAM ON PHYSICAL ACTIVITY LEVELS AND CARDIOVASCULAR FITNESS AMONG ELEMENTARY SCHOOL STUDENTS

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Abstract Elementary school students in urban areas are experiencing low physical activity and declining cardiovascular fitness, threatening their long-term health. This study examined the effectiveness of the 12-week FitKids Program in improving physical activity and cardiovascular fitness among 9–10-year-old students in Tasikmalaya City. A cluster-allocated (school-based) quasi-experimental design was conducted in six urban schools (three FitKids (EXP); three regular PE (CON), with non-random allocation based on feasibility and scheduling. The final sample comprised 150 students (experimental n75, control n75). Physical activity was assessed with the Indonesian-adapted Physical Activity Questionnaire for Children (PAQ-C), and cardiovascular fitness

via average Multistage Fitness Test (MFT) scores. The FitKids Program showed strong content validity (mean Aiken's $V=0.90$) and acceptable reliability ($\alpha=0.612$). Descriptively, EXP PAQ-C scores increased from 2.15 to 5.21, compared with 2.26 to 4.40 in CON, while MFT improved from 31.74 to 41.75 (EXP) versus declining from 28.41 to 27.17 (CON). After school clustering adjustment (ICC PAQ-C=0.129; ICC MFT=0.045) and baseline covariate control, mixed-effects modelling revealed no significant intervention effect on physical activity ($\beta=0.88$, $p=0.478$, $d=0.33$) but strong effects on cardiovascular fitness ($p<0.001$, $d=0.74$). These findings demonstrate FitKids effectively enhances cardiovascular fitness through structured interval and circuit training within regular PE sessions, though broader physical activity changes require longer duration or complementary strategies. The cluster-adjusted approach underscores the importance of accounting for school-level dependencies in educational interventions.

Key words: physical activity, cardiovascular fitness, physical education, elementary school students

Introduction

Physical and sports education (PE) as a teaching subject provides an environment conducive to the development of life skills through the practice of individual and collective physical activities (Ouaddou, et al., 2025). As simple as it may sound, being physically active might be the very thing most people from across the world need to significantly change their lives for better (Bujdoš, et al., 2025). Physical activity and cardiovascular fitness represent two fundamental indicators supporting the health of elementary school children. Adequate physical activity plays an important role in physiological function and cognitive development. Numerous studies demonstrate that participation in physical activity improves cardiac health, aerobic capacity, and energy metabolism (Cumillaf et al., 2020; Cumillaf et al., 2021). Cumillaf et al. affirmed that physical activity is directly associated with reduced obesity risk and improved cardiovascular fitness, which may contribute to disease prevention in adulthood (Cumillaf et al., 2019). Furthermore, active engagement in sports positively impacts children's learning readiness (Fonseca del Pozo et al., 2017). Another study by Nqweniso et al. demonstrated that good cardiovascular fitness can help prevent overweight and reduce future hypertension risk (Nqweniso et al., 2020). These findings underscore the necessity for school-based interventions focusing on enhancing physical activity and cardiovascular fitness.

Modern lifestyle transformation significantly impacts children's physical activity behavior. Increased screen time, changing play patterns, and limited access to child-friendly public spaces contribute to rising sedentary behavior (Jones et al., 2021; Engberg et al., 2020). In urban areas, this phenomenon is increasingly concerning, as children tend to have low physical activity levels and high sedentary time, particularly due to limited facilities and open spaces supporting physical activity (Kim & Yoo, 2019). Kärmeniemi et al. (2018) highlighted that many elementary school children in urban areas fail to meet aerobic fitness standards due to insufficient opportunities for regular physical activity participation, while their play patterns are increasingly dominated by screen time such as watching television or playing video games.

A similar situation occurs in Indonesia, where urban children exhibit high sedentary levels due to minimal safe and adequate open spaces for play (Sridhar & Gumpeny, 2024). Additionally, low student physical activity is concerning, as most engage in physical exercise only during physical education lessons without independent physical activity outside school (Mulya et al., 2025). This finding aligns with Mendes et al. (2024), who affirmed that increasing sedentary behavior is closely linked to low physical activity, negatively impacting children's physical development and cardiovascular fitness. School curricula have not fully integrated daily physical activity learning

with comprehensive health education, necessitating structured and sustained intervention strategies. Responding to these conditions, interventions such as reducing screen time, increasing outdoor play opportunities, and educating about balanced nutrition become critically important (Hassinger et al., 2023; Pandya & Lodha, 2021).

School-based interventions represent the most effective and economical approach to promoting healthy behaviors in children. Therefore, the FitKids Program was developed as a physical activity-based intervention model that not only increases aerobic capacity through structured physical activity training but also integrates healthy lifestyle education including nutritious food consumption, adequate sleep, and regular movement habits. This program adopts behavior change concepts, physical literacy, and school-based health promotion aligned with WHO-recommended whole-school approaches. The Health Promoting School (HPS) model emphasizes shifting school culture through curricula, policies, and environments supporting active lifestyles (Busch et al., 2023).

This approach has demonstrated consistent effectiveness. Langford et al. (2015) found that HPS-based interventions successfully improved student health and academic achievement through integrating health promotion activities into learning processes. This finding is reinforced by Brandes et al. (2020) who reported that HPS implementation effectively reduced obesity prevalence and improved student cardiovascular fitness. Consistent with these findings, Ngatman et al. (2025) demonstrated that nutrition education combined with active physical education successfully improved both gross motor skills and nutritional literacy simultaneously, affirming the importance of integrative approaches in school health programs.

The FitKids Program is designed to enhance cardiovascular fitness and physical activity through light-to-moderate intensity aerobic training, basic movement-based games, and reflection on healthy living habits. Integration of cognitive aspects (health knowledge), affective aspects (motivation), and psychomotor aspects (physical activity) makes it a comprehensive intervention. However, scientific evidence regarding the effectiveness of integrative interventions like FitKids in Indonesia remains limited. Many programs focus solely on physical activity without balancing nutrition education, sleep management, or daily movement habit formation. Research demonstrates that interventions targeting only physical activity without educational components do not produce significant impacts on children's overall health (Bull et al., 2020).

Furthermore, Lahti et al. (2020) affirmed the importance of an integrated approach combining physical activity with nutrition education and sleep management. The "Creating Active Schools" program in Bradford demonstrated that increased physical activity becomes more effective when accompanied by nutrition education and healthy sleep practices (Morris et al., 2023). Carson et al. (2016) added that interventions not including comprehensive educational components tend to be ineffective in improving children's cardiovascular health. Integration of physical activity, nutrition, and sleep patterns is also considered important for establishing healthy habits sustained into adulthood (Muthuri et al., 2014; Pereira et al., 2018).

To date, no comprehensive scientific publication has evaluated the effectiveness of an integrative program combining physical activity, healthy lifestyle education, and active behavior habit formation among elementary school students in Indonesia, particularly in urban areas. Furthermore, few studies employ cluster-based quasi-experimental designs, despite this design being more suitable for school intervention contexts. The novelty of this research lies in developing and implementing the FitKids Program a school-based intervention integrating interval cardio training, simple circuit exercises, and healthy lifestyle education ("Eat Smart, Sleep Well, Move More"). This approach not only enhances structured physical activity but also instills healthy living habits relevant to children in urban environments.

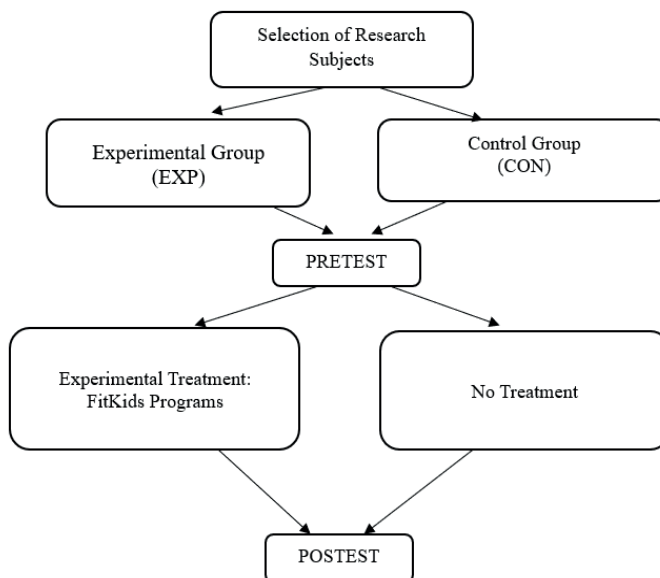
Therefore, this study aimed to analyze the impact of the FitKids Program on physical activity and cardiovascular fitness among elementary school students through a cluster-based quasi-experimental design. The findings are expected to provide empirical contributions to developing school-based health interventions in Indonesia, enrich international literature on integrative interventions in middle-income countries, and serve as reference for policymakers and educators in designing effective, applicable, and sustainable child health promotion programs.

Material and Methods

Research Design

This research employed a cluster-based quasi-experimental pretest–posttest non-equivalent control group design, with elementary schools in the urban area of Tasikmalaya City serving as cluster units. Six schools were involved: three designated as the experimental group receiving the FitKids Program and three as the control group following regular physical education instruction without additional intervention. School allocation was non-random and was determined by the principal investigator in consultation with the school principals, primarily based on implementation feasibility and scheduling considerations; therefore, no random sequence generation or allocation concealment procedures were applied. The intervention lasted 12 weeks, conducted at a frequency of one session per week with a duration of 70 minutes during scheduled physical education lessons.

Figure 1. Research flow



Participants

The study population comprised all students aged 9–10 years in elementary schools in Tasikmalaya City during the academic year of the study. The sample was obtained using a cluster sampling technique, selecting

six elementary schools with similar characteristics in terms of school status and urban environmental context. All students in the target grades meeting inclusion criteria were enrolled in the study. The six schools served as the cluster units and were allocated a priori to study conditions based on feasibility and scheduling considerations (non-random allocation), with three schools assigned to the FitKids condition (EXP) and three schools assigned to regular physical education (CON). Each school contributed 25 students to the final analysis (equal cluster sizes), yielding 75 participants in EXP and 75 participants in CON.

Of the total 180 students across six schools, 150 met inclusion criteria and comprised the final sample. Participants were divided into an experimental group ($n=75$; 42 boys and 33 girls) and a control group ($n=75$; 41 boys and 34 girls) based on their school's pre-determined cluster allocation. Inclusion criteria encompassed: (1) absence of medical conditions limiting moderate-intensity physical activity, (2) participation in the complete pretest and posttest assessments, and (3) parental or guardian written consent. Baseline characteristics and baseline outcomes are reported by group in Table 1. Because allocation occurred at the school (cluster) level without randomization, baseline equivalence between groups could not be assumed, and these baseline differences should be considered when interpreting intervention effects. The study received formal approval from the university via letter number 139/UN58.10/KM/2025, which was communicated to schools and parents. Student participation proceeded following parental or guardian signature on informed consent forms.

Table 1. Baseline Characteristics

Variable	Experimental ($n=75$)	Control ($n=75$)
Age (years), mean $\pm$ SD	9.55 $\pm$ 0.503	9.55 $\pm$ 0.501
Boys, n (%)	57.3%	54.7%
Girls, n (%)	42.7%	45.3%
PAQ-C baseline, mean $\pm$ SD	2.1479 $\pm$ 0.4314	2.2641 $\pm$ 0.3906
MFT baseline, mean $\pm$ SD	31.7387 $\pm$ 6.390004	28.4053 $\pm$ 6.44249

Table 2. Distribution of Participants Across Schools

School	Group	n
1	EXP	25
2	EXP	25
3	EXP	25
4	CON	25
5	CON	25
6	CON	25

Procedures

Experimental Group (EXP)

The FitKids Program comprised 12 structured sessions combining moderate-intensity physical activity with lifestyle education based on habit formation. Each session was conducted during regular physical education class time and divided into three phases: warm-up (10–15 minutes), core activity (± 30 –35 minutes), and cool-down (10–15 minutes). Exercise intensity was monitored using the Borg Rating of Perceived Exertion (RPE) Scale with a target range of 11–13, whereby activity was perceived as “somewhat hard” yet remained safely manageable for

students (Williams et al., 1991). Teachers regularly asked students to report their RPE values and adjusted pace, duration, or movement complexity if readings fell below 11 (too light) or exceeded 13 (too hard).

The primary physical activity components were delivered through Cardio Interval Training (CIT) and Mini Circuit Training (MCT). CIT sessions included activities such as follow-the-line run, shadow running, relay run, skipping, high-knees, jumping jacks, and structured tag games with brief work–rest interval patterns (e.g., 20–60 seconds work interspersed with 1-minute rest) to maintain moderate intensity. MCT was conducted at 4–5 stations focusing on fundamental movement skills including squat, sit-to-stand, step-up/step-on box, cone weaving/zig-zag, side shuffle, mini-hurdle, plank, and balance exercises, with 40–50 seconds per station, 60 seconds rest between stations, and 90 seconds between circuits, completed twice per session. Healthy Habit Breaks (Eat Smart, Sleep Well, Move More) were interspersed between or following physical activity blocks to reinforce understanding of balanced nutrition, healthy sleep, and daily physical activity.

Table 3. FitKids Program: 12-Week Protocol Structure

Week	Cardio Interval Training (CIT)	Mini Circuit Training (MCT)	Healthy Habit Break (HHB)
1	Follow-the-line run (5 min); skipping (1 min×2)	4 stations: basic squat, wall push-ups, step-on box, balance stand	Eat Smart: Introduction to healthy food concepts
2	Jumping jacks (30 sec×3); high-knees (20 sec×2)	Stations: squat, sit-to-stand, cone weaving, plank (10 sec)	Eat Smart: Portion sizes & “plate model”
3	Combined skipping + shadow running	Stations: step-on box, wall push-ups, jump rope, balance line walk	Eat Smart: Choosing healthy snacks
4	High-knees (30 sec×3); jumping jacks (30 sec×3)	Stations: squat, mini-hurdle step, side shuffle, plank	Eat Smart: Hydration and low-sugar beverages
5	Relay run: 1 min work – 1 min rest	Stations: sit-to-stand, cone zig-zag, skipping, wall push-ups	Sleep Well: Importance of 9–11 hours of sleep
6	Jumping jacks (30 sec×4); skipping (1 min×2)	Stations: mini step-up, balance, squat, plank	Sleep Well: Sleep routines
7	High-knees (30 sec×4); structured tag game (5 min)	Stations: cone weaving, sit-to-stand, wall push-ups, mini-hurdle	Sleep Well: Reducing screen time before bed
8	Skipping (1 min×3); jumping jacks (45 sec)	Stations: step-up, side shuffle, squat, balance stand	Sleep Well: Optimal sleep environment
9	Shadow running intervals (2 min work – 1 min rest)	Stations: skipping, plank (15 sec), cone zig-zag, sit-to-stand	Move More: Benefits of daily activity
10	High-knees (40 sec); jumping jacks (45 sec)	Stations: wall push-ups, step-up, balance, mini-hurdle	Move More: Limiting prolonged sitting
11	Skipping (1 min×3); follow-the-line run (5 min)	Stations: squat, cone weaving, side shuffle, plank	Move More: Physical activity at home/in the city
12	Combined relay run + high-knees	5 integrated stations based on previous weeks’ progression	Move More: Review of 12-week active habits

Note: Each 70-minute session comprised warm-up (10–15 min), core activity (30–35 min) including CIT and MCT components, and cool-down (10–15 min). Healthy Habit Breaks were interspersed between activity blocks. Exercise intensity was maintained at RPE 11–13 (moderate intensity) throughout all sessions

Facilitators, Training, and Fidelity Monitoring

All activities in the experimental group were facilitated by physical education teachers with a minimum qualification of a bachelor’s degree in Physical Education and adequate teaching experience at the elementary school level. Prior to intervention implementation, teachers in the experimental schools received intensive training

on the program objectives, session structure, safety procedures, use of the Borg Rating of Perceived Exertion (RPE) scale, and the FitKids fidelity monitoring procedures.

The study procedures were conducted sequentially as follows: (1) training of physical education teachers regarding FitKids implementation; (2) baseline (pretest) measurements of physical activity and cardiovascular fitness for all participants in both the experimental and control groups; (3) 12-week implementation of the FitKids Program in experimental schools, while control schools continued regular physical education instruction without additional modification; and (4) post-intervention (posttest) measurements using identical instruments, followed by data analysis to examine between-group differences and estimate intervention effect sizes.

Intervention fidelity was monitored weekly using a structured observation checklist to assess adherence to session duration, activity sequence, and delivery of the CIT, MCT, and Healthy Habit Break components. Checklist completion was performed by the physical education teacher delivering the session and assisted by the classroom teacher to support recording and cross-checking of implementation details. Fidelity indicators recorded included student attendance per session and overall attendance rate, the proportion of planned sessions successfully delivered (delivered/planned $\times 100\%$), adherence to intended session duration (minutes delivered versus minutes planned), adherence to intended exercise intensity using Borg RPE (target RPE 11–13), documentation of protocol deviations and reasons (e.g., shortened sessions, skipped components, facility/equipment constraints, or scheduling disruptions), and a brief safety log of adverse events/incidents and actions taken.

Control Group (CON)

Students in the control group participated in regular physical education (PE) instruction according to the school curriculum without any additional FitKids Program components. During PE lessons (± 60 –70 minutes per week), teachers implemented conventional activities including practice of basic locomotor and manipulative movement skills, simple games or small-ball games, and light stretching and fitness exercises, following the standard warm-up–core activity–cool-down format used in daily school practice. This group did not receive Cardio Interval Training, Mini Circuit Training, or structured Healthy Habit Break sessions, and no specific exercise intensity targets were set. As a matter of fairness and ethical consideration, after completion of all post-intervention measurements, control group students were offered the opportunity to participate in the FitKids Program and receive the same educational materials provided to the experimental group.

Measurement Instruments

Physical Activity Assessment (PAQ-C Indonesian-adapted version)

Physical activity was measured using the Indonesian-adapted version of the Physical Activity Questionnaire for Children (PAQ-C) (Sari et al., 2024). The PAQ-C is a self-administered, 7-day recall questionnaire comprising nine items that assess children's physical activity patterns across various domains including school, leisure, and sports participation. Items are scored on a 5-point Likert scale (1=minimally active to 5=very active), with an overall activity score calculated as the mean of all items, ranging from 1 to 5. The Indonesian version of PAQ-C demonstrated good convergent validity (Average Variance Extracted=0.659; Construct Reliability=0.892) and acceptable internal consistency (Cronbach's α =0.705–0.712), suitable for measuring physical activity in Indonesian children aged 9–11 years across diverse environmental contexts (Sari et al., 2024). The instrument's validity and reliability have been confirmed through Confirmatory Factor Analysis, supporting its use in school-based research.

Cardiovascular Fitness Assessment (MFT)

Cardiovascular fitness was assessed using the Multistage Fitness Test (MFT), also known as the “beep test” or progressive shuttle run test. The MFT is a maximal aerobic fitness test wherein participants perform continuous 20-meter shuttles between two lines at an incrementally increasing pace controlled by audio signals from a pre-recorded audio file. Participants continue running until they are unable to keep pace with the audio signals, at which point volitional exhaustion is typically achieved. Test performance was quantified as the average MFT score (composite performance metric across completed levels/shuttles), with higher scores indicating better cardiovascular endurance. The MFT has demonstrated excellent test-retest reliability ($r=0.94$) and validity in assessing aerobic fitness in children, making it an appropriate field-based measure of cardiovascular fitness in school settings (Mayorga-Vega et al., 2015).

Validity content of FitKids Program

The FitKids program materials were content-validated through expert review to evaluate their alignment with learning objectives, curriculum relevance, developmental appropriateness, and coverage of the targeted healthy-lifestyle behavior domains (Table 2). Analysis of the 10 items showed that all aspects exceeded the Aiken's V threshold of ≥ 0.80 , indicating adequate content validity based on expert judgment and supporting the program's suitability for implementation. The average validity coefficient across all program items was 0.90, suggesting that the healthy lifestyle habit formation program is content-valid and acceptable for application in school settings.

Table 4. Validation of the FitKids Program

No	Rated Aspect	Σs	V	Description
1	Alignment of FitKids program with physical education learning objectives and Merdeka Curriculum for upper elementary students (ages 9–10 years)	20	1	Accepted
2	Integration of physical activity, nutrition, and healthy sleep content with Merdeka Curriculum competency achievement	16	0.8	Accepted
3	Program inclusion of important aspects of children's healthy lifestyle (personal hygiene, balanced nutrition, physical activity, healthy sleep) appropriate to developmental stage.	19	0.95	Accepted
4	Appropriateness of personal hygiene content (hand washing, body cleansing, toilet etiquette, personal equipment care) with basic health learning standards for school-age children.	20	1	Accepted
5	Program incorporation of balanced nutrition concepts (Eat Smart) appropriate for ages 9–10, including healthy food selection, portion sizes, and drinking patterns	16	0.8	Accepted
6	Alignment of nutrition content with balanced nutrition guidelines for school-age children (food types, portions, healthy snack selection)	16	0.8	Accepted
7	Comprehensive physical activity components (Cardio Interval Training and Mini Circuit Training) including safe movement introduction and practice with appropriate intensity and duration	19	0.95	Accepted
8	Mini circuit training station design consistency with principles of children's physical development (progressive load, movement variety, emphasis on fundamental movement skills)	17	0.85	Accepted
9	FitKids session content relevance (CIT, MCT, Healthy Habit Break) to daily life contexts of 9–10 year-old children in school, home, and surrounding environments	18	0.9	Accepted

No	Rated Aspect	Σs	V	Description
10	Program integration of diverse topics and subtopics (personal hygiene, balanced nutrition, physical activity, healthy sleep habits) within a coherent 12-week sequence	18	0.9	Accepted
	Average	18	0.9	Accepted

Analysis of the 10 items revealed that all items successfully exceeded the Aiken's V validity coefficient threshold of ≥ 0.80 , indicating that the FitKids Program demonstrated adequate validity and is suitable for implementation. This finding demonstrates that all tested items met content validity criteria. The average validity coefficient across all program items was 0.90, indicating that the healthy lifestyle habit formation program is valid and acceptable for application in school settings.

Table 5. Reliability Reliability of the 10-item expert evaluation

Cronbach's Alpha	N of Items
0.612	10

Table 5 reports the internal consistency of the 10-item expert evaluation form used to appraise the FitKids Program content. The Cronbach's alpha coefficient was $\alpha=0.612$ (10 items), indicating moderate internal consistency of the evaluation form. This coefficient reflects the internal consistency of the expert-rating instrument and does not represent the reliability of FitKids intervention delivery itself.

Statistical Analysis

Data analysis included FitKids program validity testing using Aiken's V formula and reliability testing using Cronbach's Alpha coefficient. Intraclass correlation coefficients (ICC) and design effects (DE) were calculated to assess school-level clustering. Descriptive statistics (mean, SD, Δ mean), assumption testing (normality, homogeneity), and linear mixed-effects models (LMM) with random intercepts for schools were conducted to examine post-intervention differences while controlling for baseline scores and clustering. Fixed effects included group (experimental vs. control) and baseline scores; random effects included school variance (τ^2) and residual variance (σ^2). Cluster-adjusted effect sizes were calculated using Cohen's d ($\beta_{\text{group}}/\text{SD}_{\text{residual}}$), and normalized gains (N-gain) were computed for interpretive purposes. The significance level was set at $\alpha=0.05$.

Results

This study generated data analyzed sequentially through intervention fidelity assessment, baseline clustering analysis (ICC and design effect), descriptive statistics, assumption testing (normality and homogeneity), normalized gain (N-gain) calculations, and primary analysis using linear mixed-effects models (LMM) with school-level random intercepts on physical activity (PAQ-C) and cardiovascular fitness (MFT) variables. Results are presented systematically: intervention fidelity, clustering statistics, descriptive statistics by group/time, LMM results with cluster-adjusted estimates, and effect sizes/normalized gains. Findings are as follows.

Intervention implementation/fidelity (FitKids group)

Intervention fidelity monitoring was conducted during FitKids Program implementation (12 weeks; 12 sessions per school) using a structured weekly observation checklist. Observations and recording were performed by PE teachers facilitating sessions, assisted by homeroom teachers for documentation and verification. All experimental students ($n=75$) attended every session, achieving 900/900 student-sessions (100%). All 36 planned sessions across three schools were conducted (100%). Mean session duration was 70 minutes, with mean Borg RPE of 12 (target 11–13). No protocol deviations or safety incidents occurred.

Table 6. Summary of FitKids Intervention Implementation and Fidelity (Experimental Group)

Implementation/Fidelity Indicator	Target/Planned	Actual
Number of experimental schools (clusters)	3	3
Intervention duration	12 weeks	12 weeks
Planned sessions per school	12	12
Total planned sessions (3 schools)	36	36
Total sessions conducted	36	36
Proportion of sessions conducted (conducted/planned $\times$ 100%)	100%	100%
Number of students (experimental group)	75	75
Planned student-sessions (75 $\times$ 12)	900	900
Student-sessions attended	—	900
Overall attendance percentage	—	100%
Session duration (minutes)	70	Mean 70
Intensity (Borg RPE)	11–13	Mean 12
Protocol deviations	0	0
Safety incidents/events	0	0

Baseline Clustering Statistics

Table 7. Baseline Clustering Statistics (Intraclass Correlation & Design Effect)

Outcome	σ^2 (Within-school variance)	τ^2 (Between-school variance)	ICC	Design Effect (DE)	Effective Sample Size
PAQ-C baseline	6.893256	46.9332	0.129	4.096	36.62
MFT baseline	1.983230	42.0254	0.045	2.08	72.12

*Note: $DE=1 + (25-1)\times ICC$; Effective $N=150/DE$

Table 7 confirms school-level clustering. PAQ-C ICC (0.129) indicates 12.9% activity variation explained by between-school differences ($DE=4.096$), reducing effective sample to 36.62. Unadjusted analyses risk biased estimates. MFT shows smaller clustering ($ICC=0.045$, $DE=2.08$) but still requires mixed-effects adjustment.

Descriptive Statistics

Table 8. Descriptive Statistics by Group and Time Point

Outcome	Group	Pretest Mean±SD	Posttest Mean±SD	Δ Mean
PAQ-C	Experimental	2.1479±0.4314	5.2123±0.8140	+3.06
PAQ-C	Control	2.2641±0.3906	4.4000±0.6869	+2.14
MFT	Experimental	31.7387±6.39004	41.7453±9.04948	+10.0066
MFT	Control	28.4053±6.44249	27.1733±8.70101	-1.232

Descriptively, PAQ-C increased modestly in both groups (EXP +3.06 vs CON +2.14), showing no striking group difference. Conversely, MFT showed substantial EXP gains (+10.01) versus CON decline (−1.23), indicating clearer intervention impact on cardiovascular fitness.

Linear Mixed Model Results

Table 9. Linear Mixed Model Results for Physical Activity (PAQ-C)

Fixed Effects	Estimate (β)	SE	95% CI	t	p
Intercept	4.7242	0.9380	2.89, 6.56	5.036	0.000
Group (EXP vs CON)	0.8769	1.232380	−1.54, 3.29	0.712	0.478
PAQ-C baseline	−0.0834	0.0902	−0.26, 0.09	−0.924	0.357

Random Effects (Variance Components)

Component	Variance
School (τ^2)	46.9332
Residual (σ^2)	6.893256

LMM results show no significant group effect on PAQ-C posttest ($\beta=0.88$, $p=0.478$) after controlling for baseline scores and school variation. PAQ-C baseline also showed no significant association with posttest scores. After cluster and baseline adjustment, the intervention had no significant effect on students' physical activity.

Table 10. Linear Mixed Model Results for Cardiovascular Fitness (MFT)

Dependent variable: MFT posttest

Random effect: School (random intercept)

Fixed Effects	Estimate (β)	SE	95% CI	t	p
Intercept	0.6200	2.521357	−4.37, 5.62	0.246	0.806
Group (EXP vs CON)	0.456004	1.211639	0.28, 0.63	9.455	<0.001
MFT baseline	0.9347	0.083771	0.77, 1.10	11.159	<0.001

Random Effects (Variance Components)

Component	Variance
School (τ^2)	42.71
Residual (σ^2)	0.38

In contrast, LMM results for MFT demonstrate a significant and strong group effect ($p < 0.001$), with higher average MFT posttest scores in the experimental group compared to control. Baseline MFT scores were a highly significant predictor, indicating individual fitness performance stability. The intervention produced significant cardiovascular fitness improvements, even after controlling for baseline scores and school clustering structure.

*Cluster-Adjusted Effect Sizes***Table 11.** Cluster-Adjusted Effect Sizes and Normalized Gain

Outcome	Cohen's d (adjusted)	95% CI	Effect Magnitude	N-gain EXP	N-gain CON	Gain Category
PAQ-C	0.33	-0.59, 1.25	Small to moderate effect	1.63	0.46	Medium, Low
MFT	0.74	-3.13, 4.61	Moderate to large effect	0.315	0.043	Medium, Low

* Note: $d = \beta_{\text{group}} / SD_{\text{residual}}$; $N\text{-gain} = (\text{Post-Pre}) / (\text{Max-Pre})$

PAQ-C shows small-moderate effect (CI crosses zero, aligns with nonsignificant LMM). MFT demonstrates moderate-large effect with higher EXP N-gain, confirming intervention effectiveness for cardiovascular fitness. PAQ-C N-gain interpreted cautiously due to scale limitations.

Discussion

This study examined the effectiveness of the FitKids Program on physical activity levels and cardiovascular fitness among elementary school students. The program was designed as a school-based intervention integrating interval training, circuit training, and healthy lifestyle education (Eat Smart, Sleep Well, Move More) within a single sequence of regular PE sessions, with content aligned to the Merdeka Curriculum and validated by local experts. The sequential CIT–MCT–HHB structure within each session, utilization of Borg RPE Scale for intensity control, and application of contextually relevant visual media (images of local foods, color symbols, nutrition category cards) represent unique design features distinguishing FitKids from traditional PE models that typically focus on isolated games or single skill training.

Mixed-effects modelling results revealed differential effects across outcomes. After adjusting for school clustering (ICC PAQ-C=0.129; ICC MFT=0.045) and baseline values, the intervention did not significantly improve PAQ-C scores ($\beta=0.88$, $p=0.478$; $d=0.33$), despite descriptive gains in both groups. This finding aligns with evidence that school-based physical activity programs may face challenges in substantially enhancing self-reported activity levels within short durations (Cornett et al., 2023; Brusseau, 2015).

However, cardiovascular fitness (MFT) showed strong intervention effects ($p < 0.001$, $d = 0.74$), with experimental gains (+10.01) contrasting control declines (-1.23). This demonstrates that structured interval and circuit training effectively enhance aerobic capacity even within regular PE time constraints, consistent with Gu et al. (2020) and Seljebotn et al. (2019), who reported that systematically designed interventions improve cardiorespiratory fitness in children. FitKids not only increases activity volume but also regulates intensity through RPE control, providing measured aerobic stimulus.

The intervention's success on MFT is consistent with Meyer et al. (2014), who demonstrated that planned physical activity programs yield significant improvements in aerobic fitness, and with Zhou et al. (2019), who emphasized the importance of intensive school-based programs. Compared to single-component approaches, FitKids offers an integrative framework that combines interval training, fundamental movement circuit training, and healthy habit education into a single, implementable package.

Covariance analysis revealed that baseline ability significantly influenced both outcomes (MFT: $\beta = 0.93$, $p < 0.001$; PAQ-C: $\beta = -0.08$, $p = 0.357$). Nevertheless, the strong group effect for MFT indicates improvements were primarily attributable to the intervention (Wilhite et al., 2022; Masini et al., 2022). Emphasis on fundamental movement circuit training permitted students with lower baseline abilities to remain engaged and experience success.

Theoretically, these findings align with experiential learning and social interaction frameworks, in which integrating nutrition education into active physical activity provides opportunities for students to construct knowledge through movement experiences, observational learning, and peer/teacher interactions (Gall et al., 2020; Aceves-Martins et al., 2021). FitKids addresses the limitations of traditional models by offering an integrated approach that targets both physical and cognitive domains simultaneously.

In elementary school physical education, enhanced cardiovascular fitness has important implications for student autonomy and self-confidence, while nutrition literacy provides a foundation for long-term, healthy decision-making (Masini et al., 2022). With adaptive design, contextual visual media, and clear session structure, FitKids has the potential to reduce health participation gaps and can be adapted across diverse school contexts.

Several limitations warrant consideration. This research used a quasi-experimental design with school clustering that limits absolute causal inference, although mixed-effects modelling adequately controlled intra-cluster dependence. This research was conducted in urban elementary school contexts with relatively brief intervention duration (12 weeks), necessitating further investigation of generalization to rural contexts, resource-limited areas, or different curriculum systems. Additionally, physical activity was measured via self-report (PAQ-C), which carries potential memory and social desirability bias. Future research should incorporate objective measures such as accelerometers or pedometers, expand school and student characteristic variability, and explore integration of digital technology or game-based learning to support student engagement. Despite these limitations, this study contributes important evidence to physical education and child health literature by demonstrating that brief integrated intervention models implemented within regular class time, combining interval training, circuit exercises, and healthy habit education produce meaningful improvements in cardiovascular fitness.

The global relevance of these findings is that schools across diverse nations, particularly in regions with high sedentary lifestyle prevalence and facility limitations, may adapt the FitKids Program framework as a practical, relatively low-cost strategy supporting international physical activity recommendations for children and long-term public health goals. Future investigations should examine long-term sustainability, explore adaptations for diverse cultural contexts, and investigate potential mechanisms linking integrated PA-nutrition interventions to additional

outcomes including academic performance, mental health, and metabolic health markers in larger and more diverse populations.

Conclusion

This study's findings confirm that the FitKids Program, integrated into physical education lessons, effectively increases cardiovascular fitness, but did not significantly improve overall physical activity levels after school clustering and baseline adjustment. Meaningful cardiovascular fitness increases in the experimental group demonstrate that the combination of interval training, moderate-intensity circuit training, and healthy habit education produces tangible aerobic fitness changes.

This learning framework combining movement and knowledge within a single session provides meaningful learning experiences, supporting physical competence development alongside healthy lifestyle awareness. Based on these results, FitKids has potential for global adaptation as a flexible, relatively low-cost school intervention model, with cultural and curriculum content adjustments. Future cross-national research is needed to test effect replication, utilize more objective physical activity measurements, and explore digital technology support to enable widespread program implementation and contribute to long-term public health goals.

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THE EFFECT OF EXERCISE PROGRAMMES ON PHYSICAL AND PHYSIOLOGICAL HEALTH INDICATORS IN INDIVIDUALS WITH DOWN SYNDROME: A SYSTEMATIC SCOPING REVIEW

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Abstract Aim: The aim of this two-stage systematic review is (1) to outline the scope of health problems commonly seen throughout the lives of individuals with Down syndrome (DS) and (2) to synthesise the effectiveness of exercise interventions implemented for these problems through multidimensional health outcomes. The review aimed to comprehensively evaluate the clinical value of exercise-based approaches for problems observed in individuals with DS in the cardiovascular, respiratory, metabolic, neuromotor, musculoskeletal, postural control, gait, and cognitive/psychosocial domains.

Methods: The review was conducted in accordance with the PRISMA 2020 guidelines, and the study selection/exclusion processes were managed using the Covidence programme. Searches were conducted in the Web of Science, Scopus, PubMed, and MEDLINE databases using relevant keywords. After removing duplicate records, two independent researchers performed title-abstract and full-text screenings. Experimental or observational studies describing health problems in DS or implementing exercise/physical activity interventions for these problems were included in the review.

Results: A total of 51 studies were included. In the first phase, individuals with DS demonstrated a high prevalence of congenital heart disease (CHD) (40–67%), predominantly ventricular septal defect (VSD), atrial septal defect (ASD), and atrioventricular septal defect (AVSD). CHD markedly increased mortality risk in complex cases, while early echocardiographic screening and timely surgery improved survival. Obesity and obstructive sleep apnoea were highly prevalent from early childhood, and aerobic capacity indicators (VO_{2peak} , HR_{peak}) were consistently reduced independent of adiposity. Musculoskeletal abnormalities—including pes planovalgus, impaired postural control, and altered gait patterns—were common and contributed to reduced functional performance.

In the second phase, exercise interventions demonstrated clear multidomain clinical benefits in DS. Core stability and treadmill-based training improved balance, whereas structured motor programmes enhanced fundamental motor skills. Resistance and multicomponent exercise improved muscle strength, functional fitness, and oxidative stress markers. Sports-based interventions (e.g., swimming, Nordic walking, basketball) enhanced locomotor capacity and participation. Respiratory-focused approaches such as proprioceptive neuromuscular facilitation (PNF) and chest physiotherapy improved pulmonary function. Technology-assisted modalities—virtual reality (VR) and transcranial direct current stimulation (tDCS)—supported neuroplasticity and yielded clinically meaningful motor and cognitive gains.

Conclusion: This systematic review demonstrates that health problems affecting multiple systems are common and determine quality of life in individuals with DS; however, appropriately planned exercise programmes provide meaningful benefits at biological, motor, cognitive and psychosocial levels. Early screening and follow-up, along with individualised, multi-component exercise approaches, are considered a fundamental intervention strategy for reducing cardiometabolic risks, maintaining functional independence, and increasing social participation in DS.

Key words: Down syndrome, health, exercise, physiology

Introduction

Down Syndrome (DS) is a genetic condition that occurs in approximately one in every 700 live births (de Graaf et al., 2015), is mostly associated with trisomy 21, and is characterised by a clinical picture affecting multiple systems. These individuals, who have certain distinctive physical and physiological differences, have a higher prevalence of accompanying health problems related to the cardiovascular (Dimopoulos et al., 2023), endocrine (Szczańska-Popłonyk et al., 2024), musculoskeletal and neuromotor systems compared to the general population (Gawel et al., 2024). Congenital heart disease (CHD) is at the centre of this burden; the prevalence of CHD in different cohorts is reported to be approximately 40–67%, with the most common lesions being ventricular septal defect, atrial septal defect and atrioventricular septal defect (Alkhushi, 2024; Nordklev et al., 2024; Uludag Alkaya et al., 2023; Yaqoob et al., 2019). The presence of CHD, particularly in complex lesions, has been shown to significantly increase mortality; long-term survival in the DS + CHD combination has been shown to be lower than both the general population and individuals with CHD but without DS (Villamil et al., 2025). It has also been reported that the relationship between cardiac structure and function and body composition follows a different pattern in DS, with left ventricular mass and diastolic function parameters differing significantly from healthy peers (Fitzpatrick et al., 2020; Kelly et al., 2019). Pulmonary hypertension and the accompanying haemodynamic overload further complicate the clinical picture from childhood onwards (Bush & Ivy, 2022).

In addition to cardiovascular problems, obesity, dyslipidaemia, obstructive sleep apnoea and low aerobic capacity emerge as significant health problems from early life onwards in individuals with DS. The prevalence of obesity in children and adolescents has been found to be significantly higher than in the general population; an increased body mass index has been shown to be associated with sleep apnoea, metabolic disorders, and low physical fitness (Basil et al., 2016; Pecoraro et al., 2024). It has been reported that $\text{VO}_{2\text{peak}}$ and maximum heart rate are significantly lower in both young and adult DS populations, independent of obesity, and that cardiorespiratory responses exhibit an inefficient pattern during submaximal and maximal exercise (Dodd et al., 2023; Mendonca et al., 2022; Oviedo et al., 2021). From a musculoskeletal perspective, pes planovalgus, joint hypermobility, decreased trunk and lower extremity muscle strength, postural control and balance disorders, and wide-based and variable gait patterns have been frequently reported (Foley & Killeen, 2019; Giustino et al., 2020; Leite et al., 2018; Masaki et al., 2021). It is emphasised that these impairments are decisive in terms of functional performance, daily living activities and long-term physical activity levels, and that gait disturbances and cognitive decline with age may contribute to the risk of dementia (Beqaj et al., 2018).

Given this complex morbidity profile, exercise and physical activity interventions stand out as a non-pharmacological primary treatment and rehabilitation tool for individuals with DS. Randomised controlled and controlled studies have shown that core stability and treadmill-based programmes significantly improve balance in children (Alsakhawi & Elshafey, 2019; Jain et al., 2022), the effects of structured exercise protocols on fundamental motor skills, balance, and lower extremity functional strength (Thein Tun et al., 2025), and that basketball and multi-component programmes yield significant gains in body composition and functional fitness (Cai & Baek, 2022). Resistance training has been reported to increase muscle mass, muscle strength and functional performance, while positively modulating oxidative stress markers (Rosety-Rodriguez et al., 2021). Aerobic and resistance-based cardiorespiratory programmes provide significant improvements in blood pressure, haemodynamic responses and submaximal exercise efficiency (Seron et al., 2015). Nordic walking, swimming and community-based strength training, such as sports-based approaches, increase walking parameters, locomotor functions and social

participation, while pulmonary rehabilitation and chest physiotherapy applications offer clinically meaningful gains in respiratory functions (Nahla et al., 2022). Additionally, it has been demonstrated that single-session moderate-intensity exercise can provide acute benefits on executive functions and inhibition, and that the combination of tDCS and virtual reality can support neuroplasticity on motor-cognitive outputs (Chen et al., 2015).

Upon reviewing the entire literature, it is evident that studies on individuals with DS generally consist of a mixture of studies with heterogeneous methodological quality, typically addressing a single clinical domain or a single exercise modality. It was concluded that there are a limited number of studies that analyse cardiac, pulmonary, metabolic, and musculoskeletal profiles in individuals with DS together, address the distribution and prevalence of health problems in individuals with DS, examine the effects of exercise applications on these health problems, and summarise them systematically. In this context, the planned systematic review has a two-stage structure: in the first stage, existing epidemiological and clinical evidence regarding CHD, pulmonary hypertension, obesity, cardiorespiratory capacity, musculoskeletal anomalies, postural control, balance, and walking characteristics in children, adolescents, and adults with DS will be synthesised. The second phase will evaluate the effects of exercise and physical activity-based interventions (aerobic, resistance, multi-component, sport-based, pulmonary, and technology-assisted programmes) on cardiorespiratory fitness, muscle strength, motor skills, balance, gait, respiratory function, oxidative stress, and cognitive outcomes. This review is expected to contribute to the evidence-based restructuring of clinical monitoring and rehabilitation strategies for individuals with DS and to provide a methodological roadmap for future exercise-based intervention studies. However, the current literature consists of a mosaic of studies with heterogeneous methodological quality, mostly addressing a single clinical domain (e.g., only CHD, only obesity, or only motor skills) or a single exercise modality. There is no comprehensive review that simultaneously addresses the cardiac, pulmonary, metabolic, and musculoskeletal profile in individuals with DS to define the distribution of health problems and systematically summarise the multidimensional clinical effects of exercise interventions in the same population. In this context, the planned systematic review has a two-stage structure: in the first stage, existing epidemiological and clinical evidence regarding CHD, pulmonary hypertension, obesity, cardiorespiratory capacity, musculoskeletal anomalies, postural control, balance, and gait characteristics in children, adolescents, and adults with DS will be synthesised. In the second phase, the effects of exercise and physical activity-based interventions (aerobic, resistance, multi-component, sport-based, pulmonary, and technology-assisted programmes) on cardiorespiratory fitness, muscle strength, motor skills, balance, gait, respiratory function, oxidative stress, and cognitive outcomes will be evaluated. This review is expected to contribute to the evidence-based restructuring of clinical monitoring and rehabilitation strategies for individuals with DS and to provide a methodological roadmap for future exercise-based intervention studies.

Methods

Study Selection

The protocol for this systematic review was registered in advance in PROSPERO (CRD420251046980), and the study selection process was conducted in accordance with the PRISMA 2020 guidelines (Page et al., 2021). This study has been pre-registered on the Open Science Framework (OSF) platform in accordance with the principles of transparency and reproducibility, and the methodological details are presented in a structured manner in the relevant registration file (<https://osf.io/nq68z>). Following the literature search, records were transferred to Covidence

(Veritas Health Innovation, Melbourne, Australia) software, and duplicate records were first automatically and then manually removed. As the review was planned in a two-stage structure, the identified studies were divided into two different eligibility sets: (i) observational studies reporting the profile and outcomes of common health problems (particularly in the areas of cardiac, obesity/metabolic, musculoskeletal, balance/gait, and cardiorespiratory fitness) in individuals with DS, and (ii) experimental/quasi-experimental studies examining the effectiveness of exercise, physical therapy/rehabilitation, or physical activity interventions targeting these problems. The Web of Science, PubMed, Scopus, and Medline databases were used in the research.

A targeted strategy combining four core concept blocks was used in electronic searches. The basic query used in Web of Science was as follows: Down syndrome' OR 'Trisomy 21' AND ('physical therapy' OR 'physiotherapy' OR "rehabilitation" OR 'neurodevelopmental treatment') AND ('exercise' OR 'physical activity' OR "sports" OR 'adaptive sports' OR 'functional training') AND ('motor skills' OR 'functional improvement' OR 'outcomes'). This configuration combines (1) the population (DS), (2) the treatment/rehabilitation context (physiotherapy, rehabilitation, neurodevelopmental approaches), (3) the type of intervention (exercise, physical activity, sports, functional training), and (4) the outcome domains (motor skills, functional improvement, outcomes). Corresponding MeSH/Thesaurus terms and free-text keywords in other databases were adapted while preserving this logical block structure. As language restrictions, only English and Turkish full-text, peer-reviewed journal articles were included; no restrictions were imposed on age, gender, or work environment.

Data Extraction

Two authors (A.K. and B.Ç.) performed the extraction of original bibliographic articles. The two authors independently searched and selected articles using the following criteria: characteristics of the target population, study type, and outcome. When necessary, the third and fourth authors (M.T. and Ö.E.) assisted in the inclusion or exclusion of articles.

Participants, intervention, comparators, outcomes, and study design (PICOS) criteria were used to identify included and excluded studies. These criteria have been systematically applied to both the observational studies in the first phase and the intervention studies in the second phase.

Table 1. Study inclusion and exclusion criteria based on PICOS

	Inclusion Criteria	Exclusion Criteria
Population	Children, adolescents or adults diagnosed with genetically confirmed DS (Trisomy 21, mosaic or translocation); there are no restrictions based on gender, age or living environment.	Participants without DS, mixed samples where DS is not reported separately, and studies providing only family/caregiver data.
Intervention	First stage: congenital heart diseases and cardiac outcomes, obesity/body composition, cardiorespiratory fitness, musculoskeletal findings, and balance/gait-functional performance. In the second stage: motor skills, balance and walking, muscle strength, cardiorespiratory responses, oxidative stress/antioxidants, pulmonary functions, and cognitive performance.	Studies in which the components of the intervention cannot be distinguished and the effect of exercise/physiotherapy cannot be analysed independently; studies focused solely on pharmacological or surgical treatment.
Comparator	In intervention studies, a passive control or active control group is not required in observational studies.	Single-arm experimental studies or case series without an appropriate comparator.
Outcome	First stage: cardiac status, obesity/body composition, cardiorespiratory fitness, musculoskeletal findings with balance, walking and functional performance. Second stage: motor skills, balance and walking, muscle strength, cardiorespiratory responses, oxidative stress/antioxidants, pulmonary functions and cognitive performance.	Studies that only report subjective perceptions such as attitude, knowledge, satisfaction; studies that do not provide clinical, functional or physiological health indicators; reports that do not contain sufficient quantitative outcome data.
Study Design	Observational studies and experimental/quasi-experimental intervention studies.	Case presentations, small case series, editorial articles, commentaries, conference abstracts, reviews and meta-analyses.
Additional Criteria	Original research articles published in peer-reviewed scientific journals, with full text available in Turkish or English.	Publications whose full text is unavailable; articles in languages other than Turkish/English; works that are solely theses, reports or grey literature.

Risk of Bias and Study Quality Assessment

For this review, the methodological quality and potential for bias of the included studies were independently assessed by two researchers. The Newcastle-Ottawa Scale (NOS) was used for observational studies (cohort, case-control, and cross-sectional designs), and the PEDro Scale was used for randomised and semi-randomised studies of exercise/physiotherapy interventions (Maher et al., 2003; Stang, 2010). Each study was assessed separately according to the criteria of the relevant scale, and a total score was calculated. For PEDro, 6–10 points were interpreted as ‘high’, 4–5 points as ‘moderate’, and 0–3 points as ‘low’ methodological quality; for NOS, 7–9 points were considered ‘high’, 5–6 points as ‘moderate’, and ≤4 points as ‘low’ quality. Discrepancies between the two independent evaluators were first resolved through consensus; in cases where consensus could not be reached, a third senior researcher was consulted to make the final decision.

As a result of database searches, a total of 7,844 records were obtained (Web of Science: n=4,050, Scopus: n=3,712, PubMed: n=82). No additional records were identified from supplementary sources or grey literature. Using Covidence software, 1,416 duplicate records were automatically removed, and 6,428 unique studies were screened at the title-abstract level. At this stage, 6,042 studies that did not meet the eligibility criteria were excluded. A total of 211 studies were evaluated for full-text review; no studies were inaccessible (n=0). In the full-text evaluation, the reasons for exclusion were incorrect outcome domain (n=92), incorrect indication (n=28), incorrect study design (n=15), incorrect intervention (n=5), incorrect setting (n=3), and sample incompatible with the target population (n=1). Ultimately, 51 studies meeting the inclusion criteria were included in the systematic review (Figure 1).

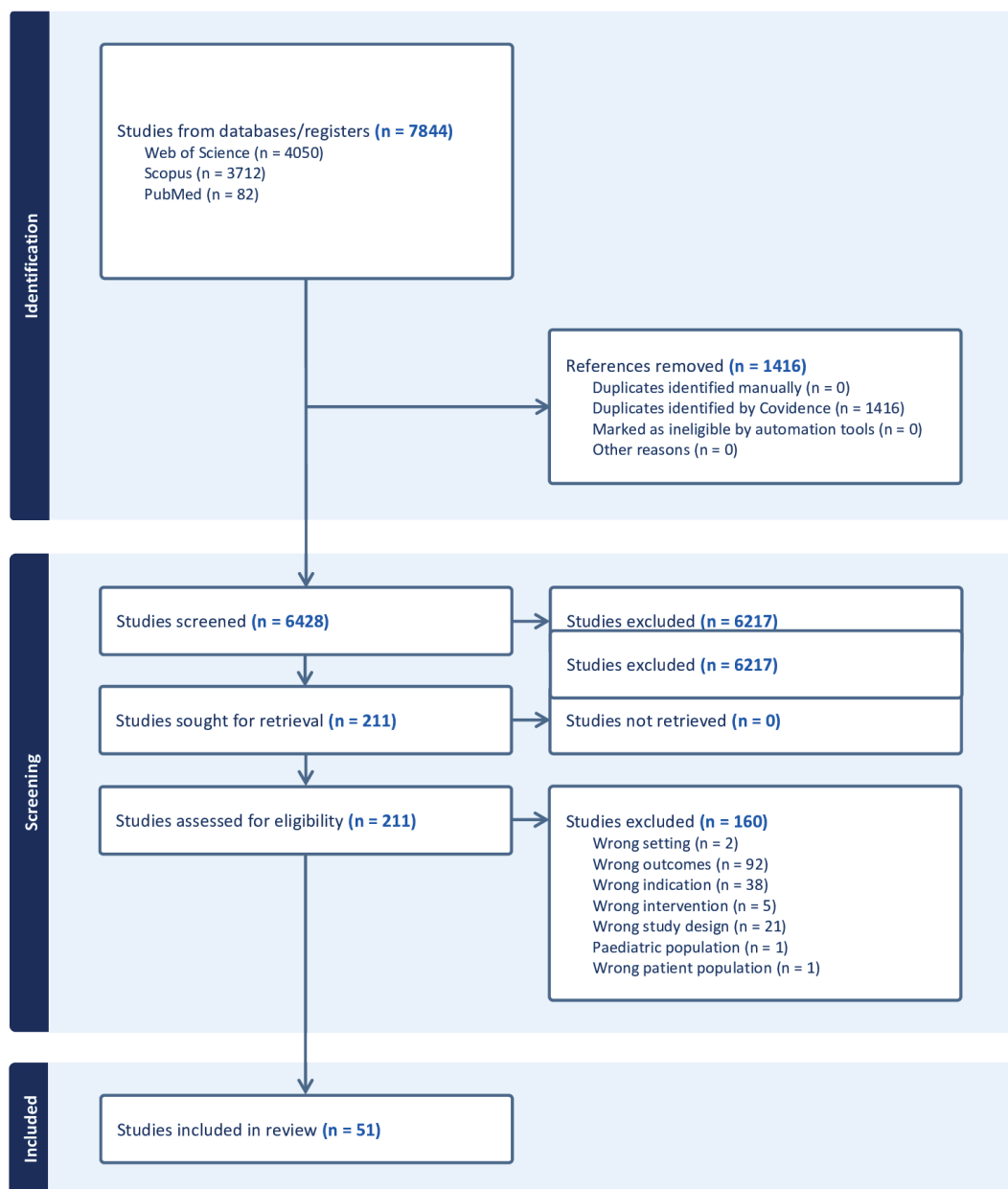


Figure 1. PRISMA diagram of study

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
Congenital Heart Defects (CHD)						
1	(Uludag Alkaya et al., 2023)	Retrospective Cohort	1731 DS Female: 573 Male: 1158 Age: 1 day – 25 years follow-up: 36 years	CHD diagnosis was made by echocardiography. Congenital heart diseases, surgical intervention, neuromotor development, and mortality were analyzed.	CHD prevalence is 52.1% VSD: 35% ASD: 31.8% AVSD: 23.4% Five-year survival is 97.4% in patients without CHD, 95.6% in mild CHD, and 86.1% in moderate-severe CHD. CHD is more common in women than in men.	The prevalence of CHD, most commonly VSD, is higher in girls with DS and shows a significant association only with hypothyroidism, while no association has been found with neurodevelopmental outcomes and other risk factors.
2	(Yaqoob et al., 2019)	Retrospective	350 DS Female: 140 Male: 210 Age: 0–18 years follow-up: 6 years	CHD diagnosis was made by echocardiography Thyroid function (T3, T4, TSH) was measured. Chromosomal analysis was performed (trisomy 21, translocation, mosaicism)	CHD prevalence: 41.8% VSD: 41% PDA: 15.4% AVSD: 12% Thyroid dysfunction: 22% Compensated hypothyroidism: 12.5% Overt hypothyroidism: 5.8% Hyperthyroidism: 3.7% CHD was more common in males, while thyroid disorders were seen at similar rates in both genders.	Congenital heart disease and thyroid dysfunction are common in individuals with DS, and early diagnosis and intervention for these conditions, accompanied by routine screening and a multidisciplinary approach, significantly improve quality of life and survival.
3	(Alkhushi, 2024)	Retrospective	254 DS Female: 113 Male: 141 Age: 1–53 years Follow-up: NA	Echocardiography reports were used; the prevalence, type, hemodynamic significance, and surgical interventions of congenital heart diseases were evaluated.	CHD prevalence: 66.5% AVSD: 33.1% Perimembranous VSD: 18.9% Right ventricular pathologies: 10.2% Hemodynamically significant CHD was observed in 52.4% of cases.	Congenital heart disease is observed in 66.5% of children with DS, most commonly AVSD and perimembranous VSD. Surgery is required in 34.4% of cases; early diagnosis and regular follow-up have a positive effect on quality of life.
4	(Nordklev et al., 2024)	Cohort	702 DS Female: 113 Male: 141 Age: 1–53 years	Participants were examined using the Norwegian Birth and Heart Registries. CHD prevalence, subtypes of AVSD, congenital characteristics, and surgical outcomes were evaluated.	CHD prevalence: 57.4%; AVSD: 44.4%). The female ratio and prematurity were higher in infants with AVSD. The survival rate up to 1 year of age was 93.2%; it was 99.7% in those without AVSD. The survival rate of those who underwent surgery was 96%.	Early cardiac screening and timely surgical intervention in AVSD cases observed in babies with DS have been reported to increase survival rates. Furthermore, it has been reported that live birth rates in Norway have remained stable over the past 20 years and that the first-year mortality risk for these babies does not differ from that of AVSD cases without chromosomal abnormalities.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
Mortality Rate						
5	(Engsner et al., 2024)	Retrospective	67,814 CHD+DS: 3285 CHD: 64,529 Controls: 26,128 Follow-up: 16	Data were obtained from the Swedish National Health Records. All-cause mortality and cardiovascular mortality are analysed.	The mortality rate DS+CHD group: 17% CHD-only group: 8% Control group: 0.8% Survival was lower in individuals with DS and complex CHD. Mortality related to CHD was higher in individuals with DS, especially in the first years after birth. Although the mortality difference decreased with age, life expectancy was low, especially in the presence of complex CHD.	DS has been shown to significantly increase the mortality risk of congenital heart disease; therefore, early diagnosis, surgical intervention, and long-term follow-up of cases with complex CHD in particular are recommended.
6	(Alsaied et al., 2016)	Retrospective cohort	1092 DS Age: 0–18 years	The study examined the effect of cardiac surgery on neurodevelopmental and academic outcomes in children with DS using a retrospective cohort design. Assessments were conducted using clinical records and at least one of the following standardized tests: Bayley-III, PLS-5, PDMS-2, WJ-III, OWLS-II, BRIEF, and CBCL.	Infants with CHD scored significantly lower on language development compared to those without CHD. Preschool children with CHD scored lower on language and visual-motor tests, but the differences were not significant. In school-age children, the presence of CHD did not affect neurodevelopmental outcomes.	In children with DS and those requiring congenital heart surgery, although language development may be delayed in early childhood, these differences are observed to disappear by school age, highlighting the importance of early intervention.
Other Cardiac Problems						
7	(Fitzpatrick et al., 2020)	Retrospective cohort	2342 DS Female: 1257 Male: 1085 Age: ≥18 years Follow-up: 20 years	Analyzed from US health system records. Prevalence of heart disease (CHD, MI, heart failure), stroke, hypertension, diabetes, and obesity was determined using ICD codes.	CHD: 0.38%, MI: 0.04%, Hypertension: 2.69%, Diabetes: 5.00%, Hypercholesterolemia: 2.69% were lower than in the general population. Stroke rates were similar. The rates of overweight (73.4%) and obesity (43.0%) were higher. Cardiovascular risk factors were generally less common in the DS group.	Although obesity is common in individuals with DS, the prevalence of cardiovascular disease is lower than in the general population, highlighting the importance of restructuring health policies and screening strategies specific to this group.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
8	(Claus et al., 2019)	Cross-sectional study	149 DS Age: 10–20 years	Cardiac structure and function were assessed using echocardiography. New cardiac findings were identified in individuals who had not previously been diagnosed.	New cardiac anomalies were detected in 6% of individuals who had not previously been diagnosed, and these findings included PDA, aortic insufficiency, mitral valve deformities, pericardial effusion, left ventricular hypertrophy, ventricular premature beats, and VSD; these new anomalies were observed in both individuals with and without a history of CHD.	Asymptomatic cardiac anomalies can be detected in adolescents with DS, independent of known CHD history, supporting the need for re-evaluation of cardiac function during adolescence.
9	(Kelly et al., 2019)	Cross-sectional study	136 DS Female: 76 Male: 60 102 healthy Female: 60 Male: 42 Age: 13–29 years	Body composition measurement using DXA Cardiac measurements using echocardiography Use of a pedometer for physical activity	The DS group had lower lean body mass and left ventricular mass values. The measurement of diastolic function was higher in the DS group. Physical activity level was lower in the DS group.	Individuals with DS have been found to have widespread diastolic dysfunction and low left ventricular mass regardless of CHD. This condition is thought to be related to possible structural, genetic, or physical inactivity, and it is recommended that the findings be evaluated with long-term follow-up.
Obesity						
10	(Basil et al., 2016)	Retrospective	303 DS Female: 136 Male: 167 Age: 2–18 years	BMI $\geq$ 95th percentile: defined as obese. Osleap apnea syndrome assessment was performed using polysomnography. Compared with a local control group.	The obesity rate 47.8% (DS), 12.1% (control group). Osleap apnea syndrome was detected in 74% of children with DS. Obese children with DS had a higher risk of Osleap apnea syndrome	The tendency toward obesity that begins early in children with DS and the associated increased risk of obstructive sleep apnea necessitate informing families from infancy and implementing structured weight management strategies during childhood.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
Aerobic capacity						
11	(Wee et al., 2015)	Cross-sectional retrospective	654 DS: 151 IDnoDS (Intellectually disabled, non-DS): 180 NoID (non-intellectually disabled): 323 Age: 8–46 years	VO ₂ peak and HR peak were measured using a treadmill test. Obesity status was classified according to BMI. VO ₂ peak and HR peak values were compared according to age and obesity.	HR peak and VO ₂ peak values were lower in individuals with DS compared to all other groups. Obesity did not affect HR peak in children with DS, but it decreased it in those without DS. VO ₂ peak was lower in obese adults with DS, but it was not affected in children.	The finding that VO ₂ peak levels are low in adults with DS, independent of obesity, indicates that interventions should be planned with a focus on increasing aerobic capacity, while obesity management has been determined to be particularly critical in individuals without DS.
12	(Mendonca et al., 2022)	Cross-sectional, multicenter observational study	100 DS Female: 30 Male: 70 Age: ≥18 years Controls: Age-matched	Exercise test: CPET (cardiopulmonary exercise testing) using the semi-occluded ramp protocol. VO ₂ peak and HR peak were measured.	VO ₂ and HR levels in individuals with DS were significantly lower than in the general population	In this study, where low VO ₂ peak and HRpeak levels were observed in all age groups, gender differences were found to be similar to those in the general population, and specific prediction equations were developed for individuals with DS.
Physical activity						
13	(Dodd et al., 2023)	Cross-sectional	79 DS Female: 41 Male: 38 Age: ≥18 years	VO ₂ max test, 7-day accelerometer data, and CANTAB cognitive test battery were used. Participants were divided into two groups based on BMI: normal weight and obese. The relationship between physical fitness, activity, and cognitive performance was analyzed.	VO ₂ max was significantly lower in the obese group. There was a negative correlation between BMI and VO ₂ max. There was no difference in physical activity duration between groups. No significant relationship was found between BMI and cognitive function.	In adults with DS, an increase in BMI negatively affects cardiorespiratory capacity but has not shown a significant relationship with physical activity and cognitive function. In line with these findings, it has been demonstrated that priority should be given to improving physical fitness in obesity prevention interventions.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
14	(Pino-Valenzuela & Benavides-Roca, 2023)	Prospective	16 DS Female: 3 Male: 13 Age: 10–25 years Follow-up: 10-year	Measurements: Body mass, height, waist/hip circumference, skinfold thickness, muscle strength, abdominal capacity, flexibility, aerobic capacity	Body fat percentage increased significantly between 2009 and 2019. Abdominal capacity decreased during the same period. An increase was observed in waist and hip circumference and BMI values. Flexibility and handgrip strength also decreased; though to a lesser extent.	Over a 10-year period, individuals with DS experienced negative changes in physical fitness and body composition due to a lack of physical activity, which adversely affected their health.
15	(Pitchford et al., 2018)	Prospective	22 DS Female: 8 Male: 14 Contol: 17 Female: 10 Male: 7 Age: 12–18 years	Body fat percentage measured by DXA, MVPA Physical activity level measured by accelerometer (Actigraph GT3X+)	In DS have higher BMI and body fat percentage, lower MVPA Moderate negative correlation between MVPA and DXA fat percentage No significant correlation between BMI and MVPA	It has been determined that fat accumulation in adolescents with DS contributes to low physical activity levels despite not being detectable by BMI, and that body fat percentage measured by DXA is significantly associated with MVPA. Therefore, it is recommended that DXA be preferred over BMI.
Musculoskeletal symptoms						
16	(Foley & Killeen, 2019)	Observational study	503 DS Female: 281 Male: 212 Age: 0–21 years	Observational musculoskeletal examination performed	Pes planus prevalence: 91% Inflammatory arthritis: 7% Scoliosis: 4.8%	This study found that musculoskeletal anomalies are common and often overlooked in children with DS, and that the risk of aggressive arthritis is particularly high.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
17	(Masaki et al., 2021)	Cross-sectional comparative study	23 DS Female: 7 Male: 16 Controls: 24 Female: 12 Male: 12 Age: 3–6 years	Pesplanus evaluated by Arch Height Index (AHI) Foot muscle thicknesses evaluated by ultrasonography	In the DS group, AHI was significantly lower, posterior tibialis and soleus muscle thicknesses were also lower. However, flexor digitorum longus muscle thickness was significantly higher in the DS group As AHI decreased, the thickness of this muscle increased.	In children with DS, as AHI decreases in relation to pes planovalgus deformity, the soleus and posterior tibialis muscle mass decreases, while a compensatory increase is observed in the flexor digitorum longus muscle; these findings should be considered in treatment planning.
18	(Shields et al., 2017)	Prospective cohort	50 DS Female: 32 Male: 28 Age: 8–18 years	Foot posture: assessed using the arch index, deformities: hallux valgus, toe shape. Shoe fit: length and width measurements. Physical activity: measured using an accelerometer over 7 days.	Shoe length exceeding foot length reduced physical activity levels No significant relationship was found between flat feet and other foot deformities and physical activity. Only 8% of the shoes were the correct size; 54% were too long, and 60% were too narrow.	This study has demonstrated that the level of physical activity in children with DS is negatively affected by the frequent use of inappropriate footwear, and that appropriate footwear selection and regular clinical evaluations play an important role in increasing activity.
19	(Chen et al., 2021)	Observational comparative	54 DS Age: 14–52 years	Manipulation skills were assessed using the Purdue Pegboard Test (PPT), hand grip strength was measured using a dynamometer, and mental age was assessed using the Peabody Picture Vocabulary Test.	Assembly" alt testinde genç grubun üstün performans gösterdiği, diğer PPT alt testlerinde ise anlamlı fark bulunmadığı; kavrama gücünün yaşla değişmediği ancak el tercihi farklılığının yaşlı grupta daha belirgin olduğu belirlenmiştir.	It has been demonstrated that manipulative motor skills in individuals with DS are not significantly affected by age, but are closely related to verbal cognitive abilities. It has been emphasized that rehabilitation approaches should be planned according to the individual's level of mental development.
20	(Valero et al., 2021)	Cross-sectional	361 DS Female: 170 Male: 191	Data collected via an online questionnaire completed by their parents Motor development: ages of crawling, first steps, and independent walking. Orthopedic conditions: flat feet, knee abnormalities.	Delayed first steps increased the risk of wide-based walking by 7%. Knee deformity and flat feet were found to be associated with wide-based walking. No significant relationship was observed with the frequency of physical therapy or the status of receiving therapy.	This study has demonstrated that wide-based walking is associated with early motor development stages (particularly crawling and walking); multidisciplinary follow-up and early motor support have been recommended to prevent postural and walking disorders.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
Postural Control and Balance						
21	(Leite et al., 2018)	Cross-sectional observational	21 DS Female: 9 Male: 12 Age: 8–12 years	Postural control was assessed using a force platform in a 30-second standing position.	Swing speed has decreased significantly with age. While no statistically significant relationship was found between postural control and gender, nutritional status, and physical activity level, 95% of participants were determined to be sedentary. COP values did not show any significant change according to age.	It has been determined that postural control, which develops with age in individuals with DS, differs from that of typically developing individuals in terms of swing rates; however, this control is not affected by factors other than age, such as gender, nutrition, and physical activity.
22	(Jain et al., 2022)	Cross-sectional	14 DS Control: 14 Female: 8 Male: 6 Age: 6–11 years	Trunk muscle strength: measured with a hydraulic dynamometer. Reach ability: modified Functional Reach Test. Balance: Pediatric Balance Scale (PBS).	In the DS group, trunk muscle strength, balance, and reach scores were significantly lower. Trunk extensor muscle strength was found to be positively associated with balance and lateral reach.	Low trunk muscle strength in children with DS limits their balance and functional reach abilities; strengthening the trunk extensor muscles in particular should be a priority in rehabilitation programs, as it can improve functional balance during sitting, standing, and transfers.
23	(Giustino et al., 2020)	Cross-sectional, comparative	22 DS Female: 9 Male: 13 Controls: 25 Female: 11 Male: 14 Age: 16–36 years	Stabilometric tests: performed in the bipedal standing position for 30 seconds each with eyes open (EO) and eyes closed (EC). Measurements using the freeMed® platform and freeStep® software.	In the DS group, the elliptical oscillation area was found to be high under both EO and EC conditions. With eyes closed, the oscillation length and speed parameters increased significantly.	It has been demonstrated that postural control in individuals with DS is associated with delayed multisensory integration; emphasizing the importance of visual input, it has been suggested that exercises targeting somatosensory, proprioceptive, and strength coordination may be considered to improve balance and functionality.
Gait Parameters						
24	(Beerse et al., 2019)	Prospective	13 DS Female: 2 Male: 11 Controls: 13 Female: 2 Male: 11 Age: 0–10 years	Conditions: slow (75% speed), fast (100% speed), and treadmill walking with a load of 2% body weight on the ankle. Measurements: Spatiotemporal gait parameters (step length, width, swing, double support, foot rotation) using the Vicon system.	Individuals with DS exhibited short stride length, wide stride width, and high variation in spatiotemporal parameters. Increased speed and ankle load supported balance by reducing this variation. There were no differences between groups in terms of timing variables.	It has been demonstrated that children with DS can adapt to walking conditions, that despite a noticeable stride width and short steps, the swing time and foot rotation are similar, and that low-level loading and fast walking have the potential to improve balance.

No	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
25	(Zago et al., 2019)	Retrospective observational cohort	230 DS Female: 103 Male: 127 Age: 7–50 years	Gait analysis was performed with 6 walks on a 10-meter course. Measurements: Gait Profile Score (GPS), Gait Variable Scores (GVs), step length, step width, walking speed, stance/swing ratio.	Gait Profile Score was higher in women (i.e., greater impairment) Step length was shorter in women. Greater impairment was observed in women in joint movements such as pelvic tilt, hip, and knee flexion. Foot rotation was more markedly impaired in men.	It has been demonstrated that walking function is more significantly affected in women with DS compared to men, although foot propulsion impairment is more pronounced in men; this highlights the importance of gender-sensitive rehabilitation approaches.
26	(Koo et al., 2022)	Comparative, observational study	6 DS 6 Healthy peer Age: 12–16 years	Joint stiffness, strength, and range of motion were measured during single-leg drop landing. Equipment: isokinetic dynamometer, force platform, 3D motion analysis system.	Children with DS had high vertical ground reaction force (VGRF) at the heel, but low knee and hip muscle strength. Joint stiffness did not differ between groups; however, a negative correlation was observed between hip/ankle stiffness and knee range of motion in the DS group.	It has been demonstrated that children with DS develop alternative motor strategies compatible with different ranges of motion during descent, that this is not related to joint stiffness, and that approaches that reduce plantar force should be prioritized in rehabilitation.

Congenital Heart Disease (CHD) in Down Syndrome (DS):

Congenital heart disease (CHD) is quite common in individuals with DS and has significant effects on quality of life and survival. Large-scale retrospective cohort studies conducted in recent years provide important information about CHD prevalence, subtypes, gender differences, and associated risk factors (Uludag Alkaya et al., 2023; Yaqoob et al., 2019; Alkhushi, 2024; Nordklev et al., 2024). The prevalence of CHD in individuals with DS ranges from 40% to 67%; meta-analyses indicate that approximately half have CHD. All studies agree that the prevalence of CHD in the DS population is very high compared to the general population (~1%). The most common CHD types are atrioventricular septal defect (AVSD), ventricular septal defect (VSD), and atrial septal defect (ASD), with AVSD rates around 30–44%, VSD 22–43%, and ASD 16–42% (Uludag Alkaya et al., 2023; Yaqoob et al., 2019; Alkhushi, 2024; Nordklev et al., 2024). Although Yaqoob et al., 2019, reported that CHD is more common in males, Uludag Alkaya et al., 2023, and Nordklev et al., 2024, reported that it is more common in females. However, other comorbidities such as thyroid dysfunction (Yaqoob, 2019) have been reported to occur at similar rates between genders. The Uludağ Alkaya (2023) study found no significant association between parental risk factors, DS type (trisomy 21, translocation, mosaicism), low birth weight, and preterm birth with CHD. CHD, especially those with significant hemodynamic implications (Alkhushi: 52.4%), significantly affects survival. However, modern surgical techniques can achieve very high success rates, and early intervention can dramatically improve survival.

It is emphasized that all newborns with DS should undergo echocardiographic screening, preferably immediately after birth or within the first few weeks. It is noted that the management of DS requires a multidisciplinary approach involving not only cardiology, but also endocrinology (thyroid function tests), neurology/physical therapy (neuro-motor development), and genetic counseling. It is emphasized that early diagnosis and intervention for congenital heart defects and other comorbidities such as hypothyroidism can significantly improve prognosis by reducing

morbidity and mortality and improving quality of life (Uludag Alkaya et al., 2023; Yaqoob et al., 2019; Alkhushi, 2024; Nordklev et al., 2024).

Mortality rates:

Engsner et al., 2024, observed that the risk of death in individuals with DS and congenital heart disease (CHD-DS) was 25 times higher than in matched controls and twice higher than in individuals with DS without CHD. They concluded that the presence of CHD in individuals with DS significantly increases the risk of death. Therefore, they emphasize the importance of early diagnosis and surgical intervention, and the need for long-term follow-up in individuals with complex CHD (Engsner et al., 2024). Additionally, Alsaied et al. (2016) reported that children with DS and CHD requiring early surgical intervention performed worse in terms of language development during infancy (Alsaied et al., 2016). However, these differences disappeared by school age, highlighting the importance of early intervention.

Other Cardiac Problems and Obesity

Fitzpatrick et al. (2020) reported that the prevalence of cardiovascular disease is lower in individuals with DS than in the general population, but obesity, a risk factor for cardiovascular disease, is higher. Basil et al. (2016) noted that children with DS are at high risk for obesity from an early age. Obesity also increases the risk of Sleep Apnea Syndrome.

Clauss et al. (2019) identified newly detected echocardiographic abnormalities in approximately 6% of adolescents with DS and found that these findings can occur in asymptomatic individuals regardless of a known history of congenital heart disease. Kelly et al. (2019) reported that DS has a significantly lower left ventricular mass and widespread diastolic dysfunction, and this is observed regardless of the presence of congenital heart disease.

Aerobic capacity

Wee et al. (2015) emphasized that individuals with DS have lower cardiovascular fitness, independent of obesity, and that obesity has a greater impact on $\dot{V}O_2$ peak than individuals without DS. Interventions should focus on increasing $\dot{V}O_2$ peak in individuals with DS; they found that obesity is not the primary factor affecting aerobic capacity in adults with DS.

Mendonca et al. (2022) presented specific equations that can be used to estimate $\dot{V}O_2$ peak and heart rate in individuals with DS. This research revealed that individuals with DS have lower $\dot{V}O_2$ peak and heart rate levels across all age groups.

Physical activity

The critical decline in physical fitness across the lifespan and the alarming prevalence of obesity in individuals with DS (DS) highlight this, necessitating targeted intervention strategies. Longitudinal observations reveal a worrying trend with significant negative changes in physical fitness and anthropometric variables over a 10-year period, a trend strongly attributed to a lack of sustained physical activity (Pino-Valenzuela & Benavides-Roca, 2023). The relationship between obesity and physical activity is complex; although increased body mass index (BMI) is inversely associated with cardiovascular fitness in adults with DS, this relationship is not always mediated by current physical activity levels, suggesting that fitness is a primary goal (Dodd et al., 2023). Furthermore, traditional BMI measurements may be insufficient for this population, as more sensitive dual-energy X-ray absorptiometry (DXA) measurements have revealed a significant inverse relationship between moderate-to-vigorous physical activity (MVPA) and body fat percentage in adolescents, highlighting the limitations of BMI and the critical role

of high-intensity movement (Pitchford et al., 2018). Importantly, proactive management through regular counseling on nutrition and physical activity has been shown to be effective and leads to improved health outcomes, such as reduced BMI and increased physical activity levels, in children with DS, despite challenges such as adverse lipid profiles and dietary nonadherence requiring specific strategies (Pecoraro et al., 2024). Collectively, these findings advocate for a dual-focused approach that prioritizes improving cardiovascular fitness through structured interventions while simultaneously implementing regular, professional guidance to combat sedentary behavior and promote sustainable weight management from childhood to adulthood.

Musculoskeletal symptoms

Musculoskeletal anomalies represent a highly prevalent yet frequently underrecognized comorbidity in individuals with DS, with significant implications for motor function and physical activity. A striking majority exhibit pes planovalgus, with a prevalence as high as 91%, a condition characterized by a lowered medial arch and linked to alterations in lower leg muscle architecture, including atrophy of the soleus and tibialis posterior and compensatory hypertrophy of the flexor digitorum longus (Foley & Killeen, 2019; Masaki et al., 2021). These structural impairments directly impact gait and posture, where a wide-based stance is associated with delays in achieving fundamental motor milestones like quadruped crawling and independent walking, underscoring the necessity of early intervention to promote normative motor development and prevent future orthopedic complications (Valero et al., 2021). Furthermore, motor proficiency, particularly manipulative skills, is more closely tied to cognitive and verbal development than chronological age, necessitating rehabilitation programs tailored to mental age rather than biological age (Chen et al., 2021). Critically, the functional impact of these deformities is often exacerbated by external factors, as ill-fitting footwear is common and is independently associated with reduced physical activity levels, highlighting the need for routine clinical footwear assessment as a simple yet effective modifiable factor (Shields et al., 2017). This complex interplay of structural, developmental, neurological, and external factors mandates a multidisciplinary follow-up approach to address the spectrum of issues from aggressive arthritis to gait abnormalities (Foley & Killeen, 2019; Valero et al., 2021).

Postural Control and Balance

Postural control and balance in individuals with DS are characterized by fundamental deficits that stem from a complex interplay of neurological and musculoskeletal factors, rather than common modifiable influences. While postural control demonstrates a developmental trajectory with age, its quality, particularly reflected in centre of pressure dynamics and oscillation speeds, remains distinctly different from neurotypical development and is not significantly affected by variables such as gender, nutritional status, or general physical activity level, indicating a primary dependence on intrinsic neurodevelopmental factors specific to the syndrome (Leite et al., 2018). A critical component of this impaired stability is profound trunk muscle weakness, which directly and negatively impacts both static and dynamic balance, as well as functional reach abilities, thereby limiting performance in essential daily living activities and transfers (Jain et al., 2022). Underpinning these motor challenges is a neurological deficit in the timely integration of multisensory inputs—somatosensory, vestibular, and visual—for maintaining equilibrium, with an identified over-reliance on visual cues to compensate for proprioceptive and vestibular processing delays (Giustino et al., 2020). Consequently, effective rehabilitation requires a targeted approach that moves beyond general activity to include adapted exercise programs specifically designed to enhance trunk muscle strength, and to rigorously challenge and improve the coordination and integration of the somatosensory and proprioceptive systems (Jain et al., 2022; Giustino et al., 2020).

Gait Parameters

Gait in individuals with DS is characterized by a distinct biomechanical profile defined by altered spatiotemporal parameters, significant muscle weakness, and gender-specific impairments. A consistent pattern emerges of shorter step length, wider step width, and heightened variability in spatial parameters, which contributes to a less stable gait pattern; however, this instability can be mitigated through faster walking speeds and light ankle loading, demonstrating a retained capacity for neuromuscular adaptation (Beerse et al., 2019). Critically, these gait deviations are not uniform across genders, with females exhibiting a greater overall impairment in gait quality (Gait Profile Score), shorter step length, and reduced pelvic and lower extremity joint movement, while males demonstrate more pronounced deficits in foot progression and propulsion (Zago et al., 2019). The underlying mechanical contributors to this aberrant gait include significantly weakened hip and knee extensor muscles, which compromise force absorption and lead to higher than normal vertical ground reaction forces (VGRF) during weight-bearing activities (Koo et al., 2022). This combination of weakness and altered kinetics necessitates the use of compensatory movement strategies, particularly during descent tasks, which are driven more by deficits in strength and available range of motion than by differences in passive joint stiffness (Koo et al., 2022). Consequently, rehabilitation must be precisely tailored, incorporating resistance training to address specific muscle weaknesses, interventions to improve movement strategies for reducing impact forces, and considerations for the individual's gender to most effectively target their unique pattern of gait impairment (Zago et al., 2019; Koo et al., 2022).

Exercise						
n	Author, year	Study type	Sample (n)	Outcome Measurements	Key Findings	Conclusion
1	(Lopes et al., 2022)	Randomized Controlled Trial	29 DS Age: 15.7 ± 2.82 years	• RCT: EG (anodal tDCS + VR) vs. KG (sham tDCS + VR) • EEG, EMG, and 3D motion analysis were used.	tDCS-assisted virtual reality training has been shown to significantly improve motor development, balance skills, and somatosensory cortex activity in children with DS.	The combined use of tDCS and virtual reality to develop cognitive and motor skills in children with DS stands out as an effective and innovative approach in clinical rehabilitation due to its neuroplasticity-supporting effect.
2	(Alsakhawi & Elshafey, 2019)	Randomized Controlled Trial	45 DS children Age: 4–6 years (mean 4.59±0.53)	• Group A: Traditional physical therapy • Group B: Traditional therapy + treadmill training • Group C: Traditional therapy + core stability exercises. • 8 weeks X 3 days • Assessment tools: Berg Balance Scale, Biodex Balance System.	In the study, a significant increase in balance was observed in all groups, while the core stability and treadmill groups were found to be superior to the control group; however, no significant difference was observed between these two interventions.	Adding core stability and treadmill exercises to traditional physical therapy has been found to significantly improve balance in children with DS.

3	(Chen & Ringenbach, 2019)	<i>Randomized Controlled Trial</i>	8 DS Age: 14–31 years	Low Intensity (%50-75 HR, Treadmill Exercise) Moderate Intensity (%75-85 HR, Treadmill Exercise) Control Group	Moderate exercise increased grip strength in individuals with DS; however, no similar effect was observed in the high-intensity exercise and control groups, and no significant difference was found in manual dexterity.	It has been found that walking exercises do not affect manual skills in individuals with DS, but they may increase grip strength.
4	(Oviedo et al., 2021)	<i>Randomized Controlled Trial</i>	40 DS adolescents Age: 14–22 years	Cardiorespiratory correlation (CRC) and entropy levels were compared using a submaximal treadmill test. Measurements were taken for SBP, DBP, HR, and VO ₂ .	Individuals with DS showed low CRC and high entropy levels, indicating reduced physiological efficiency during exercise; it has been suggested that CRC could be an alternative parameter for evaluating exercise responses.	It has been shown that adults with DS exhibit lower cardiorespiratory coordination and higher entropy during exercise, which reduces functional efficiency.
5	(Rosety-Rodriguez et al., 2021)	<i>Randomized Controlled Trial</i>	36 male adults with DS Age: 28.1±3.3 years	A resistance circuit training program consisting of 6 stations was performed 3 days a week for 12 weeks. Assessments: TAS, GSH, GR, MDA, carbonyl groups, muscle strength. • Divided into 4 groups: DS exercise (n=17), DS control (n=15), healthy exercise (n=20), healthy control (n=18). • 45-minute resistance and jumping exercise 3 days a week for 6 months. • Measurement: BMD and BMC values using DXA.	Significant increases in TAS, GSH, and GR levels were observed after exercise; significant decreases in MDA and carbonyl group levels were observed. Increases in muscle strength were observed.	Resistance circuit training is an effective, safe, and feasible method for reducing oxidative stress, enhancing antioxidant defense, and increasing muscle strength in individuals with DS.
6	(Dilek et al., 2018)	<i>Randomized Controlled Trial</i>	70 DS and healthy controls Age: 10–30 years		While exercise tends to increase bone mineral density in healthy individuals, a decrease in BMD/BMC levels in the vertebrae and femur was observed in the DS group, and it was determined that the osteogenic response was insufficient.	It has been shown that despite six months of exercise, an unexpected decrease in BMD and BMC values was observed in individuals with DS, indicating that exercise protocols need to be reevaluated.
7	(Cai & Baek, 2022)	<i>Quasi-experimental</i>	22 DS Female: 4 Male: 18 Age: 18–40 years	The experimental group participated in basketball training three days a week for 24 weeks. Evaluation: body composition (BMI, body fat), functional fitness tests.	In the exercise group, body fat percentage and BMI decreased, while muscle mass, strength, balance, flexibility, and cardiorespiratory fitness showed significant increases.	Basketball training is an effective and enjoyable method that supports physical health by improving body composition and functional fitness in young people with DS.

8	(Yamanaka et al., 2023)	<i>Analytical observational study</i>	137 children (69 with DS, 68 healthy) Age: 10–12 years	The physical activity levels of 69 children with DS and 68 normal children were assessed using a triaxial accelerometer; parameters such as SB, LPA, and MVPA were measured between 07:00 and 21:00 and statistically analyzed.	Children with DS had shorter MVPA duration, longer LPA duration, and higher total physical activity levels. However, their obesity rate was higher compared to normal children.	VPA may be limited in children with DS due to low muscle tone; therefore, increasing LPA is important in maintaining overall activity levels and combating obesity.
9	(Diaz et al., 2021)	<i>Randomized Controlled Trial</i>	36 DS Female: Not specified Male: 36 Age: 28.1 ± 3.3 years	The effect of resistance training on muscle mass and work performance in adult men with DS was evaluated using bioimpedance and biomarkers.	Resistance exercise increased muscle mass and work performance in the DS group; no changes were observed in the control group, and muscle damage markers were unaffected.	Properly planned resistance training is may be beneficial and feasible method for increasing muscle mass and function in individuals with DS without causing muscle damage.
10	(Demir-Er et al., 2025)	<i>Comparative Observational</i>	35 DS, 20 healthy Age: 3–8 years	Gait and balance were assessed in children with DS and typically developing children using the GAITRite system and Bertec platform.	In the DS group, stride length was short, cadence was high, base width was large, and AP/ML oscillations were increased; a significant correlation was observed between walking and balance.	Significant differences were found in gait and balance parameters in children with DS, necessitating individualized and comprehensive rehabilitation approaches.
11	(Reis et al., 2023)	<i>Randomized Controlled Trial</i>	23 (11 DS, 12 Healthy, Age: 27–28 years	Muscle strength and oxidative stress and inflammation markers were compared before and after acute resistance exercise performed with elastic bands.	An increase in oxidative stress was observed in individuals with DS after resistance exercise; muscle strength increased in knee extension and elbow flexion but decreased in handgrip strength; an inverse relationship was found between strength and oxidative and inflammatory markers.	While elastic band exercises are safe for individuals with DS, the oxidative stress response remains limited, and increasing the exercise load may be necessary for optimal adaptation.
12	(Chen et al., 2015)	<i>Randomized Controlled Trial</i>	20 DS Female: 4 Male: 16 Age: 15–30 years	The effect of a 20-minute treadmill walk on executive function components such as choice–response time, attention shifting, and inhibition.	Short-term moderate-intensity walking improved inhibition performance in individuals with DS, but did not produce significant changes in choice–response time and attention shifting parameters.	Moderate exercise has been found to have short-term positive effects on inhibition in individuals with DS; further studies are recommended for long-term effects.

13	(Skiba et al., 2019)	<i>Randomized Controlled Trial</i>	22 adult DS Female: 11 Male: 11 Age: 25–40 years	Nordic Walking was practiced 3 days a week for 10 weeks; walking parameters were evaluated using 3D analysis.	Nordic Walking training has significantly increased step length, walking speed, and joint range of motion in individuals with DS, positively affecting pelvic movements and joint synchronization.	Nordic walking stands out as may be beneficial and feasible intervention that improves locomotor functions in individuals with DS and brings their walking pattern closer to physiological values.
14	(Beqaj et al., 2018)	<i>Randomized Controlled Trial</i>	13 competitive swimmers (8 with DS, 5 without DS) Age: 18–28 years	Functional, motor, and physical performance were evaluated using various measurements.	Fine motor skills and grip strength were found to significantly predict daily living activities in children with DS; grip strength was found to be an important predictor of mobility and responsibility, while 9-HPT was found to be an important predictor of social/cognitive skills.	Fine motor skills and grip strength significantly predict functional performance in individuals with DS; these findings are important in intervention planning.
15	(Nahla M et al., 2022)	<i>Randomized Controlled Trial</i>	30 DS Female: 9 Male: 21 Age: 7–10 years	Participants underwent balance exercises or mechanical vestibular stimulation three days per week for 12 weeks; anterior-posterior, mediolateral, and overall balance indices were measured using Biodex.	Postural balance improved in both groups; however, more pronounced improvement was observed in the mechanical vestibular stimulation group, with decreases of 23.6%, 24.4%, and 26.4% in APSI, MLSI, and OASI values, respectively.	Vestibular stimulation in children with DS develops balance and postural control more effectively than traditional exercises.
16	(Seron et al., 2017)	<i>Randomized Controlled Trial</i>	41 DS Female: 10 Male: 31 Age: 12–20 years	The effects of 12 weeks of aerobic and resistance training on maximum and submaximal cardiorespiratory parameters were examined comparatively.	Aerobic and resistance training increased maximum ventilation in young people with DS, while VO ₂ peak remained unchanged; aerobic training increased work capacity while decreasing submaximal heart rate.	Research has shown that aerobic exercise is effective in combating sedentary lifestyles by improving the cardiorespiratory system in young people with DS.
17	(Shields et al., 2010)	<i>Randomized Controlled Trial</i>	70 DS Age: 14–22 years	Participants completed a 10-week resistance training or social activity program under student guidance; work performance, muscle strength, and physical activity were assessed.	Progressive resistance training significantly increased lower extremity muscle strength by 42% in adolescents with DS, while no significant changes were observed in upper extremity strength.	A community-based PRT approach can support long-term health gains by increasing the physical activity and work performance of youth with DS.

18	(Seron et al., 2015)	Randomized Controlled Trial	29 DS Female: 9 Male: 20 Age: 12–20 years (mean 15.7±2.82)	The hemodynamic effects of 12 weeks of aerobic and resistance training were examined comparatively; SBP, DBP, MBP, CO, HR, and PVR.	Twelve weeks of aerobic and resistance training significantly reduced SBP, DBP, and MBP in young people with DS; no changes were observed in other hemodynamic parameters such as HR, CO, SV, and PVR.	Moderate aerobic and resistance exercise in young people with DS contributes to the prevention of cardiovascular disease by lowering blood pressure.
19	(Thein Tun et al., 2025)	Randomized Controlled Trial	30 DS Female: 8 Male: 22 Age: 7–10 years	Participants engaged in a 50-minute exercise program three days a week for six weeks; motor skills, balance, and strength were measured using the TGMD-2, modified stork, and FTSTS tests.	Structured exercise significantly improved basic motor skills, static balance, and lower extremity strength in children with DS and led to improvements in TGMD-2 and other physical measures.	Structured exercise has been shown to promote motor and physical development in children with DS in the short term; further studies are needed to determine long-term effects.
20	(Cline et al., 2025)	Cross-sectional analysis (baseline data from RCT)	42 DS CHD: 21 Non-CHD: 21 Age: 25.4±1.1 years	Physical activity and cardiorespiratory fitness in individuals with DS were analyzed cross-sectionally using 7-day accelerometer and treadmill tests according to the presence of CHD.	Individuals with CHD and DS had lower MVPA levels and higher diastolic blood pressure; cardiorespiratory fitness remained low regardless of CHD status.	Despite the presence of CHD, physical fitness is generally low in individuals with DS, and no difference has been observed in terms of CR fitness; the findings support the need for inclusive exercise programs.
21	(Shields & Taylor, 2010)	Randomized Controlled Trial	23 DS Female: 6 Male: 17 Age: 13–18 years	For 10 weeks, participants underwent resistance training twice a week under student mentorship; muscle strength and functional performance were assessed using 1RM, the stair test, and the Grocery Shelving Task.	Progressive resistance training significantly increased lower extremity muscle strength in adolescents with DS, while showing moderate positive effects on upper extremity strength and functional performance.	Community-based resistance training applied to adolescents with DS has resulted in a significant increase in lower extremity muscle strength with high participation and safe implementation; further studies are recommended for long-term effects.
22	(Mohamed et al., 2021)	Randomized Controlled Trial	36 DS Age: 6–12 years	Children with DS underwent PNF or inspiratory muscle training for 6 weeks; respiratory muscle strength, chest expansion, spirometry parameters, and functional capacity were analyzed using ANOVA.	Both PNF and IMT improved respiratory function in children with DS; PNF training showed a superior effect compared to IMT in terms of muscle strength, chest expansion, and functional capacity.	PNF and inspiratory muscle training increased respiratory muscle strength, chest expansion, and functional capacity in children with DS; the effects were more pronounced with PNF.

23	(Hussein, 2017)	Randomized Controlled Trial	30 DS Female: 6 Male: 24 Age: 10–14 years	The effects of 12 weeks of chest physiotherapy and lower extremity strength training on respiratory function were evaluated using spirometry.	Chest physiotherapy in children with DS significantly increased FVC, PEFR, FEV1, and MVV, while lower extremity strength exercises only improved FVC and PEFR.	It has been shown that lower extremity strengthening exercises in children with DS can improve certain respiratory functions such as FVC and PEFR, but this effect is more limited compared to chest physiotherapy.
24	(Pessoa et al., 2023)	Multicomponent Intervention (pre-post design)	16 DS Female: 7 Male: 9 Age: 11–19 years	The effects of a 12-week multi-component exercise program on muscle strength, cardiorespiratory fitness, agility, flexibility, and body composition were evaluated.	In adolescents with DS, lower and upper extremity strength, cardiorespiratory fitness, agility, and flexibility improved significantly after intervention; no changes were observed in BMI and coordination.	The multi-component program improved physical fitness in adolescents with DS, leading to gains in strength and CRF while having limited effects on coordination and fat mass; family involvement played a critical role.
25	(Anugrah et al., 2023)	Cross-sectional correlational study	30 DS Age: 8–13 years	The relationships between variables were examined using Pearson correlation by assessing the balance, locomotor skills, and core endurance of 30 children with DS.	Strong positive correlations were found between dynamic balance and locomotor skills ($r=0.821$) and core muscle endurance ($r=0.710$) in children with DS.	Children with DS showed a strong positive correlation between dynamic balance and locomotor skills, as well as core muscle endurance; individualized approaches are recommended in exercise planning.

Cardiorespiratory and metabolic responses to exercise

Cardiorespiratory capacity in individuals with DS has been found to be limited due to genetic, neurological and structural factors. In submaximal and maximal exercise tests, it has been reported that cardiorespiratory coordination is low in individuals with DS and that their capacity to reach maximal heart rate is limited (Mendonca et al., 2022; Oviedo et al., 2021). These findings are explained by inadequate autonomic nervous system responses, sinus node dysfunction, and low chronotropic reserve. In contrast, regular aerobic and resistance training has resulted in significant improvement in cardiac and haemodynamic functions (Seron et al., 2015, 2017). These improvements are underpinned by mechanisms including increased contractile capacity of the heart muscle, vasodilation in the peripheral vascular bed, and enhanced oxygen extraction in working muscles. Resistance circuit training has regulated oxidative stress parameters and strengthened antioxidant defence in individuals with DS (Rosety-Rodriguez et al., 2021). Furthermore, it has been reported that the transient oxidative stress arising after exercise is balanced more rapidly in the DS population compared to healthy individuals (Reis et al., 2024). This situation is explained by the exercise rapidly re-establishing redox homeostasis and activating endogenous antioxidant enzymes. In terms of metabolic outputs, it has been observed that DS individuals with a high body mass index have low cardiorespiratory performance (Dodd & Shields, 2005; Pitchford et al., 2018; Wee et al., 2015). These results are associated with obesity increasing the load on the respiratory muscles, limiting ventilation capacity, and increasing cardiac workload. Findings regarding bone metabolism are limited. It has been determined that long-term resistance and jumping protocols do not increase bone mineral density to the expected level in children with DS (Dilek et al., 2018). This result can be explained by the low mineralisation, endocrine differences and growth hormone deficiencies observed in DS. Overall, these findings indicate that exercise increases cardiorespiratory fitness in individuals with DS, provides a protective effect on oxidative stress balance, and improves metabolic

outcomes. These effects can be explained through autonomic nervous system adaptations, cardiac muscle contractility, peripheral circulation regulation, redox balance, and the restructuring of energy metabolism.

When examined from the perspective of respiratory rehabilitation, respiratory functions in individuals with DS may be limited due to hypotonic respiratory muscles, narrow upper airways, and structural differences in the chest wall. Therefore, exercises aimed at respiratory rehabilitation play a critical role in increasing both functional capacity and quality of life. PNF-based respiratory muscle exercises have provided stronger improvements compared to inspiratory muscle training (Mohamed et al., 2021). This superiority is explained by the more effective activation of the diaphragm and intercostal muscles, increased thoracic mobility, and improved alveolar ventilation. Furthermore, the proprioceptive stimuli used in PNF techniques enhance the coordination of respiratory muscles by supporting neuromuscular control. Chest physiotherapy has been found to be superior to lower extremity strength exercises in terms of pulmonary function parameters such as FEV1 and MVV (Hussein, 2017). These findings are explained by the clearance of secretions, maintenance of airway patency, and increased gas exchange surface area at the alveolar level. At the same time, chest physiotherapy increases thoracic expansion, thereby improving ventilation efficiency and oxygen saturation. These results show that respiratory rehabilitation not only increases lung capacity but also has multidimensional effects on exercise tolerance, daily activity capacity, and overall functional independence. In conclusion, PNF-based respiratory exercises and chest physiotherapy are effective strategies for improving respiratory function in individuals with DS. These effects can be explained through mechanisms such as strengthened diaphragmatic activation, increased chest wall mobility, secretion clearance, and improved alveolar ventilation.

Motor and Cognitive Responses to Exercise

Exercise-based interventions provide significant contributions to motor control, postural balance, and cognitive performance in individuals with DS. Core stability and treadmill training have improved postural balance and reduced the risk of falls in children (Alsakhawi & Elshafey, 2019). This development can be explained by the compensation of hypotonia and ligamentous laxity commonly seen in DS, and the strengthening of trunk stability by activating the core muscles. Structured exercise programs have led to significant improvements in fundamental motor skills such as running, jumping, and object control (Thein Tun et al., 2025). These results are associated with the strengthening of proprioceptive sensation, increased coordination capacity of the musculoskeletal system, and support for motor learning processes. Technology-assisted approaches (virtual reality and tDCS) have improved manipulative skills and upper extremity coordination (Lopes et al., 2022). These findings are explained by increased cortical excitability, accelerated sensorimotor integration, and enhanced neuroplasticity. The contribution of aerobic exercise to executive functions is also noteworthy. A single session of moderate-intensity aerobic exercise has been shown to produce short-term improvements in attention and working memory (Chen et al., 2015). These effects can be explained by increased cerebral blood flow, oxygenation, and dopaminergic system activation. The dose-response relationship between exercise intensity and manual motor performance (Chen & Ringenbach, 2019) can be attributed to high intensity triggering greater muscle fiber recruitment and increasing the sensitivity of neural control. When age-related changes are examined, it is seen that manipulative skills decrease with age in individuals with DS, but regular exercise programs slow this decline. (Chen et al., 2021). This finding can be explained by the fact that repetitive motor activities preserve neuroplasticity and slow down age-related neurodegenerative processes. Sports-based activities such as Nordic Walking and swimming have also increased locomotor skills

as well as social interaction and self-confidence (Skiba et al., 2019). These gains are linked to physical activity increasing social participation, strengthening motivation, and reinforcing self-efficacy.

When examining Table 1 for multi-component interventions and lifestyle programs, it is evident that multi-component interventions integrating not only exercise but also nutrition, family support, and behavioral guidance yield the strongest gains in individuals with Down syndrome (DS). Combinations of exercise + nutrition + family support have demonstrated significant improvements in muscle strength, agility, and cardiorespiratory fitness in adolescent individuals with DS (Pessoa et al., 2023). These results are explained by exercise supporting musculoskeletal adaptations, healthy eating maintaining metabolic balance, and family support increasing motivation and continuity. Metabolic and anthropometric outcomes have shown that lifestyle factors are decisive in longitudinal studies. Regular physical activity and healthy eating have improved lipid profile and obesity risk (Pecoraro et al., 2024; Pino-Valenzuela & Benavides-Roca, 2023). These benefits have been associated with improved energy balance, increased insulin sensitivity, and reduced risk of dyslipidemia. The relationship between physical activity levels and obesity is of particular importance in individuals with DS. Low activity levels and poor dietary habits increase cardiometabolic disorders, while regular exercise and healthy lifestyle practices reduce these risks (Basil et al., 2016; Pitchford et al., 2018; Yamanaka et al., 2023). This effect can be explained by the balance between increased energy expenditure and energy intake. The role of family and environmental factors has been critical in the success of multi-component interventions. Family involvement and school-based programs have increased the program adherence of children with DS, while also improving their social interactions (Cline et al., 2025). These findings have been associated with social support systems increasing motivation, strengthening self-efficacy perceptions, and ensuring the sustainability of behavioral change. Consequently, multi-component interventions and lifestyle programs not only provide short-term physical and metabolic gains in individuals with DS; they also increase quality of life, social participation, and independent living skills through lasting behavioral changes. These effects can be explained by the interaction of biological (metabolic regulation, cardiorespiratory adaptation), psychological (self-confidence, motivation), and social (family and environmental support) mechanisms.

Results of Sports-Based Activities and Structured Exercise Protocols

They have been shown to significantly increase both physical capacity and functional independence and social participation in individuals with Down syndrome (DS). Sports-based programs such as Nordic Walking, swimming, and basketball improve walking speed, stride length, and locomotor patterns (Skiba et al., 2019), while also providing significant improvements in body composition and functional fitness (Cai & Baek, 2022). Such cues can be attributed to the stabilization of locomotor patterns within the central nervous system due to rhythmic steps; the availability of ideal resistive forces, as well as adequate proprioceptive stimulation, in the environment; and the utilization of psychosocial stimuli, such as motivational, feelings of membership, or self-confidence, in the case of team sport activities. Structured programs for children have improved fundamental motor skills such as running, jumping, and object control. These improvements are explained by the fact that repetitive movements support motor learning, strengthen proprioceptive sense, and improve neuromuscular coordination. Resistance training implemented under student leadership in adolescents has significantly increased lower extremity muscle strength (Shields et al., 2017; Shields & Taylor, 2010). These effects can be explained by increased motor unit recruitment, strengthened muscle fiber synchronization, and triggered hypertrophic adaptations. Community-based empowerment programs have been shown to improve work performance in young adults. These findings are associated with the transfer of functional strength gains to activities of daily living. The effects of structured

exercises on balance are also noteworthy. Programs focusing on postural stability have improved static and dynamic balance (Giustino et al., 2020). These results are explained by the strengthening of core muscles, more effective use of the vestibular system, and improvement of proprioceptive feedback mechanisms. Age is also an important factor. It has been reported that regular structured programs slow age-related decline in manipulative skills. These findings are associated with the promotion of neuroplasticity by repetitive motor activities and the slowing of age-related degenerative processes. Consequently, structured exercise protocols provide not only motor skill development but also long-term functional independence in individuals with DS. These effects can be explained through mechanisms such as neuroplasticity, musculoskeletal adaptations, motor unit activation, proprioceptive integration, and slowing age-related degenerative processes.

Conclusion

This systematic review of 66 studies demonstrates the multidimensional effects of exercise interventions in individuals with DS. The findings show improvements not only in physical fitness but also in cognitive function, cardiometabolic health, respiratory function, and social participation. Motor and cognitive gains, core stability, treadmill, and structured exercises supported these effects, which were explained by the compensation of hypotonia and ligamentous laxity, the strengthening of proprioceptive sense, and repetitive motor activities that increase neuroplasticity. Technology-assisted programs (VR, tDCS) have led to significant progress in manipulative skills through increased cortical excitability and enhanced sensorimotor integration. Cardiorespiratory and metabolic responses improved with regular aerobic and resistance training; these improvements have been linked to autonomic nervous system adaptation, vasodilation in peripheral circulation, oxygen extraction in muscles, and regulation of redox balance mechanisms. The protective effects of exercise on oxidative stress emerged thanks to the strengthening of the antioxidant defense system. Sports-based programs (basketball, swimming, Nordic walking) not only increased physical capacity but also provided psychosocial gains through motivation, social participation, and self-efficacy mechanisms. Structured exercise protocols have supported functional independence through motor unit recruitment, muscle hypertrophy, and enhanced proprioceptive integration. Respiratory rehabilitation improved respiratory function through PNF-based exercises and chest physiotherapy. These effects can be explained by the mechanisms of effective activation of the diaphragm and intercostal muscles, increased thoracic mobility, secretion clearance, and improved alveolar ventilation. Multicomponent lifestyle programs have yielded lasting gains by combining exercise with nutrition and family support. These results can be explained by the simultaneous contribution of biological (metabolic regulation, cardiorespiratory adaptation), psychological (self-confidence, motivation), and social (family and environmental support) mechanisms. Overall, exercise interventions offer multifaceted benefits in individuals with DS through a biopsychosocial approach. Findings indicate that exercise is not only a clinical treatment but also a comprehensive intervention strategy that supports neurological adaptations, cardiorespiratory health, and social participation.

Limitations: In our review, the sample sizes of the included studies are generally small, and there is marked heterogeneity in terms of study designs, exercise protocols, duration of intervention and the health outcomes assessed. The fact that some studies do not include a control group or employ a quasi-experimental/pre-post design limits the ability to interpret the findings in a causal manner.

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CHD: Congenital Heart Defects/Disease

VSD: Ventricular septal defect, PDA: Patent ductus arteriosus, AVSD: Atrio-ventricular septal defect, ASD: Atrial septal defect

HR: Heart rate

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