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Research article

Jumping Rope Improves the Physical Fitness of Preadolescents Aged 10-12 Years: A Meta-Analysis

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Abstract

To systematically review the effects of jumping rope on physical fitness among 10 to 12-year-old preadolescents, and to provide evidence-based support for its use in school physical education curriculum work. The PubMed, Web of Science, SPORTDiscus, ScienceDirect, and CNKI databases were searched for randomized controlled trials that assessed jumping rope and physical fitness among preadolescents aged 10 - 12 years. Meta-analyses were used to calculate the standardized mean difference (SMD) values and 95% confidence intervals (CI), and subgroup analyses were conducted on intervention duration, frequency and period. A total of 1048 subjects from 15 studies were included. Compared to regular physical education courses, jumping rope did not show a significant advantage in terms of body morphology. In terms of physical function, boys showed greater improvements in vital capacity, and girls showed greater improvements in resting HR. In terms of physical performance, boys showed greater improvements in speed, upper-body strength, lower-body strength, muscular endurance and agility, while girls showed greater improvements in coordination and balance. Boys experienced a minimal improvement in flexibility, while girls did not show a significant difference. Combining the results of the subgroup analyses, the optimal session time, frequency and intervention length of jumping rope for significantly improving the physical fitness of preadolescents were >40 min, 2 times/week and 8 - 12 weeks, respectively. In conclusion, jumping rope provides small to large benefits over regular physical education for both boys and girls aged 10-12 years in terms of physical function and physical performance indicators other than flexibility, while showing no significant advantage in terms of body morphology. Based on the available research, it is recommended that children aged 10 - 12 years participate in jump rope sessions for at least 40 minutes once or twice a week for 8 - 12 weeks to better develop physical fitness.

Key words: Jump rope; preadolescent children; physical fitness; physical function; physical performance; physical education.

Introduction

Despite the well-known health benefits of physical activity, physical fitness problems among children remain prominent globally. Due to a lack of basic motor skills and experience (Behan et al., 2019), as well as reduced time spent outdoors (Katzmarzyk et al., 2014), 70% of children are insufficiently physically active by the age of 13, and this is more predominant in girls than boys. The prevalence of insufficient activity in girls has not improved since 2001 (Guthold et al., 2022). In recent years, according to China's National Student Physical Fitness monitoring data, less than 30% of students have achieved above-medium standards (Zhu, 2021), the detection rate of overweight and obesity among adolescents is close to 20% (Department of Physical Health and Arts Education, Chinese Ministry of Education, 2021), the overall myopia rate is over 50% (Ministry of Education of the People's Republic of China Government portal, 2022), and growth in all physical fitness indicators has tended to stagnate (Dong et al., 2019). Most children spend almost half of their awake time at school, but the content of regular physical education courses alone cannot fully meet the needs of students' physical development (Cristiana et al., 2021; Sanz-Martín et al., 2021).

Physical inactivity in children begins primarily during secondary school, which is the preadolescent period for most children (between the ages of 10 - 12 years). There are many biological, behavioural and environmental factors that can explain the age-related decline in physical activity during this period, including the sudden increase in school burden, the timing of puberty and changes in body morphology and composition. The ages of 10 - 12 are also the prime period for motor learning, as this is when students' neurological functions develop rapidly (Viru et al., 1999). If positive stimulation is implemented during this period and continues for several weeks, it can have a multiplicative effect on the development of children's basic motor skills, physical performance and cognitive function (Hillman et al., 2005; Barnekow-Bergkvist et al., 2006; De Greeff et al., 2018). Therefore, extra attention needs to be given to the design of school physical education courses during this period.

Jumping rope is a multifunctional exercise that combines fitness, recreation and competition. Called "the most perfect health exercise" by European and American medical experts (American Heart Association, 1989), jumping rope is also recommended by the American Heart Association and the British Osteoporosis Society as a way to balance physical fitness across all ages (Royal Osteoporosis Society, 2021). Because jumping rope requires coordination of the upper and lower limbs, different movement patterns, such as weighted rope exercises, can be flexibly used to regulate the elements of movement, and promote an adaptive state of the central nervous system and neuromuscular regulation (Zhuo et al., 2015). In addition, jumping rope is more accessible to children and adolescents than

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monotonous regular physical education courses, allowing them to improve their physical fitness levels in a fun and competitive way (Loredo, 1996). According to the "National Fitness Activity Survey Bulletin 2020" released by the China National Fitness Monitoring Centre, the number of children who regularly participate in jumping rope is second only to the number of children who run, with a percentage of 11.2% (General Administration of Sport of China, 2020).In addition, the inclusion of jumping rope in physical education courses and recess activities has been rising in recent years (Kadavasal and Watson-Thompson, 2022; Guijarro-Romero et al., 2022).

A systematic review of the findings of 30 randomized controlled trials found that jumping rope is better at promoting physical fitness in students than other aerobic exercises (Gao, 2020). However, some study designs ignore the gender differences in children subjected to the same exercise intervention (Yang et al., 2020; Zeng, 2019; Zhang, 2020; 2021). The differences in physical fitness between boys and girls are not very significant before the age of 10 (Crespo et al., 2013). Growth and development patterns, behaviour and movements, hormone secretion, and muscle tissue development show similar characteristics (Crespo et al., 2013; Editorial Committee of Interpretation of National Standards for Students' Physical Fitness and Health, 2007). From the age of 10 years onwards, the growth and development of children is accompanied by a strong gender dependence in haematological indicators despite the same motor stimuli (Falz et al., 2019), and physical fitness indicators also show some gender specificity (Ranson et al., 2015; Remsberg et al., 2007). Boys produce significantly more androgens than girls of the same age, and testosterone and leptin synergistically stimulate protein anabolism and bone and muscle development, thus resulting in better strength performance in boys than in girls (Vitale et al., 2009). Furthermore, there are contradictory results on the effects of jumping rope on physical fitness indicators in children of different genders due to various sample sizes and intervention programmes used in studies. For example, in terms of body morphological indicators, while Eler concluded that jumping rope increased height in boys (Eler and Acar, 2018), Partavi reported the opposite result (Partavi, 2013). For agility, which reflects physical performance, Chen Y and Du FF reported different results in girls (Chen, 2021; Du, 2018).

Therefore, the purpose of this study was to clarify the effects of jumping rope on various physical fitness test indicators in preadolescents aged 10 - 12 years, and to provide an evidence-based practice reference for jumping rope exercise to be a part of the physical education curriculum in schools.

Methods

Literature search

A systematic review was performed using the established guidelines of the PRISMA statement (Liberati et al., 2009), and the protocol was registered at PROSPERO with the number CRD42022361160. By searching "subject words" and "free words" in the titles and abstracts, the relevant literature on the influence of jumping rope on the physical fitness of preadolescents was retrieved from the PubMed, Web of Science, SPORTDiscus, ScienceDirect and CNKI databases. In addition, the references of the included articles were manually searched for relevant studies that were missed by our initial electronic search. Multiple combinations of the following key words (with scaffolding) were used for the search: jump rope, physical fitness, and preadolescent. The identified terms with Boolean operators with different expressions are presented in Table 1. The publication deadline was June 16, 2022.

Table1. Search strategy.

1	"jump rope" OR "jumping rope" OR "rope jumping" OR "rope skipping" OR "skipping"
2	"physical fitness" OR "physical health" OR "body morphology "OR "body form" OR "body shape" OR "physical form" OR "physical function" OR "body function" OR "cardiopulmonary fitness" OR "physical performance" OR "physical functional performances" OR "physical qualities" OR "height" OR "weight" OR "BMI" OR "body fat rate" OR "body fat percentage" OR "resting HR" OR "heart rate" OR "vital capacity" OR "lung capacity" OR "aerobic capacity" OR "spirometric capacity" OR "speed" OR "strength" OR "endurance" OR "agility" OR "keen" OR "flexibility" OR "pliable" OR "coordination" OR "balance"
3	"preadolescence" OR "preadolescent" OR "children" OR "youth" OR "younger"
4	#1 AND #2 AND #3

Inclusion criteria

Inclusion criteria were as follows: (1) randomized controlled trial (RCT); (2) healthy children aged 10 - 12 years; (3) interventions where the experimental group was given jumping rope courses, and the control group was given routine physical education or training courses; and (4) outcome indicators were categorized by gender.

Exclusion criteria

Exclusion criteria were as follows: (1) duplicate studies, conference studies, review studies, non-RCT test studies; (2) subjects were obese or unhealthy people; (3) outcome measures were not categorized by gender; and (4) studies not written in English or Chinese.

Outcome indicators

In this review, we mainly refer to Eurofit (Eurofit, 1993) and the Chinese Student Physical Fitness Standards (Ministry of Education, State General Administration of Sports, 2014) and identified the following three categories of indicators related to physical fitness development, based on the classification method routinely used in China.

Body morphological indicators: height, weight, body mass index (BMI), body fat rate.

Physical functional indicators: resting heart rate (resting HR), vital capacity, and aerobic capacity.

Physical performance indicators: speed, upper-body strength, lower-body strength, aerobic endurance, muscle endurance, flexibility, coordination, balance, agility.

Data extraction

The relevant data were extracted from each study, including the first author of the study, year of publication, grades of the experimental and control groups, sample size, gender, intervention programme (session time, frequency, duration) and outcome indicators.

Methodological quality of the included studies

The Cochrane risk of bias assessment tool (Deeks, 2006) was used to evaluate the risk of bias of the included studies in seven aspects, including random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting and other biases. Each indicator was scored as "low risk of bias", "uncertain bias" or "high risk of bias". The process was conducted independently and reviewed by three researchers.

Data analysis

RevMan (The Nordic Cochrane Centre, 2014) and Stata (Wilson, 2010) were used for meta-analysis. The Q test and I^2 test were used to determine whether there was heterogeneity among studies. If $I^2 < 50\%$ and $p > 0.1$, then there was no significant heterogeneity, and a fixed-effects model was selected for analysis. If $I^2 \geq 50\%$ and $p < 0.1$, then heterogeneity was considered significant, and a random effects model was selected to analyze the source of heterogeneity (Hopkins et al., 2009). The standardized mean difference (SMD) was used as the effect index, and the 95% confidence interval (95% CI) was used to represent the effect size; $p < 0.05$ was considered statistically significant. SMD ≤ 0.2 was considered a minimal effect, $0.2 <$ SMD ≤ 0.6 was considered a small effect, $0.6 <$ SMD ≤ 1.2 was considered a medium effect, $1.2 <$ SMD ≤ 2.0 was considered a large effect, and SMD >2.0 was considered a maximum effect (Shadish and Haddock, 1994). Sensitivity analysis was used to further ensure the reliability of the meta-analysis results. After removing each article one by one, the heterogeneity results did not change significantly, and the meta-analysis results were still within the 95% CI, indicating that the meta-analysis results were stable and credible. Egger's test was used to evaluate whether publication bias existed. If $p < 0.1$, then publication bias was considered to exist (Egger et al., 1997).

Results

Study selection

A total of 569 studies were obtained in this search. After eliminating duplicate studies, the titles and abstracts were read for initial screening, and the full texts were read for rescreening, resulting in a total sample size of 1048 subjects. The literature screening process is shown in Figure 1.

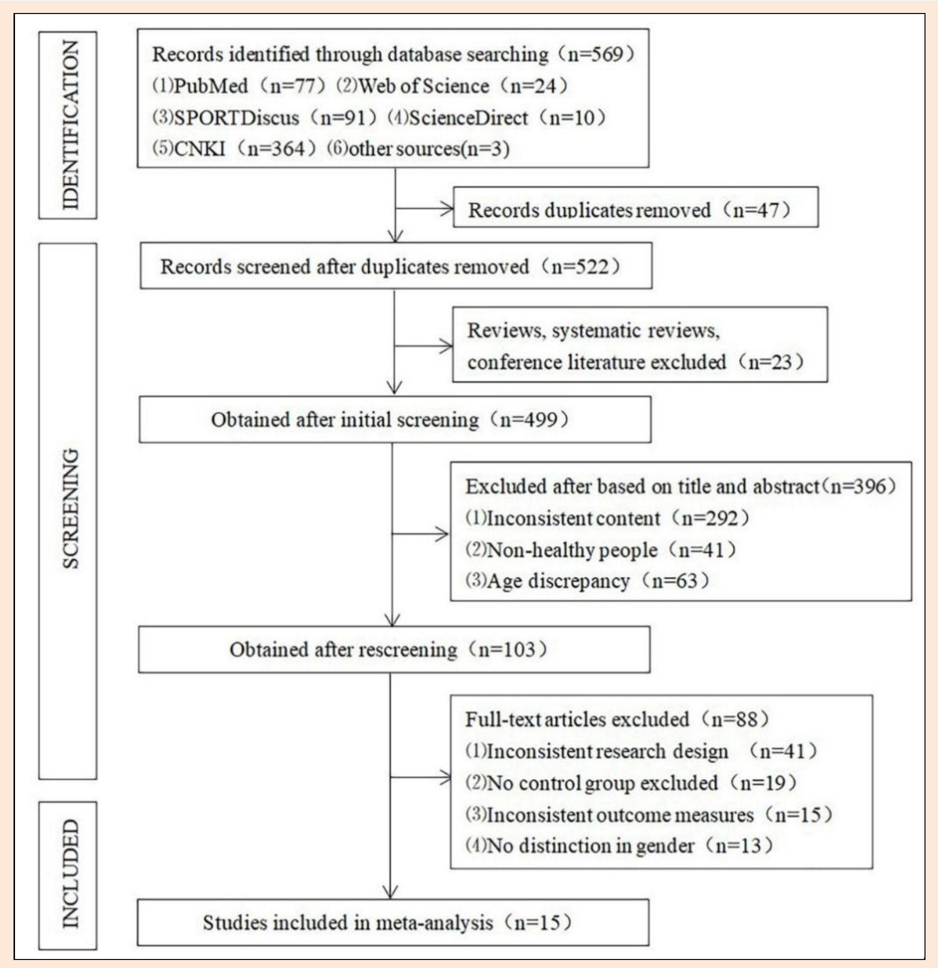

Figure 1. Flow diagram.

Table 2. **Basic characteristics of the included studies.**

Study	Basic information			Training method		Interventions				Outcome indicator	Risk of Bias
	Age (years)	Sample size	Gender (M/F)	C	E	Session time (min)	Frequency (time/week)	Duration (weeks)	Intensity (time/min)		
Arazi et al., 2016	10-12	C=10 E=12	C = 10/0 E =12/0	RP	JR	15-50	3	8	130-160	4, 7(1), 12, 13	+ ? + + + + +
Chen, 2017	10-11	C=45 E=39	C = 20/25 E = 17/22	RP	JR	40	3	16	MI	5, 6, 8, 10, 11(1), 12, 13, 14	+ ? + − + + +
Chen, 2021	10-11	C=40 E=40	C = 20/20 E = 20/20	RP	JR	10-15	3	12	140-160	1, 2, 6, 8, 11(1), 12, 13, 14	+ ? + ? + + +
Du, 2018	10-12	C=30 E=30	C = 15/15 E = 15/15	RP	JR	45	3	12	120-140	1, 2, 6, 11(1), 12, 13, 14	+ ? ? ? + + +
Eler and Acar, 2018	10-12	C=120 E=120	C = 120/0 E = 120/0	RP	JR	25-50	3	10	NR	1, 2, 4, 7(1), 10(2)	+ ? + ? + + +
Gao, 2019	11-12	C=20 E=20	C = 20/0 E = 20/0	RP	JR	60	2	8	NR	1, 2, 6, 8, 12, 13, 14	+ ? + − + + +
Gao, 2020	10-11	C=30 E=30	C = 15/15 E = 15/15	RP	JR	40	3	12	MI	8, 9, 10, 11(1), 12,13, 14	+ ? + ? + + +
Hao, 2019	11-12	C=84 E=84	C = 42/42 E = 40/44	RP	JR	10	3	15	130-150	1, 2, 6, 8, 11(1), 12, 13, 14	+ ? ? + + + +
Huang, 2015	11-12	C=30 E=30	C =5/15 E =15/15	RP	JR	40	3	10	NR	1, 2, 5, 6, 7, 8, 9, 11(1), 12, 14, 15(1), 16	+ ? + + + + +
Artavi, 2013	11-12	C=14 E=14	C = 14/0 E = 14/0	RP	JR	15-50	3	7	NR	1, 2, 3, 8, 11(2), 16(2)	+ ? + ? + + +
Qin, 2018	10-11	C=30 E= 30	C = 15/15 E = 15/15	RP	RP+JR	60	2	12	NR	1, 2, 3, 5, 6, 8, 9, 10, 11(1), 12, 13, 14, 15(1), 16	+ ? ? ? + + +

M, male; F, female; C, control group; E, experimental group; RP, regular physical education courses; JR, jumping rope; NR, not reported; MI, moderate intensity. Green circle: low risk of bias; Red circle: high risk of bias; Yellow circle: unclear risk of bias. Body morphology indicators: 1, Height; 2, Weight; 3, BMI; 4, Body fat rate; Physical function indicators: 5, Resting heart rate; 6, Vital capacity; 7, Aerobic power ((1)VO2max; (3)step test) Physical performance indicators: 8, Speed (50m speed test); 9, Upper-body strength(grip strength); 10, Lower-body strength ((1)long jump; (2)leg push); 11, Cardiorespiratory endurance((1)50m×8 PACER; (2)540m test; (3)800m test); 12, Muscular endurance(1min sit-up test); 13, Flexibility(sit-and-reach); 14, Coordination(1min Rope skipping); 15, Balance((1)One-leg standing with eye-closed; (2)YBT); 16, Agility((1)Quadrant jump; (2)T-test)

Table 2. Continue…

Study	Basic information			Training method		Interventions				Outcome indicator	Risk of Bias
	Age (years)	Sample size	Gender (M/F)	C	E	Session time (min)	Frequency (time/week)	Duration (weeks)	Intensity (time/min)		
Trecroci et al., 2015	11.3 ± 0.7	C=12 E=12	C =12/0 E = 12/0	RP	JR	15	2	8	NR	15(2), 16(2)	+ + − ? + + +
Yao, 2011	10-11	C=16 E=16	C = 16/0 E = 16/0	RP	JR	40-50	5	24	NR	5, 6, 11(3)	+ ? ? ? + + +
Zhang, 2019	10-12	C=30 E=30	C = 15/15 E = 15/15	RP	JR	30	5	14	NR	16 (1)	+ ? ? + + + +
Zhao, 2021	12.4 ± 0.7	C=15 E=15	C = 15/0 E = 15/0	RP	JR	30	3	10	NR	15(2)	+ ? − ? + + +

M, male; F, female; C, control group; E, experimental group; RP, regular physical education courses; JR, jumping rope; NR, not reported; MI, moderate intensity. Green circle: low risk of bias; Red circle: high risk of bias; Yellow circle: unclear risk of bias. Body morphology indicators: 1, Height; 2, Weight; 3, BMI; 4, Body fat rate; Physical function indicators: 5, Resting heart rate; 6, Vital capacity; 7, Aerobic power (⑴VO2max; ⑶step test) Physical performance indicators: 8, Speed(50m speed test); 9, Upper-body strength(grip strength); 10, Lower-body strength (⑴long jump; ⑵leg push); 11, Cardiorespiratory endurance(⑴50m×8 PACER; ⑵540m test; ⑶800m test); 12, Muscular endurance(1min sit-up test); 13, Flexibility(sit-and-reach); 14, Coordination(1min Rope skipping); 15, Balance(⑴One-leg standing with eye-closed; ⑵YBT); 16, Agility(⑴Quadrant jump; ⑵T-test)

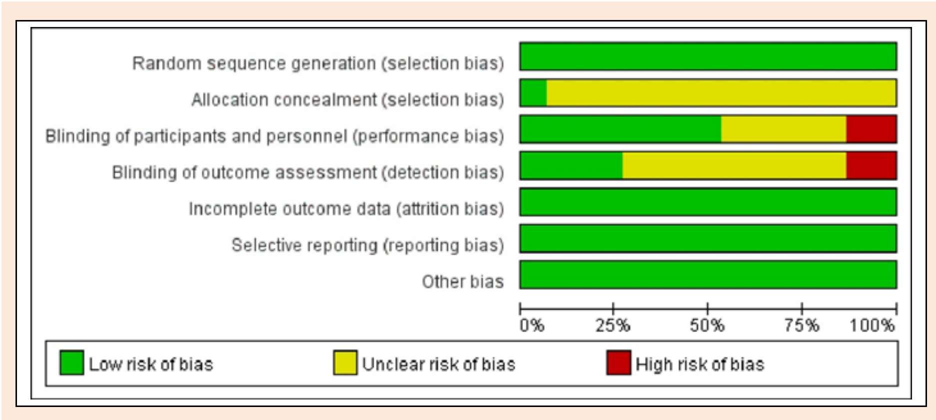

Figure 2. The risk assessment of bias by Cochrane.

Methodological appraisal of the included studies

The quality of the included studies was evaluated, and 8 studies had a low risk of bias and a high quality, while the remaining 7 studies had a moderate risk of bias. A detailed assessment of the risk of bias is shown in Figure 2 and Table 2.

Study characteristics

A total of 15 RCTs were included in this study (Arazi et al., 2016; Chen, 2017; 2021; Du, 2018; Eler and Acar, 2018; Gao, 2019; Guo, 2020; Hao, 2020; Huang, 2015; Partavi, 2013; Qin, 2018; Trecroci et al., 2015; Yao, 2011; Zhao, 2021; Zhang, 2019). The control groups were given regular physical education courses, such as track and field, martial arts or ball sports, while the experimental groups were given jumping rope courses. The basic characteristics of the included studies are shown in Table 2.

Results from the meta-analysis

Effect of jumping rope on body morphology of preadolescents aged 10-12 years

Body morphological indicators can visually reflect the growth and development of children and adolescents and are generally included in routine physical measurements, such as height, weight, BMI and body fat rate (Table 3). For the height and weight of children of different genders, the results of the heterogeneity test showed that $I^2 < 50\%$ and $p > 0.1$, so the fixed-effects model was used for analysis. The results indicated that the effect of jumping rope on the height and weight of children aged 10 - 12 years was nonsignificant compared to that of regular physical education courses ($p > 0.05$). Egger's test showed that all p values were greater than 0.05; that is, there was no publication bias in the included studies. For male BMI, the heterogeneity test showed that $I^2 > 50\%$; therefore, the random effects model was used for analysis. The results showed that the effect of jumping rope on BMI in boys aged 10 - 12 years was not significant ($p > 0.05$) compared to regular physical education courses. Egger's test showed that the p value was greater than 0.05; that is, there was no publication bias in the included studies. Of the included studies, only one study reported on the effect of jumping rope on BMI in girls, so it was not possible to test for heterogeneity, and the SMD value was not statistically significant ($p > 0.05$). This review was not able to include a sample related to body fat rate in women. For male body fat rate, the test for heterogeneity showed that $I^2 < 50\%$ and $p > 0.1$; therefore, the fixed effects model was used for the analysis. The results showed that the effect of jumping rope on body fat rate in boys aged 10 - 12 years was not significant compared to the regular physical education programme ($p > 0.05$), and Egger's test showed a p value of less than 0.05; indicating that there was publication bias in the included literature.

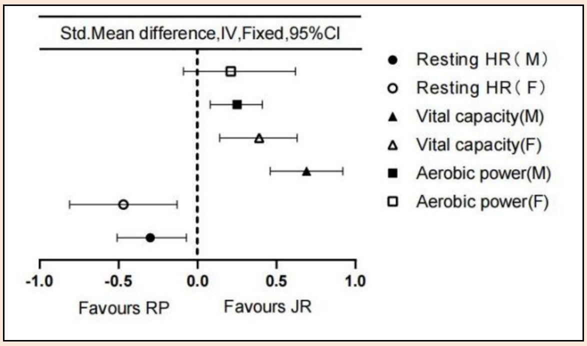

Figure 3. **Forest plot of differences in physical function indicators between the regular physical education class group and the jumping rope class group.**

Effect of jumping rope on the physical function of preadolescents aged 10-12 years

Physical function includes the function of various tissues, organs and systems of the body, the most important of which is cardiopulmonary and cardiovascular function. Routine physical fitness tests are resting HR, vital capacity and aerobic capacity. Only one of the included studies dealt with the aerobic capacity of girls, so no heterogeneity test could be conducted. The results of the heterogeneity test for the other indicators showed that $I^2 < 50\%$, and $p > 0.1$, and the fixed effects model was used for the analysis. The combined results showed that jumping rope significantly increased cardiopulmonary vascular fitness in preadolescents aged 10 - 12 years. For boys, this was mainly evident in the form of increased vital capacity (SMD = 0.69, 95% CI = 0.46, 0.92), and for girls, it was mainly evident in the form of decreased resting HR (SMD = -0.47, 95% CI= -0.81, -0.13). Egger's test results were all greater than 0.05, meaning that there was no publication bias in the included studies (Table 3 and Figure 3).

Effect of jumping rope on the physical performance of preadolescents aged 10-12 years

Physical performance is an important marker of good fitness and health. Physical performance is a general term for qualities such as speed, strength, endurance, flexibility, agility and coordination demonstrated during exercise (Textbook Editorial Committee of Physical Education Department, 2011). The results of the heterogeneity test showed that I^2 <5 0%, and $p > 0.1$, so the fixed effects model was used for the analysis. The results showed that compared to the regular physical education courses, jumping rope had a moderate impact on boys' speed (SMD = -0.74, 95% CI = -0.97, -0.51), upper-body strength (SMD = 0.70, 95% CI = 0.18, 1.23), lower-body strength (SMD = 0.65, 95% CI = 0.29, 1.01), cardiorespiratory endurance (SMD = -0.73, 95% CI = -0.97, -0.48), coordination (SMD = 1.19, 95% CI = 0.88, 1.50) and agility (SMD = -0.86, 95% CI = -1.31, -0.42), small effects on muscular endurance (SMD = 0.53, 95% CI = 0.31, 0.75) and balance (SMD = 0.39, 95% CI = 0.05, 0.72), and a minimal effect on flexibility (SMD = 0.20, 95% CI = -0.02, 0.43). For girls, jumping rope had a large effect on coordination (SMD = 1.50, 95% CI = 1.18, 1.81) and moderate effects on upper-body strength (SMD = 0.62, 95% CI = 0.10, 1.14), cardiorespiratory endurance (SMD = -0.71, 95% CI = -0.98, -0.43) and balance (SMD = 0.97, 95% CI = 0.43, 1.51). Jumping rope had small effects on speed (SMD = -0.50, 95% CI = -0.74, -0.25), lower-body strength (SMD = 0.35, 95% CI = -0.03, 0.74), muscular endurance (SMD = 0.35, 95% CI = 0.12, 0.58) and agility (SMD = -0.39, 95% CI = -0.91, 0.12), while no significant differences were observed for flexibility ($p > 0.05$). In particular, boys experienced greater effects on speed, strength and endurance, while girls showed greater effects on coordination, balance and agility (Table 3 and Figure 4). Egger's test showed a publication bias in the included studies for aerobic endurance and flexibility in boys.

Results from subgroup analysis

The potential impact of these moderating variables was further assessed by dividing single session time, exercise frequency and exercise duration into two separate subgroups each for analysis using the median segmentation method (Moran et al., 2019), as shown in Table 4. The results showed that in terms of single session time, most physical fitness indicators had a greater effect size in a single session lasting more than 40 minutes than in a single session lasting less than 40 minutes, including boys' upper-body strength, cardiorespiratory endurance, muscular endurance, coordination, balance, and agility and girls' resting HR, speed, upper-body strength, cardiorespiratory endurance, coordination, balance, and agility. In terms of frequency of jumping rope sessions per week, twice a week was more effective in increasing boys' vital capacity, speed, upper-body strength, muscular endurance, coordination, balance, and agility and girls' speed, upper-body strength, cardiorespiratory endurance, muscular endurance, coordination, balance, and agility. In terms of duration, jump rope sessions lasting 8 - 12 weeks had a greater effect size on most physical fitness indicators, including boys' vital capacity, cardiorespiratory endurance, muscular endurance, and coordination and girls' resting HR, speed, lower-body strength, cardiorespiratory endurance, muscular endurance, and coordination, than if it lasted more than 12 weeks. Taken together, these results suggest that jump rope exercise programmes that may promote healthy physical development in prepubescent children aged 10 - 12 years include a jump rope class longer than 40 minutes, a frequency of 2 sessions/week and a duration of 8 - 12 weeks.

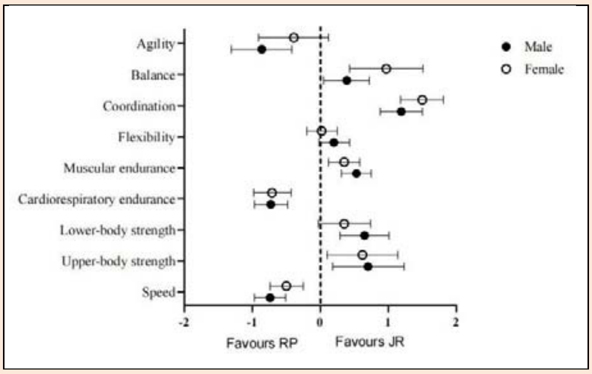

Figure 4. Forest plot of differences in physical performance indicators between the regular physical education class group and the jumping rope class group.

Table 3. Meta-analysis results of the effects of rope jumping on physical fitness of preadolescents aged 10-12 years.

Index	Gender	Simple size	Publication bias	Heterogeneity test I^2	Heterogeneity test *p*	Two-tailed test p value	SMD [95% CI]
Height	M	520	N	0%	0.85	0.44	-0.07 [-0.24, 0.10]
	F	216	N	0%	0.57	0.55	0.08 [-0.19, 0.35]
Weight	M	520	N	0%	0.46	0.06	-0.20 [-0.38, -0.03]
	F	216	N	39%	0.18	0.86	-0.03 [-0.31, 0.26]
BMI	M	58	N	79%	0.33	0.06	-0.20 [-0.49, 0.27]
	F	30	-	-	-	0.27	-0.40 [-1.13, 0.32]
Body fit rate	M	262	Y	26%	0.03	0.25	-0.26 [-0.51, -0.02]
	F	-	-	-	-	-	-
Resting HR	M	127	N	0%	0.63	0.01	-0.26 [-0.51, -0.07]
	F	137	N	0%	0.71	0.007	-0.47 [-0.81, -0.13]
Vital capacity	M	311	N	35%	0.16	< 0.00001	0.69 [0.46, 0.92]
	F	263	N	0%	0.43	0.0003	0.39 [0.14, 0.63]
Aerobic power	M	590	N	44%	0.15	0.004	0.25 [0.08, 0.41]
	F	60	-	-	-	0.03	0.21 [-0.09, 0.62]
Speed	M	557	N	1%	0.42	< 0.00001	-0.74 [-0.97, -0.51]
	F	263	N	20%	0.29	< 0.00001	-0.50 [-0.74, -0.25]
Upper-body strength	M	60	N	0%	0.88	0.008	0.70 [0.18, 1.23]
	F	60	N	0%	0.79	0.02	0.62 [0.10, 1.14]
Lower-body strength	M	367	N	0%	0.42	0.0004	0.65 [0.29, 1.01]
	F	137	N	9%	0.34	0.07	0.35 [-0.03, 0.74]
Cardiorespiratory endurance	M	309	Y	0%	0.83	< 0.00001	-0.73 [-0.97, -0.48]
	F	263	N	0%	0.55	< 0.00001	-0.71 [-0.98, -0.43]
Muscular endurance	M	341	N	0%	0.5	< 0.00001	0.53 [0.31, 0.75]
	F	293	N	0%	0.45	0.003	0.35 [0.12, 0.58]
Flexibility	M	341	Y	12%	0.33	0.08	0.20 [-0.02, 0.43]
	F	293	N	0%	1	0.83	0.02 [-0.20, 0.25]
Coordination	M	319	N	36%	0.17	< 0.00001	1.19 [0.88, 1.50]
	F	293	N	0%	0.87	< 0.00001	1.50 [1.18, 1.81]
Balance	M	168	N	0%	0.78	0.03	0.39 [0.05, 0.72]
	F	60	N	0%	0.49	0.0004	0.97 [0.43, 1.51]
Agility	M	118	N	35%	0.22	0.0001	-0.86 [-1.31, -0.42]
	F	90	N	0%	0.63	0.003	-0.39 [-0.91, 0.12]

M, male; F, female; Y, indicates the presence of publication bias; N, indicates the absence of publication bias. "-", indicates the absence of data

Table 4. Comparison of the effects of different intervention programmes (SMD).

Outcomes	Gender	Session time		Frequency		Duration	
		≤40min	>40min	2times/week	>2times/week	8-12weeks	>12weeks
Height	M	\	\	\	\	\	\
	F	\	\	\	\	\	\
Weight	M	\	\	\	\	\	\
	F	\	\	-0.91	\	-0.33	\
BMI	M	—	\	\	-0.99	-0.99	\
	F	—	\	\	—	\	—
Body fit rate	M	—	-0.31	\	-0.31	-0.31	\
	F	—	—	—	—	—	—
Resting HR	M	\	\	\	\	-0.06	\
	F	-0.39	**-0.74***	-0.39	**-0.74***	**-0.49***	-0.42
Vital capacity	M	**0.76***	0.52	**1.09***	0.63	**0.92***	0.69
	F	0.60	\	\	0.52	0.30	**0.79***
Aerobic power	M	**0.40***	0.18	—	0.20	0.20	—
	F	\	—	—	\	\	—
Speed	M	**-0.65***	-0.20	**-0.77***	-0.32	-0.25	**-0.75***
	F	-0.48	**-0.56***	**-0.56***	-0.48	**-0.71***	-0.30
Upper-body strength	M	0.66	**0.74***	**0.74***	0.66	0.70	—
	F	0.55	**0.69***	**0.69***	0.55	0.62	—
Lower-body strength	M	0.82	\	0.17	0.17	0.95	\
	F	0.68	\	0.68	\	**0.72***	0.24
Cardiorespiratory endurance	M	-0.71	**-1.17***	-0.75	**-0.82***	**-0.89***	-0.72
	F	-0.50	**-0.90***	**-0.90***	-0.50	**-0.89***	-0.24
Muscular endurance	M	0.39	**0.79***	**0.99***	0.42	**0.70***	0.23
	F	**0.39***	**0.20**	**0.56***	0.32	**0.36***	0.33
Coordination	M	0.83	**1.44***	**1.67***	0.85	**1.19***	0.72
	F	1.12	**1.58***	**1.47***	1.17	**1.49***	0.90
Balance	M	0.39	**2.30***	**1.06***	0.28	0.60	—
	F	0.79	**1.17***	**1.17***	0.40	0.97	—
Agility	M	-0.21	**-1.15***	**-1.00***	-0.52	-0.63	—
	F	0.15	**-0.52***	**-0.52***	0.15	-0.39	**0.58***

* indicates large effect sizes for subgroups. "—", indicates the absence of data; "\", indicates p≥0.05, subgroup analysis has no statistical significance

Discussion

Active sport and physical activity during childhood enhance physical, mental, cognitive, social and emotional health and well-being in preadolescence and adolescence and throughout adulthood (Strong et al., 2005; Tetsuhiro and Kanako, 2021). There is a positive association between levels of physical fitness and physical activity in children and adolescents (Wallhead and Buckworth, 2004). In this study, a comprehensive analysis of the effects of jumping rope on physical fitness indicators in preadolescent children aged 10 - 12 years was conducted. Jumping rope did not show significant advantages in terms of body morphology compared to regular physical education courses, but it significantly improved preadolescents' physical functional indicators, speed, strength, endurance, coordination, balance and agility. In terms of flexibility, boys showed a minimal effect, while girls did not show a significant difference.

Childhood is an important period of natural growth in height and weight (Lubans, 2010). Scientific exercise interventions can produce benign stimulation to the pituitary gland and increase the secretion of growth hormone, thereby further promoting growth and development and improving physical health (Janssen and Leblanc, 2010). The results of the meta-analysis showed that jumping rope did not significantly affect height and weight indicators in preadolescents compared to regular physical education courses. However, three (Chen, 2017; Eler and Acar, 2018; Guo, 2020) of the seven studies reported a reduction in body weight, which we speculate may have been influenced by the exercise programmes, all of which had an intervention period of more than 10 weeks. Internationally, height and weight are combined to jointly evaluate students' body morphology and growth levels through BMI. One study found that jumping rope reduced BMI in boys (Qin, 2018), but Partavi reported the opposite result (Partavi, 2013). Meta-analyses of related studies showed that for both boys and girls aged 10 - 12 years, jumping rope did not show a significant advantage over regular physical education courses. Moreover, the effect of jumping rope on the reduction in body fat rate in boys was not significant. Because the included literature contains few studies on the relationship between jumping rope and BMI and body fat rate (Gao, 2020; Partavi, 2013; Qin, 2018) and those that do show evidence of publication bias, the sample size needs to be expanded to further derive and validate relevant results. In addition, for obese children, jumping rope significantly reduced their body fat rate and BMI (Eskandari et al., 2020; Kim Son et al., 2020).

Of the physical functional indicators, boys had higher effect sizes in both vital capacity and aerobic capacity than girls, indicating that jumping rope caused greater improvements in cardiorespiratory fitness in boys than in girls. This is consistent with the findings of Tomkinson et al. (Tomkinson et al., 2018). It is worth noting that the results of all four included studies (Chen, 2017; Huang, 2015; Qin, 2018; Yao, 2011) showed a reduction in resting HR, but it was not significantly different from regular physical education courses. The strong negative correlation between physical fitness level and resting HR has been confirmed in previous experimental and epidemiological studies at all ages and in both sexes (Blair et al., 1984; Paffenbarger et al., 1991). As they entered adolescence, girls had a higher resting HR than boys of the same age by 5 - 15 beats per minute (Abbott and Vlasses, 2011), and there was more room for their resting HR to decrease after physical activity (Rabbia et al., 2002). Although the results were not significant, the meta-analysis showed a small effect of jumping rope on resting HR, and the effect was greater in girls than in boys. In conclusion, the results of the meta-analysis reinforce the idea that jump rope training reduces resting HR.

A good level of physical performance will determine an individual's quality of life throughout the life cycle (Behan et al, 2019). Childhood and adolescence are the key periods for muscle development and physical performance, although the focus of physical performance development varies at different ages. Younger children have not yet established motor conditioning, so they should first learn basic motor skills, such as actively participating in various sports games, learning and experiencing mobility skills, nonmobility skills and manipulative skills, to lay the foundation for future specific motor skills (Dayan and Cohen, 2011). From the age of 10, along with the growth and development of children, haematological indicators are strongly gender dependent (Falz et al., 2019), and physical performance enters a phase of rapid improvement, with displacement speed, muscle strength, coordination and agility all increasing significantly with age until they stabilize around the age of 18 (Editorial Committee of Interpretation of National Standards for Students' Physical Fitness and Health, 2007). Girls enter puberty 1 - 2 years earlier than boys, their skeletal development begins to accelerate, most body morphological indicators continue to increase (Kim et al., 2011; Long et al., 2022), and all indicators exceed those of boys of the same age (Mutz and Albrecht, 2017).

The results of this study showed that boys had higher effect sizes than girls for speed, strength, endurance and agility, suggesting that jumping rope results in greater improvements in cardiorespiratory fitness and muscle strength in boys than in girls. This is consistent with the findings of Pichardo et al. (2019) and Tomkinson et al. (2018). Muscle strength increases with age during childhood and adolescence, and girls develop their muscles earlier than boys, but at a reduced level. However, as the reproductive system develops and secondary sexual characteristics emerge during adolescence, the differences in body morphology and physical performance between boys and girls become more pronounced. In girls, puberty starts earlier than in boys, producing large amounts of estrogen, which promotes the production of insulin and glucocorticoids, leading to an increase in body fat. Boys produce significantly more androgens than girls, and testosterone and leptin synergistically stimulate protein anabolism and bone and muscle development to control fat deposition (Vitale et al., 2009); therefore, boys have harder bones and are more muscular, have a greater capacity for muscle contraction and blood transport of oxygen (Remsberg et al., 2007), and demonstrate better athleticism and object control than girls (Trecroci et al., 2021). In addition, several studies have confirmed that boys are more active in daily physical activity than girls due to social positioning and individual physical and psychological differences (Hamilton et al., 2012; Pullen et al., 2020; Tonge et al., 2016), showing an overall advantage in physical performance. Therefore, they are more likely to improve their muscle strength with the same exercise intervention, thus further improving physical performance indicators such as speed, strength and endurance.

In terms of flexibility, boys showed a minimal effect, while girls did not show a significant difference. Two (Arazi et al., 2016; Gao, 2019) of the eight studies reported an increase in flexibility. In general, boys performed less well on flexibility tests, and jump rope training provided some flexibility improvement. The sit-and-reach test assesses flexibility in terms of the range of motion possible in the trunk and hip joints at rest. The subjects included in this study were all ordinary students, and the movements chosen for the jump rope exercise intervention were relatively basic, such as single swing, double swing and simple two or multiperson jump ropes, without including large movements such as lowering the fork or lowering the bridge, and the stretching time after the exercise was short. Some studies have shown that special restrictive multi-swing movements and gymnastic-like movements designed for jump rope exercises can greatly improve joint mobility and flexibility in children (Çınar-Medeni et al., 2019; Zhang, 2020). In addition, there was publication bias in the included literature, so further research is needed to provide more reliable conclusions. As the crucial period for adolescent flexibility is characterized by continuous negative growth (Lopes et al., 2017), it is recommended that jump rope classes be designed with a conscious effort to incorporate large movements and emphasize post-class stretching and relaxation to strengthen students' flexibility.

The increased effects of both coordination and balance were greater in girls than in boys following a jump rope exercise intervention. Girls are naturally dexterous and show better motor coordination than boys from an early age (Basow, 1992; Lorke et al., 2022). Surveys have shown that girls enjoy nonconfrontational, difficult-to-perform sports such as jumping rope more than boys do and show more motivation during practice (Harrell et al., 2005; Pienaar and Brosdowski-Willis, 2022). Furthermore, as individuals enter adolescence, they tend to choose sports that are common for people of the same gender and develop similar movement behaviours (Kahn et al., 2008), in line with the views of social gender theory; therefore, these results are not surprising.

Differences in the effects of exercise interventions are the result of a combination of different dosage factors. Multiple previous meta-analyses have confirmed that conditioning variables such as session time, frequency and duration are fundamental factors influencing exercise adaptation (Lv et al., 2012; Moran et al., 2018; Pescatello et al., 2015). Based on subgroup analyses, it was found that a jump rope intervention duration of 8 - 12 weeks, performed twice a week for 40 min or more, would be well suited to promote a comprehensive and efficient development of physical fitness in preadolescents aged 10 - 12 years.

Some studies noted a positive linear relationship between the duration of physical activity and positive fitness effects; that is, the longer the duration, the better the physical fitness status (Peta et al., 1994). Nevertheless, too much jump rope training may have unwanted adverse effects, as some studies have reported episodes of tibial periostitis in participants during the experiment (Duzgun et al., 2010). The results of this subgroup analysis showed that the intervention was more effective when the duration of the intervention was shorter. This may be because the motivation and interest of children and adolescents remain high for a short period of time, but they may become bored with prolonged interventions, the organism and nerves do not recover effectively in time, or the intensity of the intervention may not be sustainable for a longer period of time (BiddleI et al., 2014). In addition, most children have not undergone long-term professional training and are prone to adaptive responses in the early stages of training. As training experience increases, the potential for sustained adaptation rapidly diminishes (Blazevich et al., 2007). According to the laws of stage development, physical fitness and physical activity should be integrated into the development of motor skills during childhood and adolescence (Zhang, 2012).

The World Health Organization (WHO) recommends that children and adolescents engage in moderate-to-vigorous physical activity for at least 60 min per day at least 3 times per week (WHO, 2010), and as physical education classes play an important role in physical activity in schools (Lorke et al., 2022), it is important to make the most of them to enhance physical activity participation and promote healthy physical development in children and adolescents. In general, secondary schools have more than two physical education sessions per week, up to one session per school day in some areas, and one physical education session lasts between 40 and 60 minutes, which coincides with the results of the subgroup analysis in terms of frequency and duration of a single jump rope session. Therefore, one or two jump rope-based physical education sessions per week of 40 minutes or more at school will have a positive impact on preadolescent children's various physical fitness indicators. It should be noted here that a jump-rope-based physical education session should not simply involve nonstop jumping; rather, the session should include a warm-up at the beginning and a warm-down at the end and be structured according to preset exercise intensity and practice density of movement.

Exercise intensity is also a core element that influences the effectiveness of physical education and sport interventions (Mark and Janssen, 2011), but some of the literature included in this study did not mention specific exercise intensities (Table 2). The intensity of exercise in school physical education courses is generally monitored through heart rate. Some studies have suggested that moderate-intensity physical education sessions are more effective in promoting physical fitness in children and adolescents than low-or-high-intensity sessions (Borghese and Janssen, 2019). It was also found that different intervals between sets produce different training effects when the content is fixed. For example, a 1 min interval had a better strengthening effect on the lower-body muscle endurance of female university students than a 2 min interval (Waldron and Highton, 2014). Jumping rope has unique characteristics, and for different exercise purposes, different exercise contents and programmes can be arranged, such as adjusting the weight of the rope handle, exercise frequency, interval time, exercise intensity, practice density and training duration, to achieve the desired training effect.

There are some limitations to this study, and the results of the meta-analysis may be influenced by factors such as methodological quality and exercise intervention protocols. This is mainly reflected in (1) the small number of included studies and small sample size, which means that the results of the subgroup analysis need to be viewed with caution; (2) the methodological quality of some of the studies was not high due to the vague description of whether the allocation protocol was concealed and the type of blinding in the included studies; and (3) the time span of the included studies was from 2011 to 2021. The test methods were constantly updated, and the environment, nutrition and lifestyle of the subjects were constantly changing, which had a certain impact on the results.

Conclusion

Jumping rope has small to large benefits over regular physical education courses in terms of physical function and most physical performance indicators. Of these, boys have higher gains than girls in vital capacity, aerobic capacity, speed, strength, endurance and agility, while girls have better gains than boys in resting HR, coordination and balance. With regard to body morphology and flexibility, jumping rope did not show significant advantages. It is recommended that the design of jump rope courses should consciously include substantial movements and focus on post-class stretching and relaxation to improve students' flexibility. Based on available subgroup analysis, it is recommended that preadolescents aged 10 - 12 years maximize their physical fitness by having 1 - 2 jump rope sessions of at least 40 min per week for 8 - 12 weeks.

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Key points

- Preadolescence is a sensitive period for the development of children's physical fitness. Appropriate jumping rope course design can improve preadolescents' physical function and performance.
- Compared with regular physical education courses, jumping rope did not significantly affect the body morphological indicators of preadolescents.
- Children aged 10-12 years participate in jump rope sessions for at least 40 minutes once or twice a week for 8-12 weeks to better develop physical fitness.

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