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RESEARCH

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Effects of physical training programs on healthy badminton players' performance: a systematic review and meta-analysis

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Abstract

Research background Despite the abundance of common physical training programs designed for healthy badminton players, there is a significant gap in comprehensive studies evaluating their impact on player performance.

Research purpose This systematic review and meta-analysis aimed to determine the effects of common physical training programs on performance outcomes of healthy badminton players.

Method To address this gap, a meticulous search was conducted across several databases, including Scopus, PubMed, Web of Science, and EBSCOhost, up until January 2024, leading to the selection of relevant articles for a systematic review and subsequent meta-analysis using Review Manager (version 6) software.

Result The review incorporated 370 participants from 15 studies, with 12 studies qualifying for the meta-analysis. These studies commonly implemented exercise interventions ranging from 4 to 10 weeks, with participants undergoing 2 to 3 sessions weekly. The meta-analysis results showed that VO2max data indicated significantly improved performance in the experimental group (EG) (SMDb = 1.27; $P = 0.0001$; $I^2 = 0.0\%$) with low heterogeneity. Agility data also demonstrated significantly improved performance in the EG (SMDb = -0.61; $P = 0.01$; $I^2 = 13\%$) with low heterogeneity. Subgroup analysis of balance performance revealed significant improvements with different physical training programs: balance related training (effect size 5.63, $p < 0.001$, $I^2 = 35\%$), pilates training (effect size 2.25, $p < 0.001$, $I^2 = 78\%$), and core training (effect size 6.82, $p < 0.001$, $I^2 = 33\%$).

Conclusion This review found that high-intensity interval training and sprint interval training both improve VO2max in badminton players. High-intensity interval training, core training, strength and resistance training, and Pilates all enhance agility. Core training and lower limb resistance training help improve power. Balance training, core training, Pilates, and balance enhancement exercises contribute to better balance. Additionally, balance training improves the reactive strength index, while core training enhances smash performance. The meta-analysis indicates that current studies are more effective than traditional exercises in improving VO2max, agility, and balance. Nonetheless, further high-quality randomized controlled trials are needed to more accurately identify effective training interventions for improving performance in healthy badminton players.

Keywords Training, Athletic performance, Exercise, Badminton players

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Introduction

More than 2000 years ago, games resembling badminton were played in ancient European and Asian civilizations [1]. In recent years, badminton ranks as one of the most popular racket sports in Malaysia and countries such as China, Indonesia, Korea, and Denmark [2]. Badminton is widely recognized as one of the most popular sports worldwide, with an estimated 220 million people regularly playing, ranging from professionals to leisure players. It is commonly reported to be the second most popular sport after football, though such rankings may vary depending on the source [3, 4].

Recognized as the fastest racket sport in the world, badminton involves repeated movements including accelerations, decelerations, jumps, leaps, lunges, and rapid changes of direction [5]. Consequently, it demands a variety of skilled postural variations and movements from players [6]. Research has shown that, among all athletic abilities, technical skills in playing badminton are paramount. Coaches also play a crucial role in addressing athletes'needs to achieve high performance levels [7, 8]. Furthermore, technology in badminton sports has become a significant focus of research, with particular attention to both equipment and performance analysis.

Over the past few decades, there has been an increase in research in the field of badminton, enhancing the knowledge of badminton players in areas such as technique, tactics, timing, body biomechanics, and psychology [9, 10]. To reach an elite level, players must possess high-level skills [11, 12]. Achieving notable success in international badminton competitions also requires athletes to focus on improving their physical fitness alongside their technical training [13]. Despite this, there is a paucity of comprehensive studies that systematically compare the effectiveness of various training programs on badminton performance [14, 15]. This gap highlights the necessity for a systematic review to consolidate existing evidence and clarify the impacts of different training methodologies.

It has been found that a player's speed in hitting the shuttlecock often correlates with their success in the game [16]. Achieving this speed requires not only general physical fitness but also specific attributes such as exceptional agility to navigate the court swiftly, significant strength to deliver powerful smashes, and sustained endurance to maintain high performance levels throughout intense matches [17, 18]. To enhance this aspect of performance, specialized training for athletes is essential [19].Badminton training should adhere to scientific principles, with appropriate training loads, gradual increases in physical intensity, and the use of diverse techniques and equipment for strength training to achieve optimal results [20]. The common physical training programs used by badminton players include plyometric training [21–25], core training [19, 26–28], interval training [29, 30], resistance training [31, 32], Pilates training [33], and routine exercise [6, 19, 21, 26–31, 33], among others. These methods are crucial in badminton due to the sport's demands for agility, speed, power, and endurance [34–40]. A comprehensive training program develops these attributes, essential for high-level competition and peak performance. Previous research is often limited by small sample sizes and inconsistent training protocols, which impede the ability to draw definitive conclusions [29, 41, 42].

In addition, opinions are divided on whether different training programs significantly enhance badminton players'performance [14, 43]. A meta-analysis allows for the aggregation of data from multiple studies, increasing statistical power and providing more accurate estimates of training program effects [44]. This approach resolves inconsistencies in previous research and identifies overarching trends, facilitating the development of optimized training strategies for badminton players [45, 46]. This study focuses on two primary goals:

1) To incorporate up-to-date data on these training programs, detailing the features of the selected research.
2) To acknowledge the limitations and prospects of existing research and suggest directions for future studies of practical significance.

Methodology

In this review, the research team adhered to the recommendations given in the update of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [47]. This protocol was registered at the International Prospective Register of Systematic Reviews (INPLASY) with registration number INPLASY2023120034. We confirm that the record has been published on inplasy.com.

Inclusion and exclusion criteria

This review includes English literature published on Scopus, PubMed, Web of Science, and EBSCOhost prior to January 2024. Studies that meet the criteria outlined in the population, intervention, comparison, outcome, and study design (PICOS) framework will be considered for analysis [48].

Inclusion criteria

1) Population: Healthy badminton players (regardless of sex, age, badminton experience or level of play).
2) Intervention: The training experiment for more than 4 weeks.

3) Comparison: The study compares the training group(s) with a control group or another training intervention group.
4) Outcome: Record evaluations of physical or physiological performance areas.
5) Study designs: RCT study design.

Exclusion criteria

1) Non-English printed articles.
2) Duplicate articles.
3) Cannot be retrieved in full text.
4) Review, meta-analysis, conference paper, book, book chapter, generic.
5) The articles do not simultaneously meet the PICOS inclusion criteria.

Search strategy and selection process

The four electronic databases that this research system searched for articles on this subject were Scopus, PubMed, Web of Science, and EBSCO host. These four databases are commonly used in the field of sports science research. Boolean search strategies were employed using'AND'and'OR'operators. Use the following search terms for a Boolean search: ("training"OR"exercise*"OR"intervention"OR"physical training"OR"exercise training"OR"resistance training"OR"strength training"OR"aerobic exercise*"OR"power training"OR"fitness training"OR"endurance training"OR"conditioning training"OR"physical therapy"OR"plyometric training"OR"interval training"OR"circuit training"OR"functional training"OR"core training"OR"high-intensity interval training"OR"HIIT"OR"mobility training"OR"balance training"OR"flexibility training"OR"speed training"OR"speed endurance training"OR"explosive training"OR"anaerobic training"OR"sports-specific training"OR"specificity training"OR"skill-based training"OR"movement training"OR"motor skills training"OR"reaction time training"OR"sport conditioning"OR"powerlifting"OR" weight training"OR"bodyweight training"OR"isometric training"OR"dynamic training"OR"metabolic conditioning"OR"cross training"OR"strength and conditioning") AND ("badminton athletes"OR"badminton players"OR"badminton beginners"OR"shuttler") AND ("performance"OR"athletic performance"OR"sport performance"OR"physical performance"OR"training effects"OR"performance improvement"OR"performance enhancement"OR"physical fitness"OR"strength"OR"flexibility"OR"agility"OR"speed"OR"power"OR"endurance" OR"coordination"OR"balance"OR"technical skills"OR"technique"OR"technical performance"OR"skill"OR"skill development"OR"skill performance"). In addition, a manual search of references and Google Scholar was done to make sure no relevant articles were missed. To guarantee accuracy and completeness, knowledgeable librarians assisted with the data collection process in the interim.

Study selection

Figure 1 illustrates the specific procedures for selecting studies. Initially, redundant articles were eliminated. The second step involved evaluating the titles and abstracts, followed by a full-text screening to assess preset eligibility requirements. This process was completed by two impartial reviewers (MSZ and XYQ), with any disagreements being thoroughly investigated. A third reviewer (KGS) was involved as needed until consensus was reached. To address potential inconsistencies in evaluations between reviewers, we implemented a calibration exercise prior to the screening process. Both primary reviewers independently assessed a subset of studies to ensure consistency in applying the inclusion and exclusion criteria. Figure 1 shows that 718 papers were identified through database searches, and 2 additional studies were found through other references. 38 studies were included in the full text assessed for eligibility. However, 22 articles were excluded because they did not simultaneously meet the PICOS inclusion criteria, and 2 were excluded because they did not report numerical results. No studies were excluded due to inability to retrieve full texts, as all relevant articles were accessible. After full text assessed for eligibility, 15 papers met all the inclusion criteria for the systematic review. However, only 12 articles were included in the meta-analysis, while the remaining 3 were excluded from the meta-analysis because they did not include three or more outcome indicators [22, 23, 32].

Data extraction and synthesis

The inclusion criteria determined which data to extract: 1) Author and year of publication; 2) Sample size; 3) Participant characteristics (e.g., sex, age, and level of exercise); 4) Intervention characteristics (type, frequency, and duration); and 5) Study outcomes. We summarized the means and standard deviations (SD) from the included studies. If a publication did not specify the mean and SD for the intervention outcomes, we extracted additional data and converted it using recognized methods [49–51]. Specifically, when estimating the post-intervention SD, we used the following formula, where SD post represents the post-intervention standard deviation, SD pre represents the pre-intervention standard deviation, and R is a constant, usually taken as 0.5:

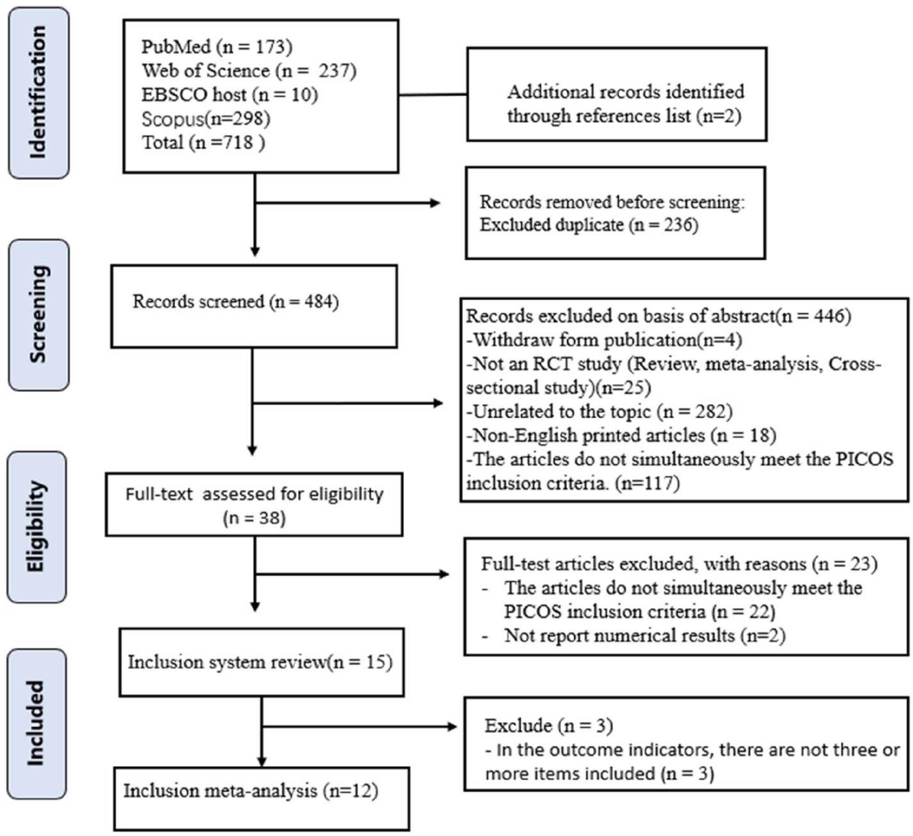

Fig. 1 Flow chart of PRISMA article screening

$$\mathrm{SD} = \sqrt{SDpost^2 + SDpre^2 - 2 * R * SDpost * SDpre}$$

If pertinent information was missing from the articles and there was no response from the corresponding author upon contact, we excluded the study.

Risk of bias and the certainty of evidence assessment

The Risk of Bias (RoB) assessment was carried out using the Cochrane RoB instrument [52]. This tool assesses the risk of bias across seven domains: incomplete outcome data, selective reporting, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, random sequence generation, and other sources of bias [53]. Each domain can be categorized as'low,"unclear,'or'high.'Two assessors conducted each procedure, and a third assessor was consulted in cases of disagreement between the first two. The findings demonstrated unclear risks in allocation concealment and blinding of participants and personnel, as well as in the bias of outcome evaluation, but showed a low risk of bias for selective reporting and random sequence generation across the studies.

Statistical analysis

In the outcome, if there are not three or more study variable indicators included, they will only be included in the systematic review and not in the meta-analysis. This threshold ensures sufficient data for robust statistical pooling and focuses on variables related to the physical and skill performance of badminton players, thereby enhancing the reliability and validity of the meta-analysis results [54]. We conducted a meta-analysis on three or more study indicators using RevMan (version 6; available at https://revman.cochrane.org).To reflect the effect size, we used the mean and standard deviation of the performance indicators before and after the intervention. We then standardized the data using the post-intervention performance indicators. The meta-analysis employed both random-effects and fixed-effects models to facilitate analysis while accounting for heterogeneity between studies. The I^2 statistic was used to assess the impact of heterogeneity, with values $<25\%$, 25–75%, and $>75\%$ indicating low, moderate, and high heterogeneity, respectively [55]. When high heterogeneity is detected ($I^2 > 50\%$), a random-effects model is used to account for the variability among studies. In cases of low heterogeneity ($I^2 \leq 50\%$), a fixed-effects model is applied, assuming that the studies estimate the same underlying effect. For outcome indicators with different units, standardized mean differences (SMD) are calculated to facilitate comparison across studies. When outcome indicators have the same units, mean differences (MD) are used for analysis. Additionally, the RoB assessment was carried out using the Cochrane RoB instrument to examine the risk of publication bias [56, 57].

Results

Risk of bias and the certainty of evidence assessment

The categorization of bias risk was based on RoB tool [58]. Studies were assessed as having a low risk of bias when they provided clear and adequate methods to minimize bias in each domain. An unclear risk of bias was assigned when there was insufficient information to determine the risk level, often due to inadequate reporting. A high risk of bias was identified when there were evident flaws in the study design or execution that could introduce significant bias. In this graph (Fig. 2), each row represents a study, and each column represents a type of bias. The color indicates the assessed likelihood of each bias type within each study: green for a low risk of bias, yellow for an unclear risk of bias, and red for a high RoB. In these reviews, the risks of allocation concealment (selection bias), blinding of participants and personnel (performance bias), and blinding of outcome assessment (detection bias) are not clearly low or high. Other biases also present unclear risks. However, there are low risks identified in selective reporting (reporting bias) and random sequence generation (selection bias). Incomplete outcome data (attrition bias) is noted to have a minimal low risk.

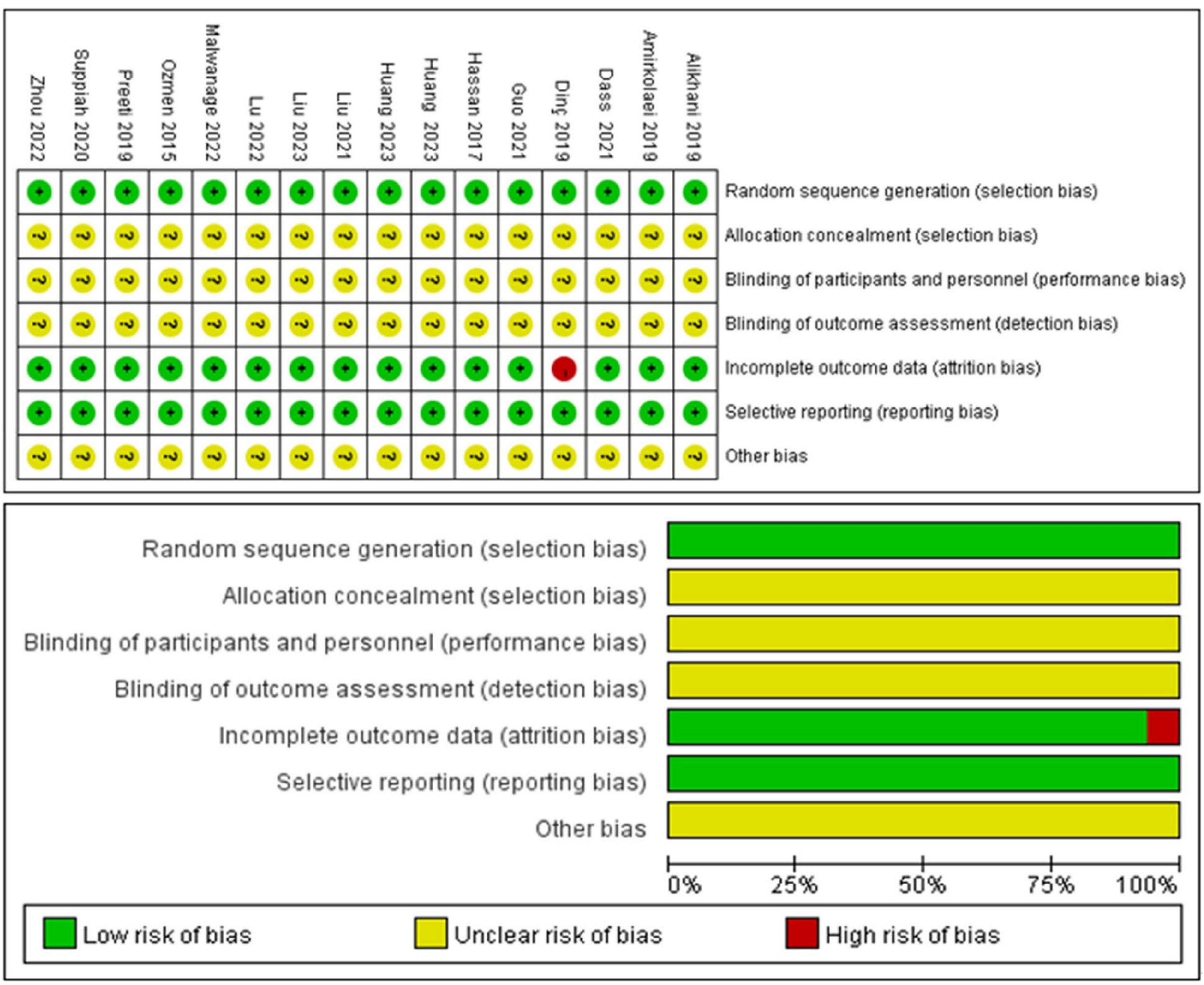

Fig. 2 Risk of bias graph and summary

Participant characteristics

Table 1 provides details on the characteristics and functional training programs of 370 participants from 15 studies that met the inclusion criteria:

1) Gender Classification: Of the studies, seven focused on male athletes [6, 19, 22–24, 26, 33], one on female athletes [21], four included both male and female athletes [25, 27, 29, 32], and three studies did not provide detailed descriptions [28, 30, 31].
2) Sample Size: The total number of individuals across the 15 studies was 370, with each study involving 16 to 40 participants. Four studies had different numbers of participants in experimental group (EG) and control group (CG) [6, 21, 26, 28], while the rest had equal numbers in both groups.
3) Nationality: The studies encompassed participants of various nationalities, including five with Chinese [22, 24, 29, 31, 32], two with Turkish [27, 28], two with Indian participants [25, 33]. Additionally, there were studies with participants from Australia [6], Malaysia [30], Canada [21], Egypt [25], the United States [23], and Iran [26].
4) Badminton Training Background: Thirteen studies provided details on the participants'years of training, with two exceptions [26, 28]. Six studies required participants to have more than five years of experience [19, 22–24, 29, 30]

Intervention characteristics

The included 15 studies were categorized based on three intervention characteristics: intervention length, intervention frequency, and intervention type.

1) Intervention Length: One study implemented an intervention for 4 weeks [32], two studies for 5 weeks [25, 33], six studies for 6 weeks [21–24, 27, 31], five studies for 8 weeks [6, 19, 26, 28, 29], one studies for 10 weeks [30].
2) Intervention Frequency: Nine studies employed a three-times-per-week frequency [6, 21–24, 26, 28–30]; three studies had a two-times-per-week frequency [19, 27, 33]; and three did not specify the frequency [25, 31, 32].
3) Intervention Type: In the EG, five studies utilized plyometric training [21–25]; four studies engaged in core training (including Swiss Ball Training) [19, 26–28]; two studies conducted interval training [29, 30]; two studies applied resistance training [31, 32]; one study opted for Pilates training [33] and one study opted for Balance training [6]. For the CG, ten studies followed routine exercise [6, 19, 21, 25–31, 33]; Three studies matched with plyometric training [22–24]; one study applied velocity-based resistance training [32] and Regularly scheduled training [27].

Outcome

VO2 max

The effect of training on badminton players'aerobic fitness has been examined in two studies [29, 30]. Suppiah tested sixteen male badminton players aged thirteen to fifteen. The EG underwent high-intensity interval functional training, while the control CG received regular training for 10 weeks. The results indicated significant differences in fitness levels between EG and CG at distances greater than 20 m. VO2 max increased significantly after 10 weeks of high-intensity interval training, as indicated by $F(1,14) = 4.663$, ($p < 0.05$) [30]. Liu's study involved 32 top badminton players, with the CG participating in regular multi-ball training sessions and two Fartlek runs over 8 weeks. In contrast, the EG engaged in Sprint Interval Training three times per week. The anaerobic threshold VO2 max in the EG significantly increased from 75 $\pm$4% to 82 $\pm$4% ($p < 0.05$), which was significantly higher than that in the CG. Similarly, in the male CG, it increased from 74 $\pm$ 10% to 85 $\pm$ 3% ($p < 0.05$) [29].

Agility

The effects of various training regimens on the agility of badminton players have been examined in six studies [24, 25, 27, 28, 30, 33]. Among them, five studies in the CG group employed conventional training, while one study used plyometric training. In Suppiah's study involving 16 male badminton players aged 13 to 15, significant differences in four-corner agility tests were observed between EG and CG ($F(1,14) = 5.443$, $p < 0.05$), indicating that agility significantly improved after 10 weeks of high-intensity interval training [30]. Another study tested 28 athletes [28], where the EG underwent core training three times a week for 8 weeks, leading to observed improvements in agility as measured by the Illinois agility test. In the study [27], badminton players were randomly divided into a EG and CG. Despite EG undergoing Combined Strength Training twice a week for 6 weeks, the Illinois agility test showed no significant changes ($p > 0.05$). The sample size of this study was 40, with the EG group undergoing Strengthening and plyometric resistance training, while the CG group performed Routine exercise. The intervention lasted for 5 weeks, but the Frequency was not specified. The Outcomes indicated that the EG group showed improvements in Vertical jump and plank test [25]. In Preeti et al.'s study [33], 40 male athletes were divided into two groups: EG (group A), which performed Pilates training alongside routine training, and CG (group B),

Table 1 Characteristics of studies examined in the present review & meta-analysis

Author (year)	Country	Sample size (T/C)	Age (years)	Gender	Weight (kg)/ Height (cm)	Exercise Level (years)	Intervention characteristics			Outcome(s)
							Type	Frequency	Length	
Dass (2021) [25]	India	40 (20/20)	T: 21.35 ± 1.954 C: 21.1 ± 1.832	All	NR	Training for at least 1–2 years	T: Strengthening and plyometric resistance training C: Routine exercise	NR	5 weeks	Vertical jump, Plank test ↑
Suppiah, (2020) [30]	Malaysia	16 (8/8)	Rang: 13–15	NR	T: 47.55 ± 3.7/ 158.96 ± 4.8 C:48.96 ± 5.7/ 160.04 ± 6.9	Training for at least 5 years	T: High intensity functional interval training C: Routine exercise	3 times/week	10 weeks	VO_2max, Agility ↑; Sprint →
Dinç (2019) [28]	Turkey	25 (15/10)	T: 19.5 ± 1.2 C: 19.4 ± 1.5	NR	T: 64 ± 8.9/- C: 67.4 ± 10.3/-	NR	T: Normal training sessions + Core Training C: Routine exercise	3 times/week	8 weeks	Standing long jump, Illinois Test ↑; Right Leg, Left Leg →; Both Legs T → C ↑
Guo (2021) [24]	China	16 (8/8)	T: 20.5 ± 1.1 C: 19.1 ± 2.2	Males	T: 68.1 ± 7.2/ 177.8 ± 5.1 C: 69.88 ± 8.94/ 179.1 ± 6.1	T: 11.4 ± 1.4 C: 10.6 ± 1.1	T: Combined Balance and Plyometric Training C: plyometric training	3 times/week	6 weeks	Modified southeast Missouri agility test, Y-Balance test, Reactive strength index →
Zhou (2022) [23]	United States	16 (8/8)	Mean: 20.5 ± 1.1	Males	T: 68.13 ± 7.22/ 177.75 ± 5.06 C: 69.88 ± 8.94/ 179.13 ± 6.06	T: 11.38 ± 1.41 C: 10.63 ± 1.06	T: Combined Balance and Plyometric Training C: plyometric training	3 times/week	6 weeks	Limb symmetry index ↑
Liu (2021) [29]	China	32 (16/16)	Male: T: 20.0 ± 1.3 C: 21.5 ± 2.2 Female: T: 20.5 ± 1.4 C: 19.4 ± 1.5	All	Male: T: 73.8 ± 6.9/ 179.6 ± 3.6 C: 72.4 ± 6.7/ 177.1 ± 7.1 Female: T: 62.6 ± 4.2/ 168.5 ± 4.2 C: 61.3 ± 4.2/ 168.2 ± 4.8	Male: T: 12.1 ± 2.2 C: 13.2 ± 3.2 Female: T: 9.5 ± 1.2 C: 9.8 ± 1.5	T: Sprint Interval Training C: Routine exercise	3 times/week	8 weeks	VO_2max ↑
Lu (2022) [22]	China	16 (8/8)	T: 20.50 ± 1.07 C: 19.13 ± 2.23	Males	T: 68.13 ± 7.22/ 177.75 ± 5.06 C: 69.88 ± 8.94/ 179.13 ± 6.06	T: 11.38 ± 1.41 C: 10.63 ± 1.06	T: Combined Balance and Plyometric Training C: Plyometric training	3 times/week	6 weeks	Dynamic postural stability index ↑
Ozmen (2015) [27]	Turkey	20 (10/10)	Mean: 10.8 ± 0.3	11 Males 9 Females	T: 31.7 ± 4.6/ 139.4 ± 2.6 C: 36.2 ± 6.3/ 141.7 ± 2.6	Experience of at least 1 year	T: Core strength Training + regularly scheduled training C: Routine exercise	2 times/week	6 weeks	Star Excursion Balance Test ↑, Illinois Agility Test T ↑, C →, Core endurance tests ↑

Table 1 (continued)

Author (year)	Country	Sample size (T/C)	Age (years)	Gender	Weight (kg)/ Height (cm)	Exercise Level (years)	Intervention characteristics			Outcome(s)
							Type	Frequency	Length	
Alikhani (2019) [21]	Canada	22 (12/10)	T: 22.00 ± 1.30 C: 22.00 ± 0.84	Females	NR	T: 2.50 ± 1.00 C: 3.00 ± 0.94	T: Combined Balance and Plyometric Training C: Routine exercise	3 times/week	6 weeks	Dynamic balance ↑
Malwanage, (2022) [6]	Australia	20 (12/8)	T: 12.75 ± 0.45 C: 13.00 ± 0.93	Males	T: 36.97 ± 10.89/ 147 ± 9 C: 36.48 ± 9.48/ 1.49 ± 0.11	More than 6 months	T: Balance training C: Routine exercise	3 times/week	8 weeks	Static balance with eyes opened ↑, Static balance with eyes closed →, Dynamic Balance T ↑ C →, Shuttle-run time T ↑ C →
Amirkolaei, (2019) [26]	Iran	29 (16/13)	T: 13.31 ± 1.2 C: 12.31 ± 1.32	Males	T: 56.28 ± 13.98/ 160.25 ± 12.39 C: 43.15 ± 12.19/ 149.15 ± 12.23	NR	T: Swiss Ball Training C: Routine exercise	3 times/week	8 weeks	Lower Limb Y Balance Test ↑, Upper Limb Y Balance Test ↑
Huang (2023) [32]	China	18 (9/9)	T: 21.2 ± 1.39 C: 22.1 ± 1.52	11 Males 10 females	APRE: 66.46 ± 10.74/ 172.4 ± 7.18 VBRT: 63.99 ± 13.27/ 168.9 ± 7.93	Minimum of 3 years of prior experience	T: Autoregulatory progressive resistance exercise C: Velocity-based resistance training	NR	4 weeks	Reactive strength index VBRT ↑, APRE →
Liu (2023) [31]	China	40 (20/20)	T: 20.72 ± 0.73 C: 20.41 ± 0.79	NR	T: 71.85 ± 8.01/ 175.03 ± 5.13 C: 70.12 ± 9.038/ 177.89 ± 5.17	4–5 years of training	T: Lower-limb resistance exercise C: Routine exercise	NR	6 weeks	Vertical jump height →, Standing long jump →
Hassan (2017) [19]	Egypt	20 (10/10)	T: 18.20 ± 0.79 C: 18.10 ± 0.74	Males	T: 72.70 ± 4.05/ 176 ± 2 C: 73.37 ± 3.14/ 173 ± 3	T: 5.20 ± 0.48 C: 5.05 ± 0.55	T: Core Stability Training C: Routine exercise	2 times/week	8 weeks	Star Excursion Balance Test ↑, Smash↑
Preeti (2019) [33]	India	40 (20/20)	T: 19.70 ± 2.44 C: 20.45 ± 1.64	Males	T: 55.85 ± 6.43/ 166.85 ± 8.84 C: 169.85 ± 5.96/ 58.65 ± 5.67	More than 2 years	T: Pilates training C: Routine exercise	2 times/week	5 weeks	Vertical Jump Test ↑, 10 m Shuttle Run Test ↑, Star Excursion Balance Test ↑, Hand–Eye Coordination Test↑

which only performed routine training. After 5 weeks, agility test results between EG and CG showed significant differences ($p < 0.05$). However, in Guo et al.'s study [24], 16 elite male badminton players were divided into a balance and enhancement training group ($n = 8$) and an enhancement training group ($n = 8$). After 6 weeks, the SEMO agility test showed no significant differences between the balance and enhancement training group and the enhancement training group.

Power

Two studies have explored the effects of various training programs on the explosive power of badminton players [28, 31]. In the study of Dinç et al. [28], 28 athletes were evaluated, with the EG participating in core training three times per week for a total of 88 weeks during the intervention period, while the CG did not engage in this additional training. The explosive power was assessed using the standing long jump, which showed a significant difference between the EG and CG ($p < 0.05$) [28]. In a separate study, 24 active badminton players were randomly assigned to either a CG or a EG [31]. The EG underwent lower limb resistance training with elastic bands, which not only increased resistance but also enhanced lower limb strength, while the CG continued with their standard training regimen. The EG outperformed the CG in measures of explosive power, as evidenced by superior results in the standing long jump and vertical jump height tests [31].

Balance

Eight studies have investigated the effects of various training regimens on the balance performance of badminton players [6, 19, 21, 22, 24, 27, 28, 33], with six incorporating strength-based interventions. These studies collectively indicate that the EG often outperforms the CG in improving balance performance among badminton players. In the study by Guo et al. [24], 16 elite male badminton players were randomly assigned to either a balance training group ($n = 8$) or an enhancement training group ($n = 8$). After a 6-week intervention, results from the Y-Balance test suggested a superior interaction effect in the BP group compared to the PL group [24]. In Alikhani's study [21], 22 healthy female badminton novices were randomly divided into a CG and an EG. The EG underwent 6 weeks of physical therapy, with dynamic balance evaluated using the Y-balance test. Post-therapy, the EG showed significant improvement in dynamic balance ($p = 0.003$) [21]. Malwanage et al. [6] involved 20 male badminton players, with the intervention group ($n = 12$) receiving 30 min of balance training in addition to regular badminton training twice a week for eight weeks, while the CG ($n = 8$) only received regular training. Assessments of dynamic balance (using the star excursion balance test) and static balance (using the single-leg stance test) were made both at baseline and after 8 weeks. Improvements in balance were observed in both groups, with significant enhancement in dynamic balance noted only in the intervention group ($p = 0.036$) [6]. Solanki et al. [19] divided 20 badminton players under 19 years of age into a core training group ($n = 10$) and a CG ($n = 10$), finding that the training group exhibited improvements in motor balance after an 8-week intervention [19]. In the study by Preeti et al. [33], 40 male athletes were randomly divided into an EG (Group A), which performed Pilates training in addition to routine training, and a CG (Group B), which adhered only to routine training. The star excursion balance test was used to assess dynamic balance, revealing significant differences between the EG and CG ($p < 0.05$) [33].

In their study, Lu et al. randomly assigned 16 elite male badminton players to either a balance enhancement training group ($n = 8$) or a regular enhancement training group ($n = 8$) [22]. Over six weeks, the balance enhancement training group underwent balance enhancement training three times weekly, whereas the regular enhancement training group participated in their enhancement training sessions only once weekly. The motion stability of the athletes before and after the intervention was evaluated using the dynamic postural stability index and the center of pressure metrics. The results demonstrated that the balance enhancement training group showed significant improvements in motion stability compared to the regular enhancement training group. Specifically, for the forward dynamic postural stability index (F-DPSI), lateral dynamic postural stability index (L-DPSI), forward center of pressure in anteroposterior (F-COPAP), forward center of pressure in mediolateral (F-COPML), forward composite center of pressure path length (F-COPPL), and lateral center of pressure path length (L-COPPL), the balance enhancement training group exhibited significant improvements ($p = 0.003$, 0.025, 0.024, 0.002, 0.029, and 0.043, respectively). However, there were no significant differences between the balance enhancement training group and the regular enhancement training group in the changes observed for lateral dynamic postural stability index (L-DPSI), lateral center of pressure in anteroposterior (L-COPAP), and lateral center of pressure in mediolateral (L-COPML) ($p > 0.907$) [22]. In the study by Dinç et al., [28] 28 athletes were evaluated. During the intervention period, the EG participated in core training three times a week for 8 weeks, whereas the CG did not engage in core training. The assessment of balance through the double right/left foot balance test revealed no significant difference between the EG and CG [28].

Reactive strength index

Two studies have investigated the impact of varied training programs on the reactive strength index in badminton players [24, 32]. In the research conducted by Guo et al., [26] 16 elite male badminton players were randomly divided into two groups: the enhancement training group ($n = 8$) and the balance and enhancement training group ($n = 8$). After a 6-week intervention period, the balance and enhancement training group showed a superior interaction effect on the reactive strength index test compared to the enhancement training group [24]. On the other hand, a different study randomly assigned 18 badminton players into two groups: the Autoregulatory Progressive Resistance Exercise group and the Variable Resistance Training group [32]. Following 4 weeks of resistance training combined with their seasonal training routine, there was no significant difference in reactive strength index changes observed between the two groups ($p < 0.05$) [32].

Smash

Only one study has examined the impact of training on badminton smash performance. Hassan et al. investigated the effect of core training on the technical performance of badminton players. In this study, 20 badminton players under the age of 19 were divided into two groups: a core training group ($n = 10$) and a control group ($n = 10$). The forehand smash performance of these two groups was tested after 8 weeks of training. The results showed significant differences in smash speed and accuracy between the two groups ($p < 0.05$) [59]. The study concluded that 8 weeks of core stability training could enhance the smash performance of young badminton players.

Meta-analysis

The CG, which underwent routine training interventions (regular training, normal training), and the EG, which received additional training interventions, were both included in a meta-analysis. Meta-analysis serves to summarize and integrate the findings from multiple studies. Therefore, we restricted the meta-analysis to metrics that were covered in more than three studies, such as the effects on maximal oxygen uptake, agility, and balance performance. Other outcomes, requiring further aggregation, were excluded from the meta-analysis due to insufficient data.

VO2 max

Two studies contributed VO2 max data. Liu et al. examined the effects of high-intensity functional interval training on the study group [29], while Suppiah investigated the impact of sprint interval training on their participants [30]. In both studies, the CG underwent routine exercise. Each study included three EG and three CG, totaling thirty-two participants across the two studies. The interventions of sprint interval training and high-intensity functional interval training were visually represented on a forest plot. Analysis revealed that there was a significant difference in VO2 max performance between the badminton players in the EG and those in the CG (SMDb $= 1.27$; $\text{Chi}^2 = 1.78$; $p < 0.001$; $I^2 = 0.0\%$; Fig. 3).

Agility

Agility data were extracted from five studies. Dass [25] applied both strengthening and plyometric resistance training, whereas Dinç et al. focused on core training [28]. Preeti et al. utilized core training [27]. The EG underwent high-intensity functional interval training in the study [30], while the CG engaged in routine or conventional training. The forest plot analysis reveals no significant difference in the agility performance among badminton players subjected to strengthening and plyometric resistance training, core training, Pilates instruction, and high-intensity functional interval training, compared to routine exercise (SMDb $= -1.45$; $\text{Chi}^2 = 84.44$; $p = 0.06$; $I^2 = 94\%$; Fig. 4). This suggests a high level of heterogeneity across the studies.

This study systematically analyzed the impact of each individual article on the overall heterogeneity in an effort to pinpoint its source. It was observed that removing one or two studies did not effectively reduce the heterogeneity. Subsequently, it was revealed that the primary source of heterogeneity stemmed from the studies conducted by

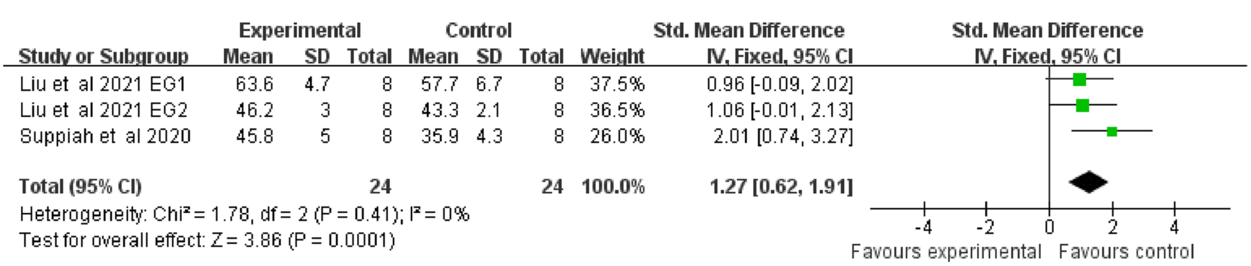

Fig. 3 VO2 max performance in comparison to the control group

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Suppiah 2020	29.5	0.42	8	31.9	0.87	8	14.9%	-3.32 [-4.97, -1.67]
Preeti 2019	4.8	0.77	20	9.1	0.88	20	15.9%	-5.10 [-6.43, -3.77]
Ozmen 2015	20.43	1.93	10	22.05	1.48	10	17.0%	-0.90 [-1.83, 0.03]
Dinç 2019	15.66	0.78	15	16.48	0.9	10	17.2%	-0.96 [-1.81, -0.11]
Dass EG2 2021	62.05	13.14	20	47.02	10.54	20	17.5%	1.24 [0.55, 1.92]
Dass EG1 2021	263.32	17.87	20	269.3	27.94	20	17.6%	-0.25 [-0.87, 0.37]
Total (95% CI)			**93**			**88**	**100.0%**	**-1.45 [-2.95, 0.05]**

Heterogeneity: Tau² = 3.25; Chi² = 84.44, df = 5 (P < 0.00001); I² = 94%
Test for overall effect: Z = 1.89 (P = 0.06)

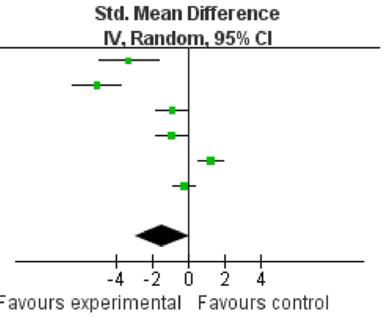

Fig. 4 Agility performance in comparison to the control group

Preeti et al. [30, 33] and Dass [25], even after the exclusion of three studies. Upon further investigation, it was found that agility performance among badminton players was influenced differently by strengthening and plyometric resistance training compared to routine exercise (SMDb = −0.61; Chi^2 = 2.29; p = 0.01; I^2 = 13%; Fig. 5).

Balance

Data on balance performance were collected from seven studies [6, 19, 21, 26–28, 33]. This study conducted a subgroup analysis based on training methods to investigate the effectiveness of core training (core strength training), pilates training, and balance-related training (combined balance and plyometric training, Swiss ball training) compared to routine exercise on badminton balance performance. The subgroup analysis results were significant (Chi^2 = 8.98, p < 0.001; Fig. 6). We found that Core Training, Pilates Training, and Balance-related Training all achieved significant effects on athletes'balance performance compared to routine exercise (p < 0.001). Under the random-effects model, the intervention effects of Balance-related Training and Core Training were significant, with effect sizes of 5.63 (95% CI [2.36, 8.90], p < 0.001) and 6.82 (95% CI [4.08, 9.56], p < 0.001), respectively. The heterogeneity was moderate, with I^2 = 35 for Balance-related Training and I^2 = 33 for Core Training. However, for the effects of Pilates Training, although a significant difference was observed, there was noted high heterogeneity (Tau^2 = 0.14, I^2 = 78%), with an effect size of 2.25 (95% CI [1.82, 2.67], p < 0.001).

Discussion

This review investigates the effects of training, such as plyometric resistance training, core training, Pilates instruction, and high-intensity functional interval training, on the physical fitness and badminton-specific skills of players. The results reveal significant positive effects of these exercises on various measured variables, encompassing VO2 max, agility, power, balance, reactive strength index, and smash. This study will focus on analyzing the impact of training on these six variables.

VO2 max

Badminton is an intermittent sport characterized by prolonged periods of high-intensity exercise interspersed with rest intervals [60]. Despite the intermittent nature of the activity, subjects exhibit elevated oxygen uptake and heart rate responses, comparable to maximal laboratory tests [60]. Previous research has highlighted a strong correlation between physiological parameters and badminton performance [61, 62]. Specifically, aerobic capacity shows a positive association with interval performance,

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Dass EG2 2021	62.05	13.14	20	47.02	10.54	20	0.0%	1.24 [0.55, 1.92]
Ozmen 2015	20.43	1.93	10	22.05	1.48	10	24.0%	-0.90 [-1.83, 0.03]
Dinç 2019	15.66	0.78	15	16.48	0.9	10	28.1%	-0.96 [-1.81, -0.11]
Dass EG1 2021	263.32	17.87	20	269.3	27.94	20	47.9%	-0.25 [-0.87, 0.37]
Suppiah 2020	29.5	0.42	8	31.9	0.87	8	0.0%	-3.32 [-4.97, -1.67]
Preeti 2019	4.8	0.77	20	9.1	0.88	20	0.0%	-5.10 [-6.43, -3.77]
Total (95% CI)			**45**			**40**	**100.0%**	**-0.61 [-1.08, -0.13]**

Heterogeneity: Tau² = 0.02; Chi² = 2.29, df = 2 (P = 0.32); I² = 13%
Test for overall effect: Z = 2.48 (P = 0.01)

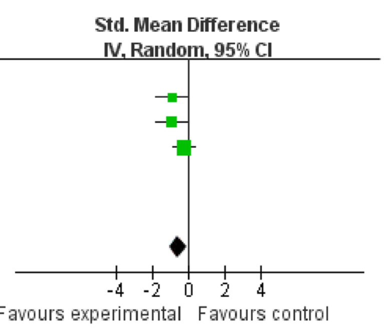

Fig. 5 Agility performance in comparison to the control group. (Exclusion of heterogeneity study)

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
1.4.1 Balance related training								
Malwanage et al 2022 EG1	15.36	4.18	12	14.59	5.34	8	2.0%	0.77 [-3.62, 5.16]
Malwanage et al 2022 EG3	90.17	12.11	12	85.73	11.85	8	0.4%	4.44 [-6.25, 15.13]
Malwanage et al 2022 EG2	9.93	13.65	12	4.56	1.19	8	0.7%	5.37 [-2.40, 13.14]
Amirkolaei et al 2019 EG2	96.26	7.05	16	89.46	7.62	13	1.4%	6.80 [1.41, 12.19]
Amirkolaei et al 2019 EG1	85.15	8.86	16	77.9	10.15	13	0.8%	7.25 [0.23, 14.27]
Alikhani et al 2019	99.12	7.6	12	88.2	7.59	10	1.0%	10.92 [4.55, 17.29]
Subtotal (95% CI)			**80**			**60**	**6.4%**	**5.63 [2.36, 8.90]**
Heterogeneity: Tau² = 5.69; Chi² = 7.69, df = 5 (P = 0.17); I² = 35%								
Test for overall effect: Z = 3.38 (P = 0.0007)								
1.4.2 Pilates training								
Preeti et al 2019 EG3	3.69	0.13	20	1.84	0.7	20	22.2%	1.85 [1.54, 2.16]
Preeti et al 2019 EG1	4.4	0.9	20	2.26	0.9	20	20.0%	2.14 [1.58, 2.70]
Preeti et al 2019 EG4	4.76	0.9	20	2.39	0.9	20	20.0%	2.37 [1.81, 2.93]
Preeti et al 2019 EG2	4.56	0.11	20	1.94	0.6	20	22.5%	2.62 [2.35, 2.89]
Subtotal (95% CI)			**80**			**80**	**84.8%**	**2.25 [1.82, 2.67]**
Heterogeneity: Tau² = 0.14; Chi² = 13.85, df = 3 (P = 0.003); I² = 78%								
Test for overall effect: Z = 10.41 (P < 0.00001)								
1.4.3 Core Training								
Dinc et al 2019	784	164.28	15	861.6	162.11	10	0.0%	-77.60 [-208.01, 52.81]
Hassan et al 2017 EG3	93.8	7.52	10	93.8	7.52	10	1.0%	0.00 [-6.59, 6.59]
Hassan et al 2017 EG1	87.3	6.43	10	81.8	4.42	10	1.7%	5.50 [0.66, 10.34]
Hassan et al 2017 EG2	98.4	6.31	10	91.6	6.06	10	1.4%	6.80 [1.38, 12.22]
Ozmen et al 2015 EG3	95.98	5.36	10	88.9	6.39	10	1.5%	7.08 [1.91, 12.25]
Ozmen et al 2015 EG2	102.88	4.16	10	93.01	5.44	10	2.2%	9.87 [5.63, 14.11]
Ozmen et al 2015 EG1	92.54	6.44	10	82.53	7.7	10	1.1%	10.01 [3.79, 16.23]
Subtotal (95% CI)			**75**			**70**	**8.8%**	**6.82 [4.08, 9.56]**
Heterogeneity: Tau² = 4.33; Chi² = 8.98, df = 6 (P = 0.17); I² = 33%								
Test for overall effect: Z = 4.88 (P < 0.00001)								
Total (95% CI)			**235**			**210**	**100.0%**	**2.86 [2.20, 3.51]**
Heterogeneity: Tau² = 0.48; Chi² = 54.20, df = 16 (P < 0.00001); I² = 70%								
Test for overall effect: Z = 8.52 (P < 0.00001)								
Test for subgroup differences: Chi² = 14.25, df = 2 (P = 0.0008), I² = 86.0%								

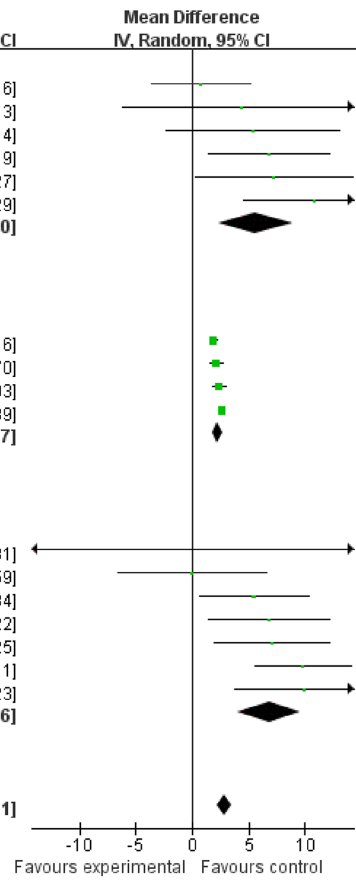

Fig. 6 Subgroup analysis of balance performance in comparison to the control group

including parameters like VO2 max, lactate/anaerobic threshold, and running efficiency [63, 64]. Also, there was a close relationship between VO2 max scaled and the density of capillary vessels, and there were also more numbers of capillaries in skeletal muscles if they were of high activity [65]. Therefore, sufficient VO2 max is essential for optimal athlete performance [66]. Traditional methods such as long slow distance and fartlek are commonly employed by badminton coaches to enhance aerobic fitness [67].

Recent studies have demonstrated that high-intensity functional interval training and sprint interval training significantly improve badminton players'VO2 max compared to regular exercise [29, 68]. The combination of high-intensity interval training with functional exercises has garnered international recognition [69, 70]. Functional training refers to specialized training tailored to athletes'specific performance improvement goals in their respective sports [67, 71]. Sprint interval training is recommended as an alternative to traditional continuous aerobic training. It involves brief, maximal effort actions with active rest periods and minimal recovery time between training sets [29]. Athletes with low overall training volume during intervals can benefit from sprint interval training, as active rest periods between multiple short, high-intensity sprint sessions typically last only 3–5 minutes [72]. As a result, these two types of training can enhance badminton players'performance in interval exercises while significantly reducing training volume.

Agility

In badminton, quick movements and rapid changes in direction necessitate brief bursts of energy. Therefore, agility plays a crucial role in the success of players [73–75]. Effective agility performance relies on various factors and inputs, encompassing physical (strength and conditioning), cognitive (motor learning), and technical (biomechanics) components [76]. While the training methods employed by the EG in most studies showed a significant impact on badminton agility tests, meta-analysis did not reveal statistically significant differences. The substantial heterogeneity observed across the five studies in the meta-analysis is likely attributed to variations in measurement methods used to quantify agility in each study. Quantifying agility has proven challenging due to the sport-specific demands of different activities, including controlling the badminton shuttlecock or swinging the racket [74].

Agility tests often involve intricate movements, making it unclear what exactly is being measured, and a high score may conceal deficiencies in other aspects of agility [74]. According to Sheppard & Young, there remains no consensus among sports scientists regarding the definition of agility [76]. Traditionally, agility has been defined as speed in changing direction [77, 78]. However, more recent perspectives suggest that agility requires perceptual skills in addition to the ability to change direction quickly, making it a complex interplay of various fitness-related factors [76, 79]. Young et al. affirmed that agility is a closed motor skill that can be planned and executed in a stable environment, challenging the previously held notion of its flexibility [80]. Nonetheless, agility involves rapid whole-body movements triggered by specific stimuli, as noted by Sheppard and Young [76].

Various agility tests, including the burpee test (squat thrust), side step test, shuttle run, quadrant jump, SEMO agility test, right boomerang run, Illinois agility run, and 505 agility test, are utilized [74, 81]. Some researchers argue that each sport necessitates unique measurement tools to assess agility [77, 82–85]. However, for badminton, there is currently no authoritative or standardized agility measurement method [86].

Power

Badminton players are required to process a significant amount of information rapidly, with little time between learning and action [87]. It appears that explosive power training may offer a solution to enhancing reaction time [88, 89]. As far as we know, data on the performance enhancement mechanisms of power athletes at the muscle cell level is unavailable. However, power training can selectively hypertrophy fast-twitch muscle fibers, potentially maximizing growth adaptations before they gradually thin out [90, 91]. When Ooi et al. investigated the physiological characteristics of elite and sub-elite badminton players, they discovered significant differences in power between the two groups [92].

The results of lower-limb resistance exercise and core training, as observed in the two studies reviewed, exhibited superior effects compared to routine exercise. Given the paramount importance of power fitness in athletes, which directly impacts efficiency, it is logical that both studies employed jump tests to assess badminton players'power quality. The dynamic nature of badminton, characterized by rapid direction changes, leaps, lunges at the net, swift arm movements, and various short, explosive motions, underscores the relevance of such tests [93].

Moreover, research indicates that athletes participating in functional training programs perform better on vertical countermovement jump tests [94, 95]. However, there is currently limited research available on methods to enhance badminton players'jumping ability, necessitating further investigation to validate this hypothesis.

Balance

Balance is the process of keeping the body's center of gravity vertically aligned over the base of support. It depends on rapid, continuous feedback from visual, vestibular, and somatosensory systems, followed by the execution of smooth and coordinated neuromuscular actions [96]. In badminton, rapid changes in direction, leaps, forward lunges, quick arm movements, and various postural adjustments are all essential [93]. Therefore, proficient balance is crucial for badminton players to execute swift postural transitions on the court effectively [97]. Reviewing the literature reveals a predominant focus on how badminton players'balance is influenced. Our research substantiates the efficacy of Swiss ball training, core stability training, combined balance and plyometric training, balance training, and core strength training. When compared to routine exercises, these interventions enhance badminton players'balance.

Previous studies have demonstrated that fatigue in trunk muscles leads to diminished dynamic stability and loss of balance control [98–101]. Swiss ball training, core stability training, combined balance and plyometric training, balance training, and core strength training contribute to improving dynamic balance and muscle coordination between the lower and upper limbs. Additionally, they help reduce the risk of injury and muscle imbalance, thereby enhancing athletes'balance [27]. The crucial role of core muscles in balance serves as a logical explanation for this phenomenon. The core comprises the diaphragm as the roof, pelvic floor and hip girdle musculature as the bottom, erector spinae and gluteal muscles as the back, and the abdominals as the front [102]. During lower and upper extremity exercises such as running, throwing, and jumping, the core muscles stabilize the spine and trunk, leading to improved balance among badminton players.

Reactive strength index

According to previous research, among all physical abilities, the most reliable predictor of badminton excellence is change of direction performance ($r = 0.74$) [103]. Therefore, optimizing this capacity is crucial for enhancing on-court performance among badminton players. To date, several change of direction ability tests, including the Hexagon test, 5–0–5 test, and Modified SEMO test, have been extensively utilized for badminton assessment [27, 104, 105], proving to be reliable indicators of players'on-court performance [24].

Young assessed the ability of muscles to transition from eccentric to concentric contractions during jumping and developed the Reactivity Intensity Index [106]. Reactive strength refers to an individual's ability to effectively utilize the stretch–shortening cycle, characterized by the capacity of the musculotendinous unit to generate a rapid and powerful concentric contraction immediately after a quick eccentric action [107]. The reactive strength index is calculated by dividing jump height by contact time during a drop jump [108]. In the study conducted by Guo et al. [24], participants underwent tests to assess their change of direction ability, including the 5–0–5 test, Southeast Missouri test, Y-Balance test, and reactive strength index, before and after the training session. Following the intervention, significant time × group interactions were observed for the 5–0–5 change of direction test, Y-Balance test for both legs, and reactive strength index, as indicated by repeated-measures ANOVA ($p <$ 0.05, partial η^2 = 0.26–0.58) [24]. Conversely, another study utilizing reactive strength index measurement showed the opposite effect [32].

Based on previous research, enhancing reactive strength index can be achieved by increasing jump height and reducing contact time. Meta-analysis conducted by Rebelo et al. [109]. Revealed that both long-term [110] and short-term [111, 112] resistance training elevate reactive strength index in teenagers, although its impact is less pronounced among experienced adult athletes.

Smash

Smash strokes often determine the outcome of a game, and they are likely the most frequently utilized strokes among younger players. The effectiveness of a smash stroke primarily hinges on accuracy and smash velocity [59]. Only one study has shown that core strength training enhances spiking ability. The badminton smash ranks among the most powerful techniques in all racket sports [113]. Speeding up and controlling the rhythm of the game are essential for gradually reducing the reliance on high balls. Accelerating the match's pace and bolstering the offensive play enhance the game's enjoyment and contribute to winning strategies [114, 115]. To create subsequent offensive opportunities, it is crucial to execute accurate and strategic kills, directly scoring points [115, 116]. The speed at which badminton players strike the shuttlecock often correlates with their success [61]. Implementing strength training is therefore essential to enhance their striking speed [117]. Targeted training programs significantly improve muscular power, allowing players to execute more forceful and faster shuttlecock strikes [16]. This increase in strength directly contributes to enhanced smash performance [118]. Consequently, integrating power-focused exercises into training regimens is crucial for optimizing smash effectiveness and overall game performance. Therefore, additional evidence regarding the impact of various training methods on badminton players'smash abilities is warranted.

Limitations

This systematic review, which adhered to PRISMA reporting guidelines. It ensures an unbiased evaluation of quality and offers pertinent data regarding the efficacy of different training methods. However, there are a number of limitations to this study, chief among them being the following five points.

1) Finding trustworthy measuring instruments is essential because the wide variation in the instruments used to evaluate each performance compromises the comparability of study results.
2) Certain studies don't provide a thorough explanation of the training program, and they omit some crucial details that could compromise the description's accuracy.
3) This meta-analysis includes studies with small sample sizes, which may lead to less robust conclusions and potential biases. Most studies in this review used small sample sizes (8–20 participants per experimental group), and only two studies disclosed how their sample sizes were calculated [26, 33].
4) Owing to the significant variations in intervention techniques across various studies, this analysis only included the majority of routine exercise (traditional training, normal training, conventional training) intervention studies for the study's CG. There was insufficient evidence for analysis in the CG of other kinds of intervention studies according to a meta-analysis [22–24].
5) This systematic review includes several multi-arm studies, which may result in statistical dependency issues. Future research should consider using multilevel or multivariate meta-analysis methods to address this problem and provide more accurate and unbiased effect size estimates.

Conclusion

Our review has found that high-intensity interval training and sprint interval training can improve VO2 max in badminton players. Additionally, high-intensity interval training, core training, strength and resistance training, and Pilates can enhance agility. Core training and lower limb resistance training can improve power, while balance training, core training, Pilates, and balance enhancement training can improve balance. Furthermore, balance enhancement training can improve the reactive strength index, and core training can enhance smash performance in badminton players. Overall, these findings highlight the importance of incorporating diverse training methods to optimize various physical performance metrics in badminton players. The meta-analysis showed that current studies are more effective than routine exercises in improving VO2 max, agility, and balance in badminton players. However, further high-quality methodological studies are needed to customize specific training programs for healthy badminton players. Coaches should tailor training programs based on skill levels, while considering frequency and intensity for optimal results. To address the identified gaps, future studies should focus on more standardized research designs, such as randomized controlled trials, to evaluate the long-term effects of these training methods on performance and injury prevention.

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Publication bias
To assess potential publication bias, we performed Egger's test. The results indicated no significant evidence of publication bias, suggesting that the available evidence is representative of all conducted studies.

Authors' contributions
Conceptualization: Shuzhen Ma. Data curation: Shuzhen Ma, Xijie Shi, and Min Sun. Investigation: Shuzhen Ma,Fan Xu. Methodology: Shuzhen Ma, Huange Liu, Jing Li. Supervision: Shuzhen Ma. Writing – original draft: Shuzhen Ma and Kim Geok Soh. Writing – review & editing: Weijia Xue and Xinzhi Wang.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
All studies included in this systematic review and meta-analysis are assumed to have received ethical approval from their respective institutional review boards or ethics committees.

Consent for publication
Not Applicable.

Competing interests
The authors declare no competing interests.

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