Heliyon 10 (2024) e28051

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effects of plyometric training on skill-related physical fitness in badminton players: A systematic review and meta-analysis

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ARTICLE INFO

Keywords:
Plyometric exercise
Stretch-shortening cycle
Physical fitness
Badminton

ABSTRACT

Skill-related physical fitness significantly correlates with sports performance. Plyometric training (PT) is an effective method for improving physical fitness in athletes. However, its impact on skill-related physical fitness in badminton players remains uncertain. Therefore, this systematic review and meta-analysis aimed to evaluate the effectiveness of PT on skill-related physical fitness in badminton players. Five electronic databases (Web of Science, PubMed, SCOPUS, MEDLINE, and SPORTSDiscus) were searched until February 2024. A PICOS approach was used to identify inclusion criteria, (1) healthy badminton players, (2) a PT program, (3) an active control group, (4) a measure of skill-related physical fitness before and after PT, and (5) randomized controlled studies. The PEDro scale was used to assess the methodological quality of PT studies, while the level of evidence certainty was determined through the GRADE framework. The calculation of effect sizes (ESs) was based on mean values and standard deviations, and heterogeneity was measured with the I^2 statistic. The extended Egger's test was employed to check for publication bias. Eleven studies comprising 445 badminton players were eligible for inclusion. The analysis revealed significant small-to-moderate effects of PT on power (ES = 0.60, $p < 0.001$), agility (ES = 0.96, $p < 0.001$), speed (ES = 0.63, $p = 0.001$), and balance (ES = 0.89; $p = 0.013$). However, no significant effect was observed for reaction time (ES = 0.56; $p = 0.189$). The certainty of evidence for outcomes was graded as either low or very low. In conclusion, our findings demonstrate that PT improved power, agility, speed, and balance, but not reaction time in badminton players. However, the small number of studies and the very low to low certainty evidence mean that these results need to be interpreted with caution.

1. Introduction

Badminton has become one of the most popular sports worldwide, attracting participants of all ages and skill levels [1]. Badminton is a complex, physically enduring sport that requires a blend of intelligent game tactics, excellent technical skills, specific physiological fitness, and thorough psychological preparation [2]. More crucially, players require robust physical fitness to engage their skills during high-speed and high-intensity matches [3]. Skill-related physical fitness refers to an individual's ability to compete in sports, which is tied to motor skills [4]. This fitness category includes speed, power, agility, balance, reaction time, and coordination [5]. Experts agree

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https://doi.org/10.1016/j.heliyon.2024.e28051
Received 1 September 2023; Received in revised form 10 March 2024; Accepted 11 March 2024
Available online 15 March 2024

that skill-related physical fitness components play a significant role in winning matches in badminton. Specifically, badminton players need to execute a variety of movements to meet the demands of the game. These movements include rapid acceleration and deceleration, quick changes of direction over short distances, and explosive movements of the upper and lower limbs [2]. In this regard, strength and conditioning programs designed for badminton typically emphasize the development of power, agility, and speed attributes [6–8]. It is worth mentioning that the forehand smash is an effective way of scoring in badminton, accounting for 54% of "unconditional win" and "forced failure" strokes in international competitions [9]. The jumping ability has been recognized as a pivotal factor affecting the smash performance in badminton players [8]. Moreover, stroke play and footwork performance stand out as two essential aspects of badminton [10]. Stroke play is notably impacted by eye-hand coordination, while footwork relies primarily on maintaining balance [10]. Furthermore, the rapid return of the shuttlecock in under 1 s demands swift cognitive processing and quick reactions to stimuli during gameplay [11]. Overall, strategies aiming to improve badminton players' skill-related physical fitness are fundamental to optimizing their performance during games.

One such strategy is plyometric training (PT), characterized by the combination of lengthening (eccentric contraction) of the muscle-tendon unit with subsequent shortening (concentric contraction), also known as the stretch-shorten cycle (SSC) [12]. Scientific studies indicate that PT has benefits in enhancing physical fitness components (e.g., muscle strength, balance, and sprint speed) regardless of sex, age, or training expertise [13–16]. Previous analyses have thoroughly investigated and reported on the underlying mechanisms of SSC (e.g., stretch reflex, and elastic energy) and its ability to enhance athletic performance [17–19]. These analyses revealed that PT triggers a variety of biomechanical and physiological adaptations, such as the inhibition and activation of muscle fibers, as well as alterations in motor unit recruitment [18,20]. From a practical standpoint, PT-induced neuromuscular adaptations should have potentially positive effects in sports such as badminton, which involve extensive movements (e.g., jumps, quick changes in direction) analogous to PT drills [21,22].

A great number of systematic reviews and meta-analyses have provided evidence for the efficacy of PT in enhancing physical fitness among athletes across various sports disciplines such as tennis [23], soccer [24], volleyball [25], handball [26], and basketball [17]. However, to our knowledge, no systematic review and meta-analysis have addressed the effects of PT on skill-related physical fitness in badminton players. Given the absence of a comprehensive analysis regarding PT's effects on player fitness in badminton and recognizing its significant practical relevance in the sport, this meta-analysis aims to evaluate the effects of PT on skill-related physical fitness in badminton players compared to control conditions.

2. Materials and methods

The research team followed the updated PRISMA statement throughout this review [27]. This systematic review and meta-analysis was preregistered (registration number: CRD42023431190) at the International Prospective Register of Systematic Reviews (PROSPERO).

2.1. Search strategy

An extensive literature search was carried out through electronic databases, including Web of Science, PubMed, SCOPUS, MEDLINE, and SPORTDiscus. The search encompassed articles published from the inception of these databases until February 2, 2024. The Boolean operations AND and OR were applied to comprehensively search the topic. We used the following Boolean search syntax: ("plyometric training" OR "ballistic training" OR "jump training" OR "plyometric exercise*" OR "power training" OR "stretch-shortening cycle" AND "physical fitness" OR "physical performance" OR "skill-related physical fitness" OR "agility" OR "change of direction" OR "balance" OR "coordination" OR "power" OR "jump" OR "speed" OR "sprint" OR "reaction time" AND "badminton" OR "shuttlecock"). Moreover, our research team conducted manual searches on ResearchGate and Google Scholar, as well as in the reference sections of the identified publications, to ensure the inclusion of all relevant studies. The detailed search strategy can be found in the Supplementary Material Appendix A.

Table 1
Selection criteria used in the meta-analysis.

Category	Inclusion criteria	Exclusion criteria
Population	Healthy badminton players, with no restrictions on their sex, age, or competition level	Participants with health problems (e.g., injuries, recent surgery)
Intervention	Programs based on the plyometric training approach considering the use of lower and upper body, unilateral or bilateral bounds, jumps, throws, and hops that commonly utilize a pre-stretch or countermovement potentiating of the stretch-shortening cycle	Exercise interventions not involving plyometric training or the plyometric training intervention mixed with other training drills (e.g., weight training, balance training) Interventions shorter than two weeks
Comparator	Active control group	Absence of active control group
Outcome	At least one measure of physical fitness (e.g., jump height, sprint speed) before and after the training intervention	Lack of baseline and/or follow-up data
Study design	Randomized controlled study	Non-randomized controlled study

2.2. Eligibility criteria

The eligibility of studies was assessed using a PICOS framework [28]. Table 1 outlines the criteria for inclusion and exclusion utilized in our meta-analysis. We only consider original full-text peer-reviewed publications, excluding other forms of documents (e.g., conference papers, letters, and book chapters). Notably, an evidence-based decision [29,30] was made to determine the minimal effective PT length (i.e., ≥ 2 weeks) for improving physical performance. Additionally, considering the difficulty of translation and the predominance of English literature on PT [29], only publications written in English were selected in this meta-analysis.

2.3. Study selection and data collection process

Before selecting articles for inclusion, retrieved publications underwent a duplication check using a specialized tool (EndNote X9 for Windows, Clarivate Analytics). Following the elimination of duplicates, the titles of the remaining articles were reviewed, followed by an assessment of the information provided in the article abstracts, and finally, a comprehensive analysis of the full text of the published papers. The process was carried out independently by two researchers (ND and DH). Potential disagreements between the two researchers were settled by consensus. The reasons for excluding full-text articles were documented. The information extracted from the articles was entered into a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA).

2.4. Data items

As dependent variables, skill-related physical fitness attributes assessed in selected papers were extracted: power (e.g., jump height); agility (e.g., Illinois test); speed (e.g., 10–30 m sprint); balance (e.g., Y balance test); reaction time (e.g., visual-motor reaction time test); and coordination (e.g., wall-toss test). Moreover, the extracted data encompassed participant details such as age, gender, sample size, competition level, and sports experience. Furthermore, data on PT characteristics included training length, frequency, time, and exercise type.

2.5. Methodological quality of included studies

The methodological quality of the publications was evaluated using the PEDro scale [31,32]. The PEDro scale comprises 11 items, with the first item not being scored. Hence, the scoring range for the scale is from 0 to 10, where 0 represents the lowest score and 10 represents the highest. In agreement with previous PT-related meta-analyses [33,34], the criteria for quality assessment were interpreted as follows: studies with a score of ≤3 were classified as having poor quality, those with a score of 4–5 were deemed to be of moderate quality, and those with a score of 6–10 were considered to be of high quality. Two assessors (ND and DH) independently evaluated the methodological quality of selected papers. Any discrepancies in their evaluations were settled through discussions and consensus involving a third author (KGS).

2.6. Certainty of evidence

The Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) approach was utilized to aid in synthesizing and verifying the certainty of evidence regarding the limitations found in the studies (e.g., bias risk, indirectness, and imprecision) [35–38]. Two assessors (ND and DH) conducted the assessment of evidence certainty. The results of this assessment were subsequently verified by experts in our research team (KGS and BBA). Any differences of opinion were resolved through additional discussion within the team.

2.7. Statistical analyses

According to the guidelines in the Cochrane Handbook [39], it is possible to conduct meta-analyses with a minimum of two studies [40]. Therefore, we opted to perform meta-analyses in cases where two or more documents provided data related to the mentioned fitness outcomes. The effect size (ES; Hedges' g) was calculated using the means and standard deviations of pre- and post-intervention fitness results for both the PT and control groups. Post-intervention standard deviation values were utilized for data standardization. To account for variations across trials that could affect the PT effects, the random-effects model was employed [39,41]. The ES values are displayed with their respective 95% confidence intervals (95% CIs). These ESs were interpreted according to the following scale: <0.2 trivial, 0.2–0.6 small, >0.6–1.2 moderate, >1.2–2.0 large, >2.0–4.0 very large, >4.0 extremely large [42,43]. When authors did not provide sufficient data (either absent or presented graphically), we courteously reached out to the corresponding author to request the necessary information. If the data were only shown in graphs without corresponding numerical values in the text or tables, and the authors did not reply to our inquiries, we employed a validated online tool (WebPlotDigitizer) ($r = 0.99$) [44], to extract data from the figures. The I^2 statistic was used to assess heterogeneity, with values categorized as follows: >25% low, 25–75% moderate, and >75% high [45]. Egger's test evaluated whether bias risk existed [46]. If Egger's test produced a significant outcome, a sensitivity analysis was conducted. The threshold for statistical significance was set at $p < 0.05$. All analyses were conducted utilizing the Comprehensive Meta-Analysis software (version 3; Biostat, Englewood, NJ, USA).

3. Results

3.1. Results of the search

As shown in Fig. 1, five databases yielded a total of 750 papers, and a search on Google Scholar, ResearchGate, and references yielded 15 additional studies. Following the screening process, eleven papers were found to fully align with the inclusion criteria set for the systematic review and meta-analysis.

3.2. Methodological quality

Table 2 displays the results of the methodological quality evaluation conducted using the PEDro scale. Nine studies were deemed to have "moderate" quality, with ratings of 4 or 5. The methodological quality of two other studies was deemed "high", with ratings ranging from 6 to 10 points.

3.3. Certainty of evidence

Table 3 outlines the results of the GRADE analyses. Following the GRADE evaluation, the certainty of the evidence for the outcomes was categorized as either low or very low.

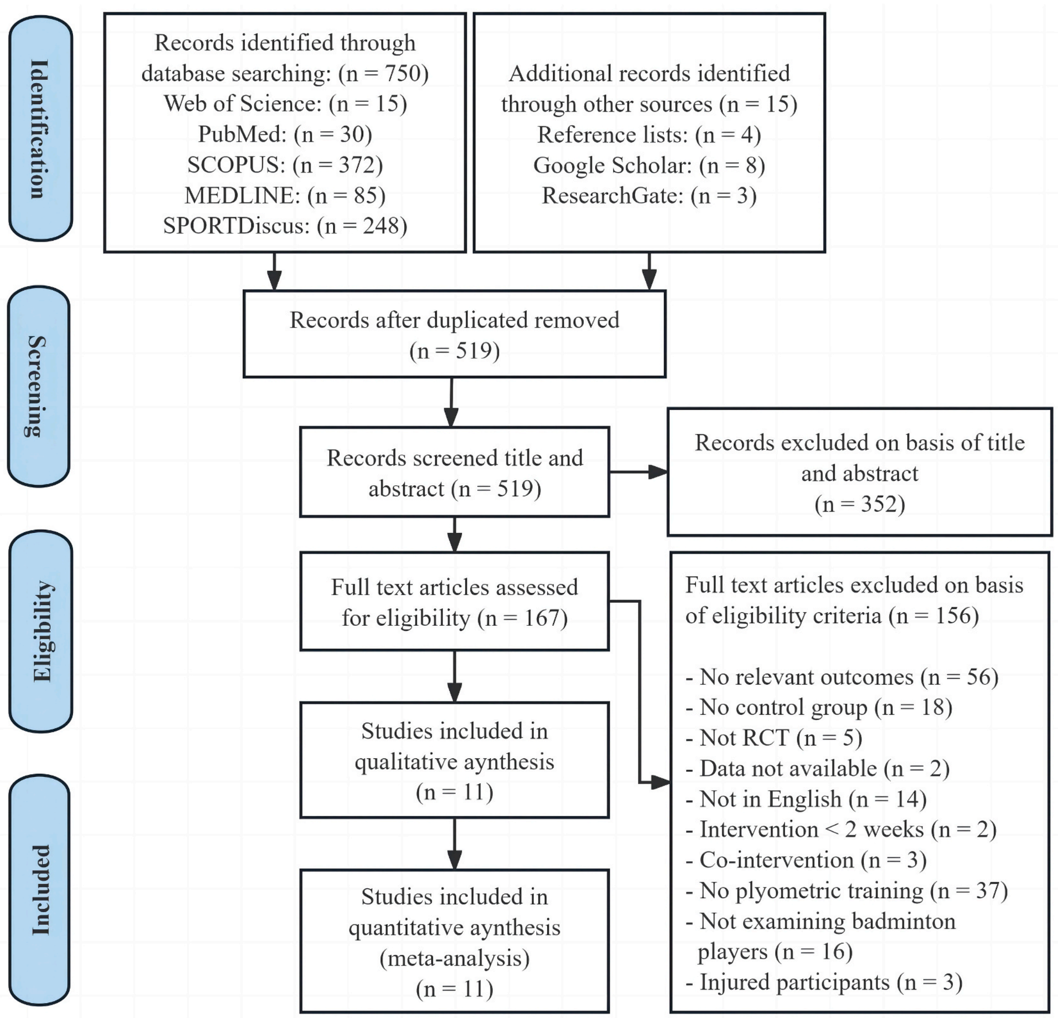


Fig. 1. PRISMA flow diagram.

Table 2
Physiotherapy Evidence Database (PEDro) scale ratings.

Study name	N° 1	N° 2	N° 3	N° 4	N° 5	N° 6	N° 7	N° 8	N° 9	N° 10	N° 11	Total[a]	Study quality
Heang et al., 2012 [47]	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
Özmen & Aydoğmuş, 2017 [48]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Alikhani et al., 2019 [49]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Narang & Patil, 2021 [50]	0	1	0	1	0	0	0	1	1	1	1	6	High
Panda et al., 2022 [51]	1	1	0	1	0	1	1	1	1	1	1	8	High
Chou, 2022 [52]	0	1	0	1	0	0	0	1	1	0	1	4	Moderate
Albayati et al., 2022 [53]	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
Chandra et al., 2023 [54]	1	1	0	1	0	0	0	1	1	1	1	5	Moderate
Walankar & Shetty, 2023 [55]	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
Sawant, 2023 [56]	0	1	0	1	0	0	0	1	1	0	1	5	Moderate
Low et al., 2023 [57]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate

Note: A detailed explanation for each PEDro scale item can be accessed at https://www.pedro.org.au/english/downloads/pedro-scale.
[a] From a possible maximal punctuation of 10.

3.4. Study characteristics

The study characteristics are listed in Table 4, and the data used for the meta-analyses are presented in Supplementary Material Appendix B. There were a total of 445 participants, comprising five studies with mixed-gender participants (n = 228) [47,48,50,51,55], two studies focusing on males (n = 122) [54,56], and one study concentrating on females (n = 22) [49]. The participants' ages ranged between 10.14 and 25 years. Six studies targeted adults [47,49,50,52,54,57], two focused on youth players [48,53], and three encompassed both adults and youth players [47,52,54,56,57]. Regarding the expertise level of badminton players, five studies involved college or university athletes [47,52,54,56,57], two studies included players from local sports clubs [49,50], one study categorized participants as state-level players [51], and one study recruited amateur athletes [55]. However, two studies did not provide information on the participants' expertise level [48,53]. Furthermore, eight studies reported participants' badminton experience ranging from one to seven years [47–51,54,55,57], while three studies omitted this information [52,53,56]. The length of PT ranged from 3 to 12 weeks, with a weekly frequency varying from one to four sessions. Among the selected papers, seven indicated that session durations lasted between 20 and 90 min, while four papers lacked information on the duration of sessions. A detailed description of PT protocols can be found in Supplementary Material Appendix C.

3.5. Meta-analysis results

3.5.1. The effect of PT on power

Data from nine studies were collected to analyze power performance (pooled n = 320). The results revealed a significant small

Table 3
Certainty of evidence for meta-analyzed outcomes.

Outcomes	Certainty assessment					No of participants and studies	Certainty of evidence (GRADE)
	Risk of bias	Inconsistency	Indirectness	Imprecision	Risk of publication bias		
Power follow-up: range 3–12 weeks	Serious[a]	Not serious	Not serious	Serious[c]	Serious[f]	320 (9 RCTs)	⨁◯◯◯VERY LOW
Agility follow-up: range 3–12 weeks	Serious[a]	Serious[b]	Not serious	Serious[c]	Not serious	302 (8 RCTs)	⨁◯◯◯VERY LOW
Speed follow-up: range 3–12 weeks	Serious[a]	Not serious	Not serious	Serious[c]	Not serious	216 (5 RCTs)	⨁⨁◯◯LOW
Reaction time follow-up: range 6–12 weeks	Serious[a]	Not serious	Not serious	Serious[c]	Not serious	78 (3 RCTs)	⨁⨁◯◯LOW
Balance follow-up: 6 weeks	Serious[a]	Not serious	Not serious	Serious[c]	None	46 (2 RCTs)	⨁⨁◯◯LOW

GRADE, Grading of Recommendations Assessment, Development and Evaluation; RCT, randomized controlled trial.
GRADE Working Group grades of evidence High certainty: we are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: we are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect.
Very low certainty: we have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.
[a] Downgraded by one level due to average PEDro score being moderate (<6).
[b] Downgraded by one level due to high impact of statistical heterogeneity (>75%).
[c] Downgraded by one level, as $\geq$ 800 participants were available for a comparison but there was an unclear direction of the effects.
[f] Downgraded by one level (Egger's test <0.05).

Table 4
Characteristics of the studies examined in the present review.

Study	Population characteristics				Intervention	Comparator	Test (s)	Outcome (s)
	Sex	n	Age	Level/Exp				
Heang et al., 2012 [47]	Mixed (15 M/ 27F)	42	18–20 yrs	College EG: 2.0 ± 1.4 yrs CG: 1.4 ± 0.8 yrs	Freq: 1 time/ week Time: NR Length: 6 weeks	EG: Plyometric training + college co-curriculum programme CG: College co-curriculum programme	Agility (Illinois test)	Illinois test ↑
Özmen & Aydoğmuş, 2017 [48]	Mixed (9 M/ 11F)	20	12.5 ± 0.2 yrs	NR At least 2 yrs	Freq: 2 times/week Time: NR Length: 6 weeks	EG: Plyometric training CG: Routine training	Agility (Illinois test), power (SJ)	Illinois test ↑ SJ ↑
Alikhani et al., 2019 [49]	F	22	EG: 22.00 ± 1.30 yrs; CG: 22.00 ± 0.84 yrs	Club ≥3 yrs	Freq: 3 times/week Time: 20 min Length: 6 weeks	EG: Plyometric training CG: Routine training	Balance (Y balance test)	Y balance test ↑
Narang & Patil, 2021 [50]	Mixed	40	18–25 yrs	Clubs 1 yr	Freq: 2 times/week Time: NR Length: 8 weeks	EG: Ballistic six exercises CG: Theraband exercises	Power (MBT), reaction time (plate tapping test)	SMBT ↑ plate tapping test ↑
Panda et al., 2022 [51]	Mixed (37 M/ 8F)	90	EG1: 19.06 ± 1.33 yrs; EG2: 18.26 ± 1.09 yrs; CG: 17.5 ± 0.52 yrs	State-level ≥2 yrs	Freq: 2 times/week Time: 35 min Length: 4 weeks	EG1: Plyometric training EG2: Electromyostimulation training CG: Routine training	Agility (*t*-test), speed (30 m), power (VJ)	T-test ↑, 30 m ↑, VJ ↑
Chou, 2022 [52]	NR	16	19.8 ± 3.34 yrs	College NR	Freq: 3 times/week Time: 60–90 min Length: 8 weeks	EG: Plyometric training + regular training CG: Regular training	Power (VJ), speed (30 m), agility (6 × 4-m shuttle run)	VJ ↑, 30 m ↑, 6 × 4-m shuttle run ↑
Albayati et al., 2023 [53]	NR	21	EG:13.43 ± 0.53 yrs; CG:13.14 ± 0.69 yrs	NR	Freq: 3 times/week Time: 25–30 min Length: 12 weeks	EG1: Core training EG2: Plyometric training CG: Elastic resistance training	Power (VJ), agility (*t*-test), speed (10 m), reaction time (reaction test)	VJ ↑, *t*-test↑, 10 m↔, reaction test↔,
Chandra et al., 2023 [54]	M	102	18–25 yrs	College ≥3 yrs	Freq: 2 times/week Time: 20 min Length: 3 weeks	EG: Plyometric training CG: Routine training	agility (*t*-test), speed (30 m), power (SBJ)	T-test ↑, 30 m ↑, SBJ ↑
Walankar & Shetty, 2023 [55]	Mixed (20F/ 16 M)	36	EG1: 17.4 ± 2.8 yrs; EG2: 16.9 ± 2.9 yrs; CG:18.9 ± 2.3 yrs	Amateur EG1: 5.8 ± 3.2 yrs EG2: 6.6 ± 3.9 yrs CG: 6 ± 3.6 yrs	Freq: NR Time: 20–30 min Length: 6 weeks	EG1: Plyometric training + regular training CG: Speed agility quickness CG: Regular training	Agility (Illinois test), balance (mSEBT), Speed (30 m), reaction time (visual reaction time task)	Illinois test ↑, mSEBT ↑,30 m ↑, visual reaction time task↑
Sawant, 2023 [56]	M	20	17–19 yrs	College NR	Freq: 4 times/week Time: 90 min Length: 6 weeks	EG: Plyometric training CG: Regular training	Power (VJ, MBT)	VJ ↑, MBT ↑
Low et al., 2023 [57]	NR	36	EG1: 20.75 ± 1.14 yrs; EG2: 20.42 ± 1.31 yrs; CG: 20.67 ± 1.15 yrs	University At least 4 yrs	Freq: 2 times/week Time: NR Length: 4 weeks	EG1: Flywheel eccentric overload training + regular training EG2: Plyometric training + regular training CG: Regular training	Power (CMJ), agility (badminton specific agility test)	CMJ ↑, badminton specific agility test ↑

M, male; F, female; Freq, frequency; reps, repetitions, NR, not reported; yrs, years; Exp, sport experience; EG, experimental group; CG, control group; mSEBT, modified star excursion balance test; VJ, vertical jump; SBJ, standing broad jump; CMJ, countermovement jump; SJ, squat jump; MBT, medicine ball throw; ↑, significant within-group improvement; ↔, non-significant within-group.

effect of PT on power performance (ES = 0.60; 95% CI = 0.34–0.86; $p < 0.001$; I^2 = 18.74%; Egger's test p = 0.550; Fig. 2).

3.5.2. *The effect of PT on agility*

Data from eight studies were collected to analyze agility performance (pooled n = 302). The results indicated a significant moderate effect of PT on agility performance (ES = 0.96; 95% CI = 0.45–1.47; $p < 0.001$; I^2 = 75.41%; Egger's test p = 0.905; Fig. 3).

3.5.3. *The effect of PT on speed*

Data from five studies were collected to analyze speed performance (pooled n = 216). Egger's test yielded a p = 0.005. After conducting a sensitivity analysis, we excluded one article [54], which resulted in Egger's test yielding a p-value ≥0.05. As a consequence, four studies were finally included. PT showed a significant moderate impact on speed performance (ES = 0.63; 95% CI = 0.26–0.99; p = 0.001; I^2 = 0.00%; Fig. 4).

3.5.4. *The effect of PT on reaction time*

Data from three studies were collected to analyze reaction time performance (pooled n = 78). The results revealed a small effect of PT on reaction time performance (ES = 0.56; 95% CI = −0.29–1.41; p = 0.198; I^2 = 70.21%; Egger's test p = 0.168; Fig. 5).

3.5.5. *The effect of PT on balance*

Data from two studies were collected to analyze balance performance (pooled n = 46). The results indicated a significant moderate effect of PT on balance performance (ES = 0.89; 95% CI = 0.19–1.59; p = 0.013; I^2 = 29.10%; Fig. 6). Since there were only two studies, an Egger's test was impossible.

4. Discussion

This study represents the inaugural meta-analysis to explore the impact of PT on badminton players. The findings showed that PT significantly improved essential components of skill-related physical fitness (i.e., power, agility, speed, balance). However, no substantial changes were observed in reaction time. The heterogeneity in findings ranged from low to high (I^2 = 0.00%–76.67%). Furthermore, the GRADE analysis revealed that the certainty of evidence for the assessed outcomes ranged from very low to low.

4.1. *The effect of PT on power*

Badminton is a sport that places high demands on an athlete's muscular power, enabling them to execute quick and powerful movements [58]. This meta-analysis found that PT induced significant improvements in the power of badminton players (ES = 0.60, small). The findings of several previous meta-analyses further reinforce this perspective, as they demonstrate substantial and practically relevant increases in power induced by PT in soccer [24], basketball [17], and volleyball players [25]. Moreover, the increase in muscle power induced by PT supports several studies in racket sports [59,60]. The observed gains in muscle power could have been caused by a number of muscular adaptations, such as changes in muscle size and/or architecture, and variations in muscle-tendon mechanical stiffness characteristics [61–64]. Other potential neural adaptations resulting from PT include changes in the excitability of the stretch reflex and modifications in strategies for activating leg muscles during vertical jumps, especially in the pre-landing phase [18,61,65]. Notably, jump abilities are the main muscle power testing method in this review. Enhancing badminton players' jumping skills is crucial to their athletic performance and competition outcomes [66]. For example, players with greater jump heights are emblematic of heightened capabilities and often exhibit enhanced shuttlecock speeds [67]. This attribute also operates as a tactical

Study name	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ozmen & Aydogmus, 2017	1.273	0.473	0.224	0.345	2.201	2.690	0.007
Narang & Patil, 2021	0.265	0.311	0.097	-0.345	0.876	0.852	0.394
Chou, 2022	0.077	0.473	0.224	-0.850	1.004	0.164	0.870
Albayati et al., 2022	0.783	0.522	0.272	-0.240	1.806	1.500	0.134
Panda et al., 2022	0.217	0.256	0.065	-0.284	0.718	0.849	0.396
Chandra et al., 2023	0.734	0.203	0.041	0.335	1.132	3.611	0.000
Walankar & Shetty, 2023	0.956	0.418	0.174	0.137	1.774	2.289	0.022
Sawant, 2023	0.431	0.434	0.188	-0.419	1.281	0.994	0.320
Low et al., 2023	1.171	0.429	0.184	0.330	2.011	2.730	0.006
	0.600	0.131	0.017	0.344	0.856	4.596	0.000

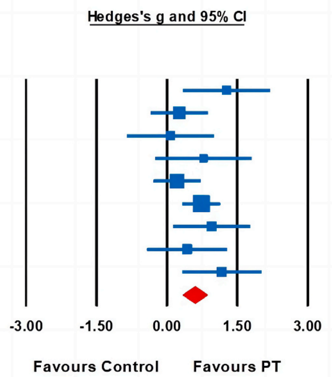
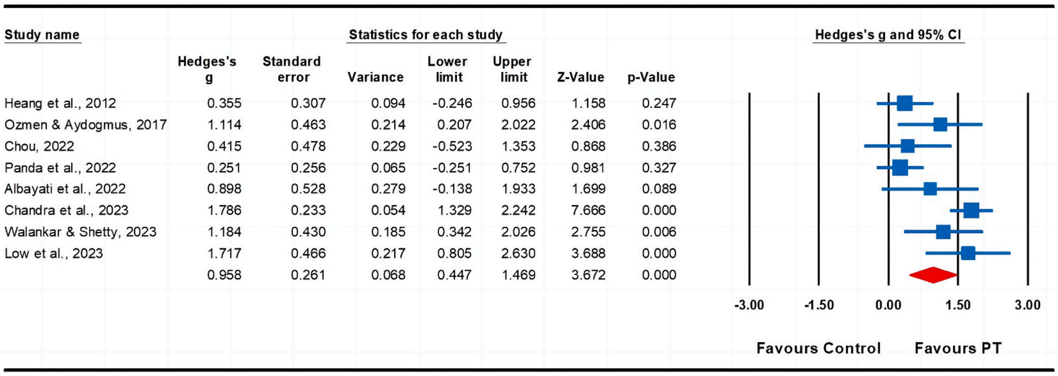
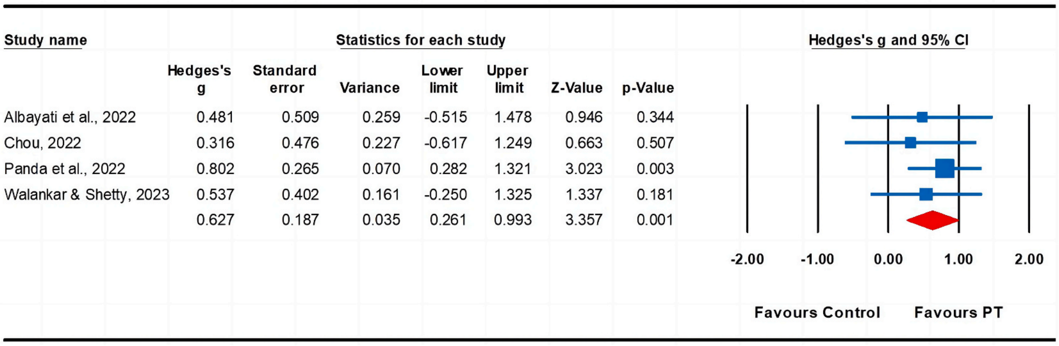


Fig. 2. Forest plot of changes in power performance in badminton players participating in training intervention compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. PT: plyometric training.



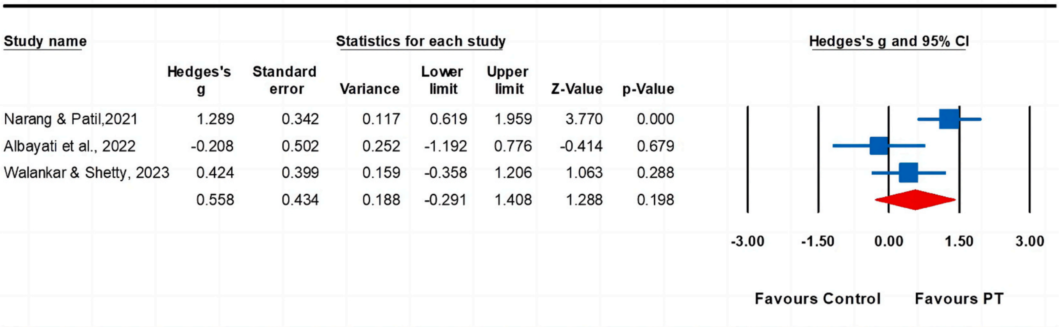
Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Heang et al., 2012	0.355	0.307	0.094	-0.246	0.956	1.158	0.247
Ozmen & Aydogmus, 2017	1.114	0.463	0.214	0.207	2.022	2.406	0.016
Chou, 2022	0.415	0.478	0.229	-0.523	1.353	0.868	0.386
Panda et al., 2022	0.251	0.256	0.065	-0.251	0.752	0.981	0.327
Albayati et al., 2022	0.898	0.528	0.279	-0.138	1.933	1.699	0.089
Chandra et al., 2023	1.786	0.233	0.054	1.329	2.242	7.666	0.000
Walankar & Shetty, 2023	1.184	0.430	0.185	0.342	2.026	2.755	0.006
Low et al., 2023	1.717	0.466	0.217	0.805	2.630	3.688	0.000
	0.958	0.261	0.068	0.447	1.469	3.672	0.000

Fig. 3. Forest plot of changes in agility performance in badminton players participating in training intervention compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. PT: plyometric training.



Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Albayati et al., 2022	0.481	0.509	0.259	-0.515	1.478	0.946	0.344
Chou, 2022	0.316	0.476	0.227	-0.617	1.249	0.663	0.507
Panda et al., 2022	0.802	0.265	0.070	0.282	1.321	3.023	0.003
Walankar & Shetty, 2023	0.537	0.402	0.161	-0.250	1.325	1.337	0.181
	0.627	0.187	0.035	0.261	0.993	3.357	0.001

Fig. 4. Forest plot of changes in speed performance in badminton players participating in training intervention compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. PT: plyometric training.



Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Narang & Patil,2021	1.289	0.342	0.117	0.619	1.959	3.770	0.000
Albayati et al., 2022	-0.208	0.502	0.252	-1.192	0.776	-0.414	0.679
Walankar & Shetty, 2023	0.424	0.399	0.159	-0.358	1.206	1.063	0.288
	0.558	0.434	0.188	-0.291	1.408	1.288	0.198

Fig. 5. Forest plot of changes in reaction time performance in badminton players participating in training intervention compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. PT: plyometric training.

element, enabling players to execute sharper smash strokes instead of merely achieving greater shuttlecock speeds [67]. Moreover, proficiency in skill-based actions among badminton players is closely linked to their explosive power in the upper limbs [68]. However, only a few investigations in our review examined the power of the upper body using a medicine ball throw test [50,56]. Consequently, further research with a specific focus on upper body power is warranted.

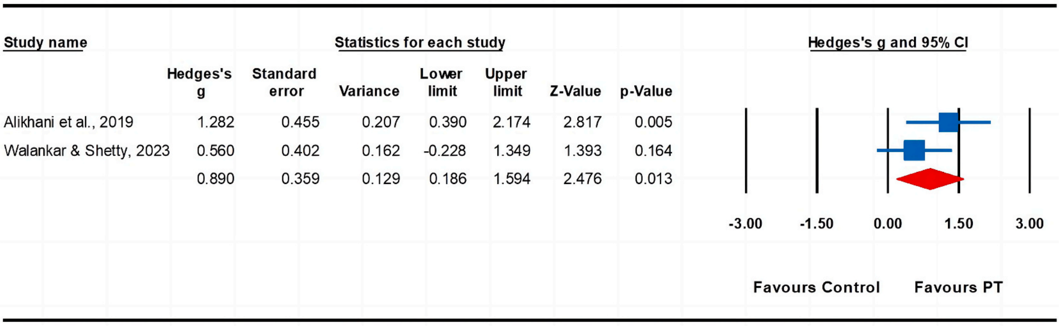


Fig. 6. Forest plot of changes in balance performance in badminton players participating in training intervention compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. PT: plyometric training.

4.2. The effect of PT on agility

Agility in footwork is a pivotal physical trait in badminton performance, forming the fundamental basis for executing precise technical skills [69]. Our meta-analysis revealed that agility performance was significantly improved after PT (ES = 0.96, moderate). This result aligns with findings from prior meta-analytic studies examining the impact of PT on agility among tennis [23], volleyball [25], and basketball players [17]. Enhancements in agility demand rapid force generation [70], and evidence indicates that PT may enhance the factor [71]. Moreover, PT may have elevated the eccentric strength of the thigh muscles, a critical element during the deceleration phase of agility [72]. Furthermore, in the context of SSC muscle function, tasks that involve changes in direction require the leg extensor muscles to quickly transition from eccentric to concentric actions [73]. Hence, it has been claimed that SSC training (e.g., PT) might improve agility performance by increasing muscle power output and maximizing movement efficiency [17]. Recently, Ramirez-Campillo and colleagues [74] found that agility is significantly influenced by the maturation stage of individuals. Those in the pre-peak height velocity stage saw greater agility improvements with PT compared to those in the post-peak stage [74]. Asadi et al. [75] conducted a meta-analysis indicating that improvements in agility are most pronounced between ages 13 to 15.9 and 16 to 18, aligning with periods of rapid physiological development. However, some trials in the present review [48,53] involved young badminton players but lacked information regarding the maturity status of their subjects. Throughout maturation and growth, a series of biological processes unfold, leading to rapid increases in stature, alterations in muscle-tendon architecture, and substantial gains in fat-free mass [76–78]. All these factors have the potential to impact a participant's responsiveness to PT. Therefore, more research is needed to investigate how PT affects agility performance, considering maturation and its underlying mechanisms.

4.3. The effect of PT on speed

Enhancing speed performance holds significant advantages for badminton players, as it improves their ability to move quickly, react effectively, and maintain pressure on opponents throughout a match [3]. Our analysis indicated a significant improvement in speed performance (ES = 0.63, moderate) following PT compared to the control group. The findings corroborate previous research suggesting that PT can enhance athletes' sprinting performance through the stretch-shortening mechanism [79–83]. Indeed, PT is highly relevant for proficient athletes requiring explosive movements, quick accelerations, and short/high-intensity sprints [84]. Several factors can contribute to enhanced sprint performance following PT, such as neural aspects (e.g., enhanced stimulation of spinal reflex pathways and heightened capacity for muscular activation) [85,86], muscular factors (e.g., augmented force per muscle fiber and expanded cross-sectional area), and adaptations within the muscle-tendon unit (e.g., increased efficiency in storing and releasing elastic energy) [18]. Moreover, a significant correlation exists between maximum sprint speed and lower extremity strength [87]. Furthermore, some research indicates that training programs placing a significant emphasis on horizontal acceleration (e.g., horizontal jumps and hops) may lead to maximal gains in speed performance [86]. A larger horizontal PT load is anticipated to provide greater benefits during initial acceleration, as horizontal force application is crucial for shorter distances (e.g., 10 m) [24,88]. Additionally, prioritizing vertical movement in PT may be advantageous for sprinting at high speeds, especially after sessions focusing on vertical exercises with faster force development and shorter ground contact times [89]. Of note, most studies included in this meta-analysis employed a combination of PT protocols, incorporating both horizontal and vertical exercises. These practices may explain observed enhancements in sprint speed among badminton players.

4.4. The effect of PT on reaction time

Reduced reaction times enable players to swiftly change direction, quickly reach their target positions on the court, and react more effectively to fastballs [79]. Scientific studies indicate that a badminton player positioned defensively only has approximately 0.1 s to respond to the opponent's attacking move [11,90]. However, our meta-analysis revealed that the reaction time of badminton players was not significantly improved after PT (ES = 0.56, small). There are various factors such as age, gender, left- or right-hand dominance, vision, fatigue, exercise, type of personality, and medical condition that influence reaction time [90]. Some experts also highlight that significant differences between athletes from different competition levels may influence their reaction times [91]. However, the conclusions of other research are in less agreement. Salonikidis & Zafeiridis [79] found that incorporating plyometric exercises into the regular training program resulted in improved reaction time in novice tennis players. Turgut and colleagues [92] observed that a twelve-week PT program notably enhanced reaction time in female volleyball players competing at the national level. Chottidao et al. [93] demonstrated that eight weeks of PT increased amateur male boxers' reaction time. Of note, the scarcity of research in the scientific literature regarding the effect of PT on reaction time makes it challenging to compare our results to previous reports. In addition, the small number of trials analyzed in this meta-analysis (n = 3) may limit our ability to reach definitive conclusions at present. Therefore, further investigation is needed.

4.5. *The effect of PT on balance*

In badminton, players must quickly shift positions for jumping, twisting, swinging, and back-and-forth motion, which requires improved balance skills [48]. The data presented in the current meta-analysis demonstrate an enhancement in balance following PT, with a moderate magnitude (ES = 0.89). Consistent with our results, a recent meta-analysis suggests that PT is effective in enhancing balance ability in healthy individuals [14]. Numerous investigations point to inadequate balance skills being a contributing factor to sports-related injuries [94–98]. Moreover, previous research emphasizes that injuries associated with badminton often affect the lower limbs as the most vulnerable area [99,100]. Furthermore, studies have demonstrated that prophylactic and post-acute physical therapy for ankle sprains can effectively reduce the likelihood of subsequent injuries [101,102]. Consequently, PT serves not only to elevate athletic performance but also to heighten the safety of the sport. Given the dynamic nature of PT, which encompasses various dynamic jump-landing activities, maintaining strong postural control is crucial for successfully executing plyometric exercises [14]. Furthermore, PT enhances muscle power, aiding in sustaining or regaining balance during sports maneuvers (e.g., a smash in badminton) [103]. Notably, some researchers have suggested integrating balance training with plyometric exercises to enhance force transmission more effectively, owing to improved postural alignment [104]. For instance, Lu et al. [105] and Guo et al. [106] found that a six-week training regimen combining balance and plyometric exercises yielded superior dynamic balance performance in elite badminton players compared to pure PT. Nonetheless, the absence of a control group in these studies renders the true impact on balance improvement somewhat unclear.

5. Limitations

Some limitations should be acknowledged. Firstly, a limited selection of studies (n = 11) was analyzed. Secondly, due to the small number of trials, the moderator impact of subgroups (e.g., players' age, sex, and training factors) on physical fitness measures could not be detected. Thirdly, coordination is an essential skill-related physical fitness component, encompassing the ability to execute rhythmically smooth and accurate movements in badminton [107]. However, no research in the present review investigated the effect of PT on badminton players' coordination performance. Future PT research should incorporate coordination performance measurements as part of badminton players' physical fitness assessments to increase the data basis on the link between skill-related physical fitness and badminton. Fourthly, no physiological maturity status was documented in any of the PT investigations, including those involving young badminton players. Given that physiological maturation can affect young athletes' responses to PT [76], future research should actively address the methodological challenges encountered in their study. Finally, some of the studies included in our review lacked full descriptions of their training protocols, such as details regarding intensity and rest periods between repetitions/sets (Supplementary Material Appendix C). To improve the overall methodological quality, future PT research should provide comprehensive explanations of all training parameters considered during interventions.

6. Practical applications

PT has demonstrated its effectiveness in enhancing power, agility, speed, and balance in badminton players. The gains we observed should attract the interest of researchers, coaches, and physical education specialists. These findings are particularly significant as badminton relies on these physical fitness factors, all of which were notably improved through the implementation of PT programs. Hence, we propose PT as a valuable training method for enhancing essential skill-related physical fitness aspects in badminton players. However, the review lacks clear dose-response data to determine optimal training parameters. As a general recommendation, coaches might consider integrating PT into the routine training of badminton players, lasting 3–12 weeks, with 1–4 sessions per week, each lasting 20–90 min. This time frame appears to offer a suitable stimulus. However, more PT studies are required to ascertain the optimal dosage for enhancing the fitness of badminton players and to gain insights into the interaction among training factors.

7. Conclusions

This systematic review and meta-analysis demonstrates that PT effectively enhances power, agility, speed, and balance among badminton players. However, no significant effects on reaction time were observed. As the report was based on a relatively small number of trials and very low to low certainty evidence, the results need to be considered with caution.

Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Nuannuan Deng: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kim Geok Soh:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Borhannudin Bin Abdullah:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Dandan Huang:** Writing – review & editing, Visualization, Validation, Software, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e28051.

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