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The impact of core training on overall athletic performance in different sports: a comprehensive meta-analysis

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Abstract

Background and objectives Despite widespread implementation of core training in athletic preparation, evidence regarding its effectiveness across different sports and performance domains remains fragmented. This meta-analysis examined the effects of core training on athletic performance across multiple sports, addressing limitations of previous analyses that focused on single sports or limited performance measures.

Methods Following PRISMA guidelines, we conducted a systematic review across five databases (PubMed, Web of Science, Scopus, SPORTDiscus, and Google Scholar). We assessed methodological quality using the PEDro scale and risk of bias using the Cochrane tool. Eligibility criteria included randomized controlled trials published between 2014–2024 involving healthy athletes aged 15–25 years, with core training as the primary intervention.

Results From an initial 1,670 records identified, 29 studies met rigorous inclusion criteria, comprising 956 athletes aged 15–23 years. Core training demonstrated significant improvements in general athletic performance (SMD = 1.38, 95% CI [0.85, 1.82], $p < 0.001$), with notably strong effects on core endurance (SMD = 1.32, 95% CI [0.57, 2.08], $p < 0.004$) and balance (SMD = 0.99, 95% CI [0.29, 1.69], $p = 0.01$). Core training revealed a moderate but insignificant effects on sport-specific performance (SMD = 0.62, 95% CI [-0.08, 1.31], $p = 0.084$). The analysis revealed non-significant effects sport-specific outcomes: speed (SMD = -0.28 [-0.86, 0.31], $p = 0.28$); maximal strength (SMD = 7.57 [-7.75, 22.89], $p = 0.27$); flexibility (SMD = 0.48 [-0.76, 1.73], $p = 0.3$); change of direction (SMD = 0.10 [-0.56, 0.76], $p = 0.69$); technical skill performance (SMD = 0.71 [-4.38, 5.81], $p = 0.75$); throwing velocity/distance (SMD = 1.52 [-0.43, 3.48], $p = 0.1$) and vertical jump height (SMD = 0.90 [-0.23, 2.03], $p = 0.1$). The high heterogeneity across outcomes ($I^2 = 37–100\%$) indicates that training responses vary substantially depending on competitive level, intervention duration, and sport-specific contexts, suggesting the need for carefully tailored core training approaches.

Conclusion This analysis demonstrates that core training effectively improves foundational athletic qualities but shows variable effects on sport-specific performance measures. The findings suggest core training should be integrated with sport-specific training for optimal performance enhancement. Future research should address the high heterogeneity observed by implementing standardized protocols and examining long-term training effects.

Keywords Core stability, Athletic performance, Strength training, Sports performance, Meta-analysis

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Introduction

Core training has emerged as a fundamental component of athletic conditioning programs across various sports disciplines. The integration of core training into athletic preparation reflects growing evidence that core stability and strength significantly influence sports performance through enhanced force transmission, improved balance, and better movement efficiency [1–3]. While implemented widely from amateur to elite levels, questions remain about optimal structure and sport-specific effects of core training programs.

In the context of athletic training, several related but distinct terms describe core-focused interventions. Core training serves as an umbrella term encompassing various exercises and protocols targeting the trunk musculature. Core stability specifically refers to the ability to control trunk position and motion over the pelvis to allow optimal production, transfer, and control of force and motion to distal segments during integrated athletic activities. Core strength, in contrast, describes the ability of the trunk musculature to generate and maintain force for spinal stability and movement production [1, 4–6].

Core training targets the muscular system responsible for trunk stability and force transfer between upper and lower extremities. This system includes both deep stabilizing muscles (transversus abdominis, multifidus, pelvic floor muscles) and superficial force-generating muscles (rectus abdominis, external obliques, erector spinae). Research indicates these muscles work synergistically to provide a stable foundation for sport-specific movements while facilitating efficient force transfer throughout the kinetic chain [7–9].

Despite widespread implementation of core training in athletic programs, evidence regarding its effectiveness shows considerable variation across different athletic populations and performance measures. While some studies demonstrate significant improvements in balance, power output, and sport-specific skills, others indicate limited transfer to athletic performance [1, 3–5, 10, 10, 11]. This inconsistency in findings appears to stem from variations in training protocols, athlete populations, and assessment methodologies.

Recent meta-analyses have provided conflicting evidence regarding core training effectiveness. Dong et al. found that while core training significantly enhanced athletes'balance and endurance, its impact on sport-specific performance measures such as power, speed, and agility showed only small effects compared to control groups [4]. Conversely, Luo et al. demonstrated that core training could improve skill performance across multiple sports, including football, basketball, swimming, and combat sports [12]. Their analysis revealed that core training optimizes force production and transfer through the kinetic chain while enhancing spinal stability and reducing energy loss during movement. However, their review did not account for important moderating variables such as competitive level and training duration.

The methodological quality of core training research also merits careful consideration. Bakbergenuly et al. highlighted meta-analyses involving heterogeneous interventions often present unique challenges in estimating between-study variance and overall effects. Their analysis demonstrated that small sample sizes are particularly problematic, and meta-analyses involving numerous small studies require especially careful methodological approaches [13]. This finding has important implications for evaluating core training studies, where sample sizes and methodological rigor vary considerably across the literature.

Recent systematic reviews have attempted to address these methodological challenges while examining core training's effectiveness. Xiao et al. conducted a comprehensive review of effects of functional training on physical and technical performance among athletes. Their findings indicated that functional core training can significantly enhance both physical capabilities and sport-specific technical performance. However, they noted that the magnitude of improvement varied considerably depending on factors such as training duration, athlete experience level, and the specific focus of training regimens [14]. This variability in outcomes emphasizes the need for more standardized approaches to both training implementation and outcome measurement.

Sport-specific analyses have further illuminated the varied effects of core training. Llanos-Lagos et al. investigated its impact on running economy, finding that high-load training and combined methods produced small to moderate improvements, while plyometric training showed positive effects [15]. Similarly, Ma et al. reported improvements in badminton players'strength, power, balance, and technical skills following core training interventions [5]. These studies highlight the sport-specific nature of core training adaptations while emphasizing the need for a more comprehensive understanding of the underlying mechanisms responsible for performance enhancement.

The varying effects of core training across different sports and skill levels point to the need for a more careful understanding of its implementation. Current evidence suggests that while core training may provide foundational benefits across various athletic populations, its optimal application likely requires sport-specific adaptations and consideration of individual athlete characteristics.

Previous meta-analyses examining core training effects have typically focused on single sports or specific performance measures. However, a comprehensive analysis of core training effects across multiple sports and performance domains, accounting for various moderating factors such as training duration, competitive level, and athlete characteristics, is lacking in the literature. Therefore, this meta-analysis aims to: (1) evaluate the effectiveness of core training on sport-specific performance measures including power, speed, and flexibility across different athletic populations; (2) assess the effects of core training on general athletic performance indicators such as core endurance and balance; (3) analyse how core training effects vary across different sports and competitive levels; and (4) examine potential moderating factors influencing training effectiveness. This comprehensive analysis will provide evidence-based insights to inform the development and implementation of core training programs across various athletic populations.

Methodology

Protocol and registration

This systematic review and meta-analysis comprehensively investigate and quantify the impact of core training on overall athletic performance across different sports. The review was founded on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles guiding the data collection, analysis, and reporting. The review was registered by the International Platform of Registered Systematic Review and Meta-analysis Protocols (INPLASY: https://inplasy.com/), protocol registration number INPLASY2024100048 (DOI: https://doi.org/10.37766/inplasy2024.10.0048).

Search strategy

A comprehensive systematic search was conducted across five major electronic databases (PubMed, Web of Science, Scopus, SPORTDiscus, and Google Scholar) between October 15 2024 and October 30 2024. The search strategy was developed through careful consideration of three key concept areas: core training interventions, athletic performance outcomes, and study design parameters. To ensure comprehensive coverage while maintaining precision, controlled vocabulary terms with free-text searching, adapting the syntax for each database's specific requirements were adopted. All database searches were restricted to English-language publications from 2014 to 2024, focusing on peer-reviewed original research articles. Complete search strategies for each database, including all search terms, field codes, and filters, are provided in Appendix 1.

The review was limited to English-language publications from 2014–2024. This timeframe was selected to capture contemporary research incorporating modern training methodologies and assessment techniques [16, 17], while the English-language restriction was implemented to ensure accurate data extraction and interpretation [18, 19]. These restrictions are acknowledged as potential limitations of the study; their implications are discussed in the limitations section.

Inclusion and exclusion criteria

Inclusion criteria

Studies were included if they met all the following criteria: the study design adopted randomized controlled trials (RCTs) or controlled clinical trials to ensure methodological rigor in assessing intervention effects. The study population must be healthy athletes aged 15–25 years. Athletes were defined as individuals who regularly participated in organized sports training and competition at youth, collegiate, amateur, semi-professional, or professional levels with a minimum of two years of consistent involvement in their respective sports. This definition encompassed participants from various competitive levels including those in developmental programs, recreational leagues, intercollegiate competitions, and elite professional settings. The athletes' age range was selected because it encompasses the critical developmental periods for athletic performance, from mid-adolescence through early athletic maturity, when core training adaptations are most pronounced [20].

Core training was the primary intervention method, defined as structured exercise programs specifically targeting the muscles of the lumbopelvic-hip complex. Acceptable interventions included: core stability exercises, progressive core strength training and combined core training protocols (when core exercises comprised >50% of the intervention). Studies with control groups receiving either traditional training without specific core focus and no additional intervention beyond regular sport training were considered. In regard to outcome measures, studies reporting at least one quantifiable measure of athletic performance. Athletic performance was categorised into general and sport-specific where the former included core endurance, strength-to-bodyweight ratio outcomes while the latter speed, power, agility, and technical skills. Studies published between 2014-2024 were considered; the timeframe was selected to capture contemporary training methods while ensuring sufficient sample size for meta-analysis.

Exclusion criteria

Studies were excluded based on the following criteria. Non-randomized studies, pilot studies, systematic reviews, or meta-analyses were excluded to maintain methodological consistency and avoid duplicate data inclusion. Non-English language publications were excluded due to resource limitations for accurate translation and potential bias in interpretation. This limitation is acknowledged in the discussion of study constraints. Studies involving injured athletes, athletes outside the 15–25 age range, non-athletic populations, mixed populations where athletic and non-athletic data could not be separated were excluded. Studies where core training was not the primary intervention and the intervention protocol was insufficiently described were excluded as well. Studies that did not report quantitative performance outcomes, used non-validated assessment tools and failed to provide sufficient statistical data for effect size calculation were excluded. Studies lacking full text availability, essential methodological details, complete outcome data and clear statistical analysis were also excluded.

Study selection process

This systematic review followed PRISMA guidelines, employing a comprehensive search strategy developed through reviewer consultation [21]. The selection process utilized two specialized software tools: Zotero (version 6.0) for reference management so more removal of duplicates and ASReview (version 1.0) for initial screening, enhancing efficiency while maintaining methodological rigor.

A systematic search across five electronic databases (Web of Science, PubMed, Scopus, SportDiscus, and Google Scholar) initially identified 1,670 records. ASReview, an open-source machine learning software, facilitated the initial screening process. The software was trained using clearly defined inclusion and exclusion criteria, after which it assisted in prioritizing relevant records while maintaining human oversight throughout the process. Two independent reviewers conducted subsequent detailed evaluations using standardized assessment forms designed to examine methodological quality, intervention protocols, and outcome measurements. The review process progressed through multiple stages: initial title and abstract screening against broad eligibility criteria, followed by full-text assessment against detailed methodological and content criteria. Special attention was given to verifying that core training constituted the primary intervention focus in each study. Regular calibration meetings among reviewers ensured consistency in decision-making and assessment standards. When disagreements arose, they were resolved through structured discussion, with a third reviewer available for arbitration. All exclusion decisions were documented with specific rationales, maintaining transparency throughout the selection process. This approach ensured that only studies meeting strict methodological criteria and featuring core training as the primary intervention were included in the final analysis.

Data extraction

A standardized data extraction process was implemented to ensure systematic and reliable data collection. The extraction form was developed and piloted on five randomly selected studies before full implementation. Based on pilot results, the form was refined to ensure clear categorization and comprehensive data capture. The final extraction template included five main domains: (1) study characteristics which included bibliometric data (authors, year, journal), study design details (randomization method, allocation concealment), population characteristics (sample sizes), participant demographics (age range and mean ± SD, gender distribution), sport type (categorized as team, individual, combat, or racquet sports) and competitive level (professional, semi-professional, amateur, youth competitive). (2) Intervention characteristics comprised of core training type (clearly defined as either isolated core training, core stability training, core strength training, or combined protocols) and program details (duration in weeks, session frequency, session duration). (3) Control group characteristics included type of control condition (no intervention, regular training, alternative training), detailed description of control group activities and duration and frequency of control condition. (4)The outcome measures were general athletic performance measures (Core endurance (measured in seconds), balance (standardized test scores) and strength-to-bodyweight ratio. Whilst, sport-specific performance measures included speed (sprint times), power (jump height, throwing velocity), technical skills (sport-specific performance tests), flexibility, change of direction and maximal strength. (5) Statistical data included pre- and post-intervention means and standard deviations, *p*-values and statistical significance and complete outcome data for meta-analysis calculations. For studies reporting multiple outcomes or time points, data was extracted from all relevant measurements. When studies reported adjusted and unadjusted values, adjusted values were extracted.

In studies with pre- and post-outcome measures, post-intervention values were extracted for primary analysis. For studies using multiple methods to measure a single outcome, the average of the results was calculated and extracted unless one method was clearly identified as primary by the study's authors. Two independent reviewers extracted data from all included studies using a standardized form that was developed and piloted on five randomly selected studies. Regular calibration meetings were held throughout the extraction process to resolve discrepancies and ensure consistency in data interpretation. When the two primary extractors could not reach consensus on specific data points, a third reviewer served as an arbitrator to make the final decision. All extraction decisions, including resolved disagreements and special cases, were documented in a decision log to maintain transparency and reproducibility.

Quality assessment

The Physiotherapy Evidence Database (PEDro) [22, 23] scale was used to assess the methodological quality of the included studies. It consists of 11 items that assess internal validity and the interpretability of trial results. The scale focuses on key aspects like randomization, blinding, and follow-up, with a score range from 0 to 10 (since one item is not scored). Preferred PEDro scale values are 9–10 points denoting excellent methodological quality; 6–8 points (good methodological quality); 4–5 points (fair methodological quality) and below 4 points (Poor methodological quality) [24, 25]. The Cochrane Risk of Bias (RoB) tool was used to assess the risk of bias [26, 27]. The risks have three levels: low risk of bias, some concerns and high risk of bias. Low risk of bias denotes adequate measures are in place to minimize bias in the study; some concerns imply there are aspects of the study that raise concerns about the potential for bias, but they may not be serious enough to substantially influence the results; whilst, high risk of bias elucidate significant flaws exist in the study that likely introduce bias and affect the validity of the findings.

Statistical analysis

Statistical analyses were conducted using Cochrane Review Manager software (RevMan) and RStudio version 4.2.3. The random-effects model using the Restricted Maximum-Likelihood (REML) method for estimating between-study variance (τ^2) was employed for meta-analysis. REML was adopted because this approach provides more accurate estimates than the traditional DerSimonian-Laird method, particularly when dealing with high heterogeneity and smaller numbers of studies [13, 28, 29]. Standardized mean differences (SMD) with 95% confidence intervals were calculated for all outcomes to ensure comparability across studies using different measurement scales. The Hartung-Knapp-Sidik-Jonkman (HKSJ) method was used for calculating confidence intervals. HKSJ provides more conservative and reliable estimates by better accounting for uncertainty in the variance estimation, especially important given the study's relatively small number of studies and observed heterogeneity [28, 30–32]. Meta-analysis was only undertaken for outcome categories with a minimum of three independent studies ($k > 3$) to ensure sufficient data for meaningful statistical synthesis and reliable heterogeneity assessment, with outcomes having fewer studies addressed narratively in the discussion section [33, 34].

Heterogeneity was assessed using I^2 statistics to quantify the proportion of observed variance reflecting real differences in effect size. The magnitude of heterogeneity was classified using I^2 values, where $I^2 \leq 25\%$ indicated low heterogeneity, $25\% < I^2 < 75\%$ indicated moderate heterogeneity, and $I^2 \geq 75\%$ indicated high heterogeneity [35, 36]. Effect sizes were interpreted following established guidelines for standardized mean differences (SMD) according to Cohen: small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), and very large (> 2.0) [37, 38].

Publication bias was assessed through visual inspection of funnel plots, examining the relationship between study precision (standard error) and effect size. While statistical tests such as Egger's test provide objective assessment of funnel plot asymmetry, these tests are recommended only when meta-analyses include at least 10 studies [39–41]. As the largest number of studies for any outcome in this meta-analysis was 9 (for technical skill performance), with most outcomes having fewer studies, Egger's statistical tests for publication bias were not appropriate. Simulation studies have demonstrated that both rank-based and regression-based methods for assessing publication bias have reduced statistical power when including fewer than 10 studies [40, 41]. Furthermore, even with 10 studies, visual assessment of funnel plot asymmetry remains challenging, as funnel plots can frequently appear asymmetric by chance when there is no underlying asymmetry, and conversely, publication bias can exist despite symmetrical distribution [39]. The interpretation of funnel plot asymmetry therefore warrants caution, as asymmetry may arise from various sources including between-study heterogeneity, choice of effect size metric, statistical artifacts, and chance, rather than exclusively from publication bias.

Risk of bias (ROB) assessment used the Cochrane Collaboration's ROB 2 tool to evaluate the design, conduct, and reporting of trials and their impact on the reliability of findings. The tool assessed seven domains: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other sources of bias [42, 43].

This methodological approach was selected a priori based on several key considerations protocol [44, 45]. First, the inherent diversity across included studies - varying training protocols (4–24 weeks), different competitive levels (youth to professional), and diverse sporting contexts - suggested that true effect sizes would likely vary between studies. Second, the relatively small number of studies in some analyses (as few as 4 studies for some outcomes) warranted more conservative statistical approaches. Finally, the observed high heterogeneity in preliminary analyses supported the need for methods that could better account for between-study variance and uncertainty in effect size estimation.

Sensitivity analyses were conducted software to assess the robustness of the meta-analysis results as recommended by [46]. Following Cochrane Handbook guidance [34], a"one study removed"approach was implemented to evaluate whether any single study exerted disproportionate influence on the pooled effect estimates. This method systematically excluded each study individually and recalculated effect sizes to determine if statistical significance, effect magnitude, or heterogeneity substantially changed. Sensitivity analyses were performed using RevMan software and results were evaluated for meaningful changes in effect estimates, confidence intervals, and statistical significance to determine the stability of findings across different model specifications. The results in the analysis were presented in tables and figures.

Results

Results of study selection

The systematic search and selection process yielded a final set of studies for analysis through multiple screening stages. The ASReview screening resulted in the exclusion of 1,462 records based on title and abstract review, leaving 178 unique records for review. These articles were further reviewed based on the abstract using ASReview screening and human manual review, leaving 65 articles for full-text assessment where only 63 articles were retrieved and subjected to full text review (see Fig. 1). These records were exported to Zotero for duplicate removal. Through Zotero's automated duplicate detection and manual verification, 12 records were removed leaving 51 for full-text review. These articles underwent detailed eligibility assessment by three independent reviewers. Of the 51 articles identified for full-text review, 29 articles were excluded for the following reasons: core training not being the primary intervention

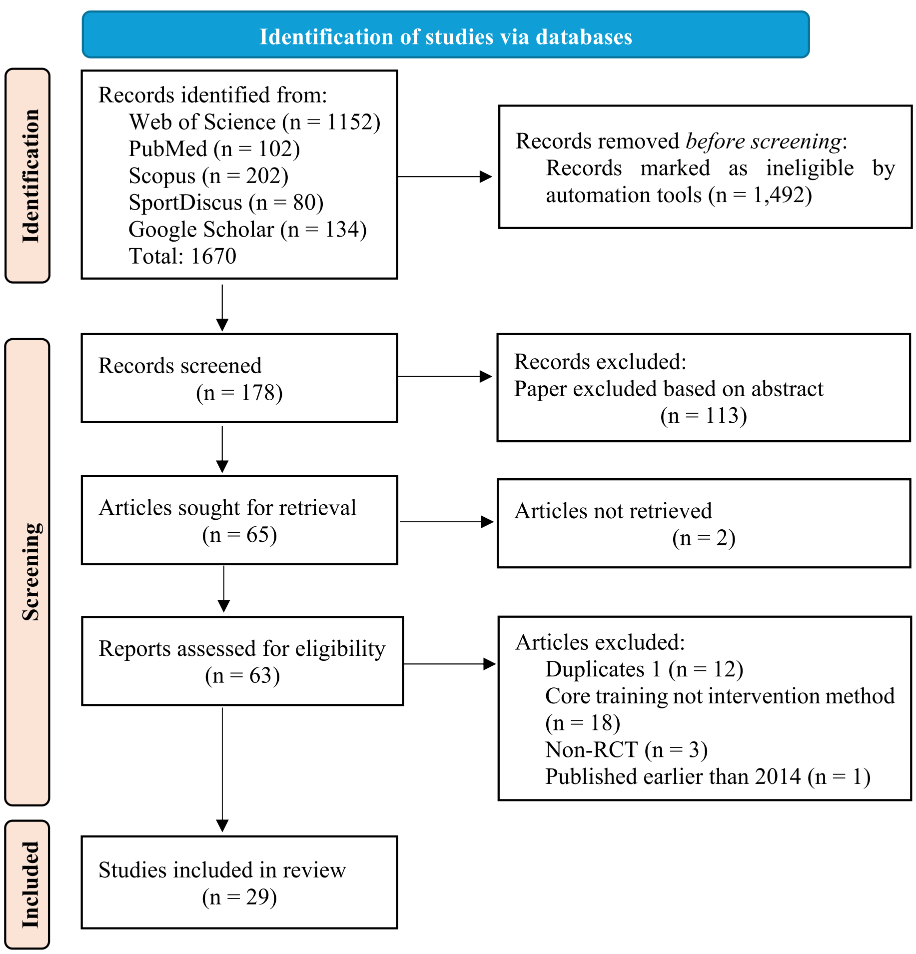

Fig. 1 PRISMA flow chart for the included articles

(n = 15); non-RCT study design (n = 3); and publication date earlier than 2014 (n = 1).

After the initial screening process identified 32 studies, a secondary methodological review was conducted to ensure strict adherence to the study's core training definition. This additional review resulted in the exclusion of three studies where core training was not the primary intervention: Blagrove et al. (2018) focused primarily on plyometric training, Dæhlin et al. (2017) emphasized general strength development, and Lum et al. (2023) concentrated on isometric squat training without specific core muscle focus. This secondary screening ensured all included studies specifically targeted core muscle development as their primary intervention. The final selection yielded 29 studies [47–75] meeting all inclusion criteria for the meta-analysis (see Fig. 1). Throughout the screening process, disagreements between reviewers were resolved through discussion and consensus, with a third reviewer consulted when necessary. This rigorous selection process ensured that only studies with clear core training interventions were included in the final analysis.

Study characteristics

Table 1 and Table 2 show the study characteristics, intervention and outcome variables reported by the authors of the 29 studies included in the meta-analysis. The analysis included 29 studies involving 956 participants with sample sizes ranging from 12–103 participants. Most participants were aged 15–23 years (mean age: intervention group = 18.74 ± 1.52; control group = 19.09 ± 1.69; I^2 = 55%) [47–49, 52–54, 57–61, 63–66, 69, 71, 73–75]. Males comprised the majority of participants (13 studies, I^2 = 44%) [47, 48, 50, 51, 54, 60, 64, 66, 68, 70–72, 74], with 10 studies [52, 55–58, 61–63, 65, 69] using mixed-gender samples, 5 studies examining females exclusively [53, 59, 67, 73, 75], while one study did not state the gender of the participants [49]. Professional (national team, first division); Semi-professional (regional level); Amateur (recreational); Youth competitive (developmental); Age presented as mean ± standard deviation where available; Sports categorized as: Team sports, Individual sports, Combat sports, and Racquet sports; n = number of participants [49].

Studies encompassed four competitive levels: professional (6 studies [54, 60, 62, 66, 71, 74], I^2 = 44%), semi-professional (6 studies [48, 53, 64, 65, 72, 75], I^2 = 75%), amateur (7 studies [47, 50, 59, 68–70, 73], I^2 = 0%), and youth competitive (10 studies [49, 51, 52, 55–57, 61, 63, 67], I^2 = 0%). Sports categories included team sports which included soccer, basketball, handball, volleyball (14 studies [47, 48, 50, 53, 54, 59, 60, 62, 64–67, 70, 73], I^2 = 0%), individual sports including swimming, gymnastics, tennis; track events, distance running (8 studies [4, 56, 58, 61, 68, 71, 72, 74], I^2 = 67%), combat sports (3 studies [49, 51, 57], I^2 = 0%), and racquet sports (2 studies [63, 75], I^2 = 0%).

In regard to training protocols intervention durations ranged from 4–24 weeks, with most implementing 7–12 week protocols (n = 17) [47, 48, 50–54, 57, 66, 67, 69–75], while a smaller number explored shorter (4–6 weeks) [49, 55, 59, 60, 62–65, 68] or longer (12–24 weeks) interventions [56, 58, 61]. Training frequency typically involved 2–3 sessions weekly (I^2 = 0%) [47, 49, 51, 52, 54–57, 62, 66–70, 73, 75], while session duration varied from 20–120 min (I^2 = 17%). Four distinct intervention types emerged: core stability training, core strength training, combined interventions, and progressive loading protocols. Shorter interventions (4–6 weeks), exemplified by studies like [51] and [63], often employed more frequent sessions (up to 4 per week), potentially compensating for the reduced overall duration. The moderate-duration protocols (8–10 weeks), represented by studies such as [66] and [48], demonstrated considerable variation in session duration (20–90 min) while maintaining consistent weekly frequencies. This suggests that the total training volume can be effectively distributed across different session lengths while maintaining the core principle of regular, consistent training exposure.

Four core training interventions were identified namely core stability training, core strength training, combined interventions (core + sport-specific training) and progressive loading protocols (see Table 2). The studies measure several outcomes but the study focused on balance, change of direction (seconds); core endurance (seconds); flexibility (cm); maximal strength (kgs); sprint performance (speed) (seconds); technical skill performance (%); throwing velocity/distance (cm) and vertical jump height (cm).

Quality assessment

Methodological quality

The PEDro Scale analysis for methodological quality for the 29 included studies has an average score of 5.65 which studies falls within the fair methodological quality range (4–5 points), approaching the good quality threshold (6 points) [4, 24, 25] (see Table 3). The scores ranged from 4 to 8 points while three items (blind participants, blind therapists, and blind assessors) scored zero and only two had random allocation; the findings resonate with [4] and [76].

Risk of bias

The risk of bias was assessed using the Cochrane Collaboration's risk of bias tool across seven domains. The overall assessment revealed varying levels of methodological quality across the included studies (see Fig. 2 and

Table 1 Characteristics of included studies in the meta-analysis

Authors and year	Study design	Participants	Demographics	Sport	Competitive level
Arslan et al. (2021) [47]	RCT	38 young male soccer players	SSGcore group ($n = 20$): 16.30 ± 0.47 years; SSG group ($n = 18$): 16.50 ± 0.51 years	Team (Soccer)	Amateur
Brull-Muria & Beltran-Garrido (2021) [48]	RCT	14 youth male soccer players	SCS ($n = 7$): 17.14 ± 0.69 years, GCS ($n = 7$): 16.86 ± 0.69 years	Team (Soccer)	Semi-professional
Bulak & Özdal (2021) [49]	RCT	21 taekwondo athletes	SCG (11): 15.60 ± 1.78 years; DCD ($n = 10$): 13.55 ± 1.86 years	Combat (Taekwondo)	Youth competitive
Chandrakumar & Ramesh (2016) [50]	RCT	24 high school male football players	Not specifically mentioned, but participants were high school players. CSST ($n = 12$); CEG ($n = 12$)	Team (Soccer)	Amateur
Dehnou et al. (2020) [51]	RCT	20 junior Greco-Roman wrestlers	CSST ($n = 12$); CEG ($n = 8$); 16.8 ± 1.1 years	Combat (Greco-Roman wrestling)	Youth competitive
Dongaz et al. (2023) [52]	RCT	36 child gymnasts	TG ($n = 18$): 10.02 ± 1.13 years; CG ($n = 18$): 10.08 ± 1.05 years; Range: 7–12 years	Individual (Gymnastics)	Youth competitive
Ferri-Caruana et al. (2022) [53]	RCT	18 female handball players	CTG ($n = 10$): 19.7 ± 1.5 years; CG ($n = 8$): 19.2 ± 1.4 years	Team (Handball)l	Semi-professional
Hessam et al. (2023) [54]	RCT	35 male basketball players	22.8 ± 4.4 years (experimental – $n = 18$), 22.0 ± 4.1 years (control – $n = 17$)	Team (Basketball)	Professional
Jha et al. (2022) [55]	RCT	70 healthy collegiate athletes	Experimental group: $n = 35$; Control group: $n = 35$; Overall mean: 21.6 ± 1.7 years	Combination (various collegiate sports)	Youth competitive
Jia et al. (2022) [56]	RCT	20 young swimmers	Born after 2000	Individual (Swimming)	Youth competitive
Kabadayı et al. (2022) [57]	RCT	29 karate athletes	CST ($n = 16$): 12.75 ± 0.77 years; CG ($n = 13$): 13.00 ± 0.91 years	Combat (Karate)	Youth competitive
Kiss et al. (2019) [58]	RCT	103 recruitment-age kayak-canoe athletes	Intervention group ($n = 50$): 15.22 ± 3.70 years; Control group ($n = 53$): 15.55 ± 3.97 years	Individual (Kayak-canoe)	Youth competitive
Kuhn et al. (2019) [59]	RCT	20 female recreational handball players	CST ($n = 10$): 24.1 ± 3.8 years; CON ($n = 10$): 23.7 ± 5.2 years	Team (Handball)	Amateur
Li (2022) [60]	RCT	12 college basketball players	Experimental group ($n = 6$): 20.5 ± 1.33 years; Control group ($n = 6$): 20.8 ± 0.86 years	Team (Basketball)	Professional
Lum, Barbosa, Joseph, et al. (2021) [61]	RCT	33 floorball players	Con ($n = 9$); RIST ($n = 12$); SIST ($n = 12$); All groups: 23.9 ± 3.1 years	Team (Floorball)	Professional
Lum, Barbosa, & Balasekaran (2021) [62]	RCT	20 Kayaking athletes	TRAD ($n = 10$): 21 ± 4 years; IST ($n = 10$): 22 ± 4 years	Individual (Sprint Kayaking)	Youth competitive
Ozmen & Aydogmus (2016) [63]	RCT	20 badminton players	TG ($n = 10$): 10.9 ± 0.3 years; CG ($n = 10$): 10.8 ± 0.4 years	Racquet (Badminton)	Youth competitive
Ozmen et al. (2020) [64]	RCT	20 male handball players	CST ($n = 10$): 14.9 ± 0.31 years; CON ($n = 10$): 14.90 ± 0.56 years	Team (Handball)	Semi-professional

Table 1 (continued)

Authors and year	Study design	Participants	Demographics	Sport	Competitive level
Palmer et al. (2015) [65]	RCT	46 softball and baseball players	Power Stability (PS) ($n = 25$): 19.8 ± 1.2 years; Endurance (traditional) Training (ET) ($n = 21$): 20.3 ± 1.3 years	Team (Softball, Baseball)	Semi-professional
Prieske et al. (2016) [66]	RCT	39 elite youth soccer players	CSTS (Core Stability Training Stable—$n = 20$): 16.6 ± 1.1 years; CSTU (Core Stability Training Unstable – $n = 19$): 16.6 ± 1.0 years	Team (Soccer)	Professional
Shahin (2016) [67]	RCT	14 female volleyball players	Experimental group: $n = 7$; Control group: $n = 7$; Age range: 16–17 years	Team (Volleyball)	Youth competitive
Soflaei et al. (2022) [68]	RCT	30 snooker players	Pilates group: $n = 15$; Control group: $n = 15$; 18–40 years	Individual (Snooker)	Amateur
Srivastav (2016) [69]	RCT	25 recreational	Group A (Swiss ball—$n = 8$): 23.22 ± 1.397 years; Group B (Mat exercises—$n = 8$): 22.22 ± 1.394 years; Group C (Control—$n = 9$): 21.22 ± 1.567 years	Combination (various recreational sports)	Amateur
Subramanian (2014) [70]	RCT	30 cricket players	20.07 ± 1.48 years	Team (Cricket)	Amateur
Sung et al. (2016) [71]	RCT	60 right-handed male elite golfers	Control group (CG – $n = 20$): 24.0 ± 1.0 years; Core exercise group (CEG – $n = 20$): 23.0 ± 0.5 years; non-dominant arm + core exercise group (NCEG—$n = 20$): 23.2 ± 0.6 years	Individual (Golf)	Professional
Suryanarayana & Kumar (2024) [72]	RCT	72 intercollegiate male athletes	18 to 25 years	Individual (Track events)	Semi-professional
Taskin (2016) [73]	RCT	40 female soccer players	CTG ($n = 20$): 19.05 ± 1.15 years, CG ($n = 20$): 18.55 ± 0.76 years	Team (Soccer)	Amateur
Vitale et al. (2018) [74]	RCT	24 elite junior skiers	EG ($n = 12$): 18 ± 1 years; CG ($n = 12$): 18 ± 1 years	Individual (Skiing)	Professional
Wang et al. (2022) [75]	RCT	23 female university tennis players	EG ($n = 12$): 18.2 ± 1.9 years; CG ($n = 11$): 17.9 ± 2.2 years (control group)	Racquet (Tennis)	Semi-professional

RCT Randomized Controlled Trial, *EG* Experimental Group, *CG* Control Group, *TG* Training Group

Table 2 Core training interventions and outcome measures

Authors and Year	Intervention	Training Duration Protocols	Outcome Measures	Key Findings	Conclusions
Arslan et al. (2021) [47]	Core strength training combined with small-sided games	6 weeks, 3 sessions/week (60–70 min each)	YYIRTL- 1, 20 m sprint, CMJ, Y-balance test	Significant improvements in speed, strength, and balance in the SSGcore group	Core training with small-sided games improves soccer performance
Brull-Muria & Beltran-Garrido (2021) [48]	Sport-specific core stability exercises vs. general core stability exercises	8 weeks, 3 sessions/week (20 min/session)	Sprint, Change-of-Direction Manoeuvrability	Both groups improved sprint and agility with no significant differences	General and core stability training enhance performance equally in youth soccer players
Bulak & Özdal (2021) [49]	Static and dynamic core training	6 weeks, 3 sessions/week (60 min/session)	Bandal-Tchagui kick fatigue & Kick impact pressure	No significant effects on kick fatigue	Dynamic and static core training does not affect kick fatigue in taekwondo athletes
Chandrakumar & Ramesh (2016) [50]	Core functional training vs. football practices	8 weeks, 3 sessions/week (One hour/session)	Leg strength, flexibility	Improved leg strength and flexibility in the experimental group	Core functional training enhances strength and flexibility in high school soccer players
Dehnou et al. (2020) [51]	Core-specific training vs. regular wrestling training	4 weeks, 4 sessions/week	Medicine Ball Throw, Suplexes, Bridges	Core training improved performance in wrestling-specific tasks	Core-specific training improves strength and endurance in wrestlers
Dongaz et al. (2023) [52]	Core stability exercises vs. classic gymnastics training	8 weeks, 3 sessions/week	Balance, endurance, strength, agility, flexibility, Jump performance	Experimental group had better improvements in strength and flexibility	Core stability training enhances fitness parameters in gymnasts
Ferri-Caruana et al. (2022) [53]	Core strength training vs. routine training	8 weeks, 2 sessions/week	Bilateral and unilateral jump height, balance	Significant improvements in jump height, reactive strength, and balance	Core strength training improves jump performance in handball players
Hessam et al. (2023) [54]	McGill core stability training vs. routine training	12 weeks, 3 sessions/week (45 min/session)	Functional movement screen (FMS), shooting	Experimental group showed greater improvements in movement patterns and shooting	McGill core training improves movement and shooting in basketball players
Jha et al. (2022) [55]	Core stability training vs. routine training	5 weeks, 3 sessions/week (45 min/session)	Upper quarter Y-balance test, Functional Throwing	Significant improvements in balance and upper extremity performance	Core stability training enhances upper extremity performance
Jia et al. (2022) [56]	Core training vs. regular swimming training	6 months, 3 sessions/week	Freestyle time (400 m, 800 m)	Greater improvements in freestyle times for core training group	Supplemental core training enhances performance in young swimmers
Kabadayı et al. (2022) [57]	Core strength training vs. regular karate training	8 weeks, 3 sessions/week (30–35 min/session)	Flexor endurance, back strength, karate kick, flexibility, change of direction, sprint test	Core strength training improved endurance and karate kick performance	Core strength training is effective for karate performance but limited for other fitness measures
Kiss et al. (2019) [58]	Trunk prevention training vs. regular training	6 months, 3 sessions/week	Core strength, flexibility, lumbar control	Significant improvements in core strength and flexibility	Trunk prevention training improves core strength and flexibility in kayak-canoe athletes
Kuhn et al. (2019) [59]	Core stability training vs. handball training	6 weeks, 2 sessions/week (45 min/session)	Throwing velocity, isometric strength, core endurance	Improved core muscle strength but no significant enhancement in throwing velocity	Core stability training improves strength but not throwing performance in handball players

Table 2 (continued)

Authors and Year	Intervention	Training Duration Protocols	Outcome Measures	Key Findings	Conclusions
Li (2022) [60]	Core strengthening vs. traditional strength training	6 weeks, 3 sessions/week	Fast dribbling passes, shooting	Experimental group showed higher fast dribbling passes and shots	Core strengthening training improves fitness and technical skills in basketball players
Lum, Barbosa, Joseph, et al. (2021) [61]	Rapid isometric squat (RIST) vs. sustained isometric (SIST) vs regular training	6 weeks, 2 sessions per week	Countermovement jump, 30 m sprint, isometric squat	SIST resulted in better jump height and sprint times compared to RIST	Sustained isometric squat training is more effective for strength and performance
Lum, Barbosa, & Balasekaran (2021) [62]	Isometric strength training (IST) vs traditional strength training	6 weeks, 2 sessions per week	200 mTT performance, Isometric squat test, Isometric bench press, Isometric prone bench pull, peak force (PF) and rate of force development (RFD)	IST group showed greater improvements in 200 mTT performance, peak force in most isometric tests and rate of force development	Inclusion of isometric strength training, either consecutively or periodically, can lead to greater improvements in sprint performance compared to control
Ozmen & Aydogmus (2016) [63]	Core strength training vs. regular badminton training	6 weeks, 2 sessions/week	Balance, agility, core endurance	Improved balance and core endurance but not agility	Core strength training enhances balance but may not improve agility in adolescent badminton players
Ozmen et al. (2020) [64]	Core strength training vs routine handball training	6 weeks, 2 sessions/week	Dynamic balance (SEBT), Vertical jump height, Throwing velocity	Significant improvements in dynamic balance and vertical jump height in the CST group, but no significant difference in throwing velocity between groups	Core strength training did not improve dynamic balance, vertical jump height and throwing velocity in adolescent male handball players
Palmer et al. (2015) [65]	Power-stability training vs. traditional endurance training	7 weeks, 2 sessions/week (30 min/session)	Throwing velocity, chop/lift power	Power-stability training showed greater improvements in throwing velocity	Power-stability training is more effective than traditional endurance training for throwing
Prieske et al. (2016) [66]	Core training on stable vs. unstable surfaces	9 weeks, 2–3 sessions/week (~ 30 min/session)	Trunk strength, sprint, agility, kicking	Both groups improved in trunk strength and kicking, with no significant differences between surfaces	Core training, whether on stable or unstable surfaces, improves trunk strength and performance
Shahin (2016) [67]	Core strengthening vs. regular volleyball training	10 weeks, 3 sessions/week (90 min/session)	Vertical jump, spike performance, balance	Significant improvements in vertical jump and balance	Core strengthening improves volleyball-specific skills and physical abilities in female players
Soflaei et al. (2022) [68]	Pilates exercises vs. regular snooker training	6 weeks, 3 sessions/week	Break score, balance, foul number	Pilates improved balance and break scores	Pilates exercises improve balance and performance in snooker players
Srivastav (2016) [69]	Core stability training vs. regular training	12 weeks, 2 sessions/week	Muscular strength, back strength, flexibility	Significant improvements in strength and flexibility	Core strength training enhances physical and physiological parameters in recreational athletes

Table 2 (continued)

Authors and Year	Intervention	Training Duration Protocols	Outcome Measures	Key Findings	Conclusions
Subramanian (2014) [70]	Core strength training vs. No specialized training	8 weeks, 3 sessions/week (90 min/session)	Muscular strength, Back strength, Flexibility	Experimental group showed significant improvements in all outcome measures compared to the control group	Core strength training can produce significant changes in the physical and physiological parameters of cricket players
Sung et al. (2016) [71]	Core and non-dominant arm training vs. core training alone	8 weeks, 2 sessions/week (60 min/session)	Drive distance, isokinetic strength	Non-dominant arm + core training showed the greatest improvements in drive distance and strength	Combining core and non-dominant arm training is more effective for improving drive distance in golfers
Suryanarayana & Kumar (2024) [72]	Staircase training, Core Strength Training vs. core training	12 weeks, 3 sessions/week	Endurance, reaction time	Both training methods improved endurance and reaction time; staircase training was more effective	Both staircase and core training are effective, but staircase training provides superior endurance benefits
Taskin (2016) [73]	Core training vs. regular training	8 weeks, 3 sessions/week	Speed, acceleration, vertical jump	Core training improved speed, acceleration, and jumping	Core training enhances functional performance in female soccer players
Vitale et al. (2018) [74]	Neuromuscular training vs. standard warm-up	8 weeks, 2 sessions/week	Y-Balance Test, Countermovement jump, Drop jump	Core training improves dynamic balance	The neuromuscular warm-up program improved dynamic balance ability but not vertical jump performance in elite junior skiers
Wang et al. (2022) [75]	Core strength training vs Traditional strength training	9 weeks, 3 sessions/week (30 min/session)	Core strength (leg lift, back extension, bridge tests, abdominal fatigue), Serve speed	Core strength training improved core strength measures and tennis technical skills (serve speed, accuracy)	Core strength training was more effective than traditional strength training for developing core strength and enhancing technical skills in female university tennis players

Intervention duration reported in weeks; Training frequency reported as sessions per week; Session duration reported in minutes; Outcome measures include standardized tests and sport-specific performance measures; Key findings report statistically significant results ($p < 0.05$) unless otherwise noted

SSG Small-Sided Games, *CSST* Core Stability Specific Training, *CIST* Core Isometric Strength Training; Training types categorized as: Core stability training, Core strength training, Combined interventions, Progressive loading protocols

Table 3 PEDro Scale scores of the studies

No	Study	EC	RA	CA	BC	BP	BT	BA	AFU	ITT	BGC	PMV	Total Score
1	Arslan et al. (2021) [47]	1	1	0	1	0	0	0	1	0	1	1	6
2	Brull-Muria & Beltran-Garrido (2021) [48]	1	1	0	1	0	0	0	1	0	1	1	6
3	Bulak & Özdal (2021) [49]	1	0	0	1	0	0	0	1	0	1	1	5
4	Chandrakumar & Ramesh (2016) [50]	1	0	0	1	0	0	0	1	0	1	1	5
5	Dehnou et al. (2020) [51]	1	1	0	1	0	0	0	1	0	1	1	6
6	Dongaz et al. (2023) [52]	0	1	0	0	0	0	0	1	1	1	1	5
7	Ferri-Caruana et al. (2022) [53]	1	1	0	1	0	0	0	1	0	1	1	6
8	Hessam et al. (2023) [54]	0	1	0	0	0	0	0	1	1	1	1	5
9	Jha et al. (2022) [55]	0	1	0	1	0	0	0	1	1	1	1	6
10	Jia et al. (2022) [56]	1	1	0	1	0	0	0	1	1	1	1	7
11	Kabadayı et al. (2022) [57]	0	1	0	0	0	0	0	1	1	1	1	5
12	Kiss et al. (2019) [58]	1	1	0	1	0	0	0	1	0	1	1	6
13	Kuhn et al. (2019) [59]	0	1	0	1	0	0	0	1	0	1	1	5
14	Li (2022) [60]	0	0	0	0	0	0	0	1	1	1	1	4
15	Lum, Barbosa, & Balasekaran (2021) [61]	1	1	0	1	0	0	0	1	0	1	1	6
16	Lum, Barbosa, Joseph, et al. (2021) [62]	0	0	0	1	0	0	0	1	0	1	1	4
17	Ozmen & Aydogmus (2016) [63]	1	0	0	1	0	0	0	1	0	1	1	5
18	Ozmen et al. (2020) [64]	1	0	0	1	0	0	0	1	0	1	1	5
19	Palmer et al. (2015) [65]	1	1	0	1	0	0	0	1	0	1	1	6
20	Prieske et al. (2016) [66]	1	1	0	1	0	0	0	1	0	1	1	6
21	Shahin (2016) [67]	1	1	0	1	0	0	0	1	0	1	1	6
22	Soflaei et al. (2022) [68]	1	1	0	1	0	0	0	1	0	1	1	6
23	Srivastav (2016) [69]	1	0	0	1	0	0	0	1	0	1	1	5
24	Subramanian (2014) [70]	1	0	0	1	0	0	0	1	0	1	1	5
25	Sung et al. (2016) [71]	1	1	0	1	0	0	0	1	1	1	1	7
26	Suryanarayana & Kumar (2024) [72]	1	1	0	1	0	0	0	1	1	1	1	7
27	Taskin (2016) [73]	1	1	0	1	0	0	0	1	0	1	1	6
28	Vitale et al. (2018) [74]	1	1	1	1	0	0	0	1	1	1	1	8
29	Wang et al. (2022) [75]	1	0	0	1	0	0	0	1	0	1	1	5
Average													**5.65**

Scale Items: *EC* Eligibility Criteria (not included in total score), *RA* Random Allocation, *CA* Concealed Allocation, *BC* Baseline Comparability, *BP* Blind Participants, *BT* Blind Therapists, *BA* Blind Assessors, *AFU* Adequate Follow-Up (> 85%), *ITT* Intention-to-Treat Analysis, *BGC* Between-Group Comparisons, *PMV* Point Measures and Variability. Scoring: 1 = criterion satisfied; 0 = criterion not satisfied or unclear; Total score range: 0–10 points (EC not included in total); Score interpretation: 9–10 = excellent; 6–8 = good; 4–5 = fair; < 4 = poor. Statistical Notes: Mean score calculation excludes EC criterion; Overall methodological quality based on total score; Inter-rater reliability assessed using Cohen's kappa

Fig. 3). All studies demonstrated a low risk of bias in measurement procedures (100%), selection of reported results (89.7%) and an overall bias of 79.3% (low). However, significant concerns were identified in several areas more related to bias arising from the period and carryover effects (37.9%) and randomization process (31.0%) which were not explicitly outlined in the selected articles. The highest risk was noted in deviations from intended interventions (96.6%), missing outcome data (82.8%) and bias arising from period and carryover effects (59.4%). Across individual studies, consistent patterns emerged, and all studies maintained high methodological quality in outcome measurement and result reporting. However, intervention adherence and implementation fidelity were problematic across nearly all studies, as evidenced by the consistently high-risk ratings for deviations from intended interventions (see Fig. 3). Missing outcome data presented another systematic challenge, potentially affecting the reliability of reported results. Several studies [47, 54, 55] demonstrated exemplary methodological quality across most domains, while others [49, 50] showed more methodological limitations. These variations in study quality were considered in the interpretation of results and subsequent analyses. The overall bias assessment indicates that while the fundamental research methodology was sound, particularly in measurement and reporting, there were significant challenges in intervention implementation and data completeness. These

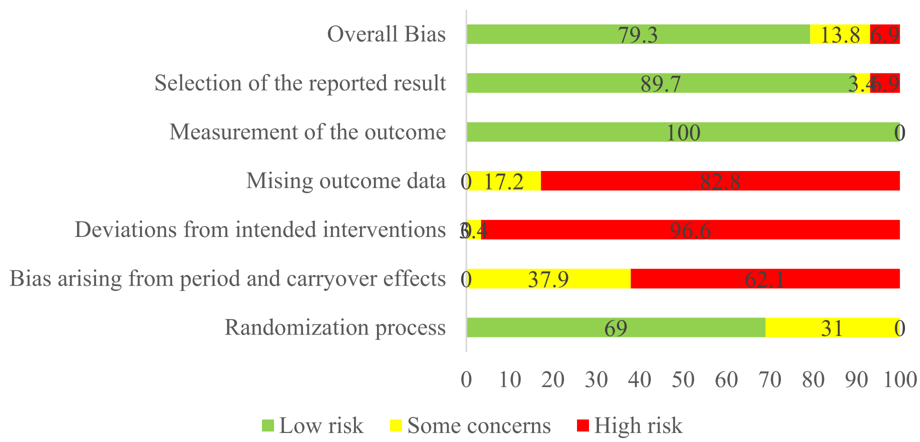

Fig. 2 Risk of bias. Visual representation of risk of bias assessment across seven domains for all included studies (*n* = 29). Assessment conducted using the Cochrane Risk of Bias tool. Colour coding indicates low risk (green), some concerns (yellow), and high risk (red) for each domain. Percentages represent the proportion of studies in each risk category per domain

limitations are common in exercise intervention studies but should be considered when interpreting the effectiveness of core training programs. However, the analysis showed stronger methodological quality in outcome measurement compared to similar reviews.

Publication bias

Visual inspection of the funnel plots across the measured performance outcomes revealed distinct patterns of potential publication bias. The analysis examined asymmetry and distribution patterns separately for each outcome category, though strength-to-bodyweight ratio could not be included in this analysis as it was only reported in two studies, providing insufficient data points for meaningful funnel plot interpretation.

Balance and core endurance measures Balance outcomes (Appendix 2a) demonstrated relatively symmetric distribution around the mean effect size (SMD range: − 2.0 to 2.0), with studies clustering tightly at moderate standard errors (0.2–0.4). This pattern suggests minimal publication bias for balance measures. Core endurance outcomes (Appendix 2c) showed wider dispersion (SMD range: − 4.0 to 8.0), with asymmetric distribution favouring positive results, particularly among studies with larger standard errors. This asymmetry indicates potential publication bias toward positive findings in core endurance research.

Movement performance measures Change of direction performance (Appendix 2b) exhibited notably symmetric distribution (SMD range: − 1.5 to 1.5) with consistent precision (SE <0.5), suggesting robust reporting practices for this outcome. Speed performance measures (Appendix 2e) showed broader distribution (SMD range: − 3.0 to 3.0) with some asymmetry toward negative effects, indicating possible selective reporting of performance improvements (as negative values indicate faster times).

Technical and strength outcomes Technical skill performance (Appendix 2f) demonstrated the widest dispersion (SMD range: − 5.0 to 5.0) with marked asymmetry, suggesting potential selective reporting of positive and negative results. The funnel plot for throwing velocity (Appendix 2 g) showed moderate asymmetry favouring positive outcomes, particularly among studies with larger standard errors (SE >0.6).

Additional performance measures Flexibility measures (Appendix 2d) displayed relatively symmetric distribution but with notable gaps in the mid-precision range, suggesting possible unreported studies with moderate effects. Vertical jump performance (Appendix 2h) showed clustering around small-to-moderate positive effects with some asymmetry, indicating potential selective reporting of favourable outcomes.

Meta-analysis results

The overall effect of core training on athletic performance

Meta-analysis results demonstrate different patterns of effectiveness between sport-specific and general athletic performance measures. For sport-specific outcomes (k =44), core training showed a moderate positive effect that approached but did not reach statistical significance (SMD =0.62, 95% CI [− 0.08, 1.31], p = 0.084), with high heterogeneity (I^2 = 96.99%). In contrast, general athletic

Study ID	D1	DS	D2	D3	D4	D5	Overall
Arslan 2021	+	!	-	-	+	+	+
Brull-murria 2021	+	-	-	-	+	+	!
ChandraKumar 2016	!	-	-	-	+	+	!
Dehnou 2020	+	-	-	-	+	+	+
Dongaz 2023	+	-	-	-	+	+	+
Ferri-Caruana 2022	+	-	-	-	+	+	+
Jha 2022	+	!	-	-	+	+	+
Hessam 2023	+	!	-	-	+	+	+
Jia 2022	!	!	!	!	+	-	-
Kuhn 2019	+	!	-	!	+	+	+
Lum 2021a	+	!	-	!	+	+	+
Ozmen 2016	+	-	-	-	+	+	+
Ozmen 2020	!	-	-	-	+	+	+
Prieske 2016	+	-	-	-	+	+	+
Soflaei 2022	+	-	-	-	+	+	+
Sung 2016	+	-	-	-	+	+	+
Taskin 2016	+	-	-	-	+	+	+
Vitale 2018	+	!	-	-	+	+	+
Wang 2022	!	-	-	-	+	+	+
Bulak 2021	!	-	-	-	+	+	+
Jia 2022	!	!	-	-	+	-	-
Kabadayı 2022	+	!	-	!	+	+	+
Li 2022	!	!	-	-	+	!	!
Lum 2021	+	!	-	!	+	+	+
Palmer 2015	+	-	-	-	+	+	+
Shahin 2016	+	-	-	-	+	+	+
Srivastav 2016	!	-	-	-	+	+	+
Subramanian 2014	+	-	-	-	+	+	+
Suryanarayana 2024	!	-	-	-	+	+	!

Fig. 3 Risk of bias for each study. Detailed risk of bias assessment for each included study across six domains (D1-D5). D1 = Randomisation process; DS = Bias arising from period and carryover effects; D2 = Deviations from intended interventions; D3 = Missing outcome data; D4 = Measurement of outcome; D5 = Selection of reported result. Color-coded visualization shows risk assessment for each domain per study

performance measures (k = 16) revealed a large, statistically significant positive effect (SMD = 1.38, 95% CI [0.86, 1.89], $p < 0.0001$) (see Fig. 4) with high heterogeneity ($I^2 =$ 85.13%).

General athletic performance

Three general athlete performance outcomes namely, balance, core endurance and strength-to-bodyweight ratio were considered in the analysis and discussion. However, strength-to-bodyweight ratio was excluded from the analysis because it had only 2 studies (k < 3) hence a degree of freedom of 1 which limits the variability of the result.

Core endurance

Core endurance was examined across 8 studies comprising 247 participants (132 experimental, 115 control). Meta-analysis using the Hartung-Knapp-Sidik-Jonkman method revealed a significant positive effect of core training on core endurance (SMD = 1.32, 95% CI [0.57, 2.08], $P < 0.004$) (see Table 4 and Appendix 3a). High heterogeneity was observed across studies ($I^2 = 77\%$). The largest

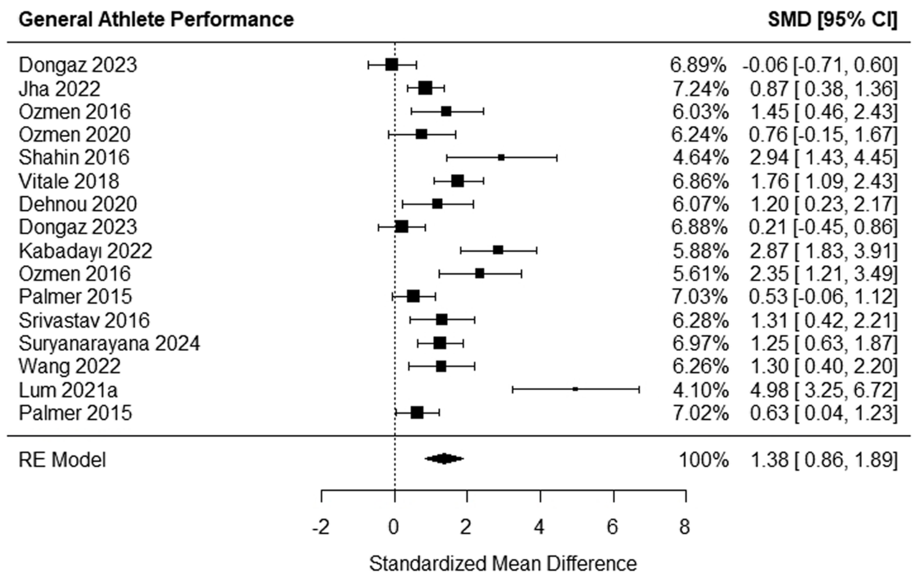

Fig. 4 Moderator analysis of core training's effects on general athlete performance. Forest plot displaying the moderator analysis of core training's effects on general athletic performance across 13 studies (The forest map contains duplicate reports, so there are only 13 studies reported). Effect sizes shown as standardized mean differences (SMD) with 95% confidence intervals. Overall effect size: SMD = 1.38 [95% CI: 0.86, 1.89]. Individual study weights indicated by box size

Table 4 Summary table of meta-analysis results

Outcome Measure	Number of Studies (k)	Sample Sizes (Exp/Ctrl)	Effect Size (SMD [95% CI])	*P* value	I^2 Value (%)
Core Endurance	8	132/115	1.32 [0.57, 2.08]	0.004	77
Balance	7	112/110	0.99 [0.29, 1.69	0.01	62
Speed	6	98/95	− 0.28 [− 0.86, 0.31]	0.28	58
Maximal Strength	7	95/95	7.57 [− 7.75, 22.89]	0.27	100
Flexibility	4	99/99	0.48 [− 0.76, 1.73]	0.30	83
Change of Direction	5	71/67	0.10 [− 0.56, 0.76]	0.69	37
Technical Skill Performance	9	110/103	0.71 [− 4.38, 5.81]	0.75	99
Throwing Velocity/Distance	6	86/78	1.52 [− 0.43, 3.48]	0.10	93
Vertical Jump Height	8	116/110	0.90 [− 0.23, 2.03]	0.10	90

effects were reported by [57] and [63] with standardized mean differences of 2.87 (95% CI [1.79, 3.95]) and 2.68 (95% CI [1.40, 3.95]) respectively. More moderate effects were found by [51] (SMD =1.20, 95% CI [0.22, 2.19]) and [69] (SMD =1.31, 95% CI [0.41, 2.22]), while [52] reported the smallest effect (SMD =0.21, 95% CI [− 0.45, 0.86]).

Balance
Meta-analysis of balance performance across 7 studies encompassing 222 participants (112 experimental, 110 control) demonstrated a significant positive effect of core training interventions (SMD =0.99, 95% CI [0.29, 1.69], $P=$ 0.01). The analysis revealed moderate heterogeneity ($I^2=$ 62%) (see Table 4 and Appendix 3b). Effect sizes varied considerably across studies, with [67] reporting the largest improvement (SMD =2.94, 95% CI [1.28, 4.59]), followed by [74] (SMD =1.76, 95% CI [1.09, 2.43]). More modest effects were observed by [47] (SMD =1.18, 95% CI [0.48, 1.87]) and [55] (SMD =0.87, 95% CI [0.37, 1.36]), while [52]demonstrated the smallest effect (SMD =0.08, 95% CI [− 0.58, 0.73]). The 95% prediction interval [− 0.53, 2.59] suggests substantial variability in potential effects across different contexts.

Sport-specific performance measures

Speed

Analysis of sprint performance across 6 studies involving 193 participants (98 experimental, 95 control) revealed no significant improvement in speed following core training interventions (SMD = − 0.28, 95% CI [− 0.86, 0.31], P = 0.28). The analysis demonstrated moderate heterogeneity (I^2 = 58%). Individual study effects varied considerably, with [47] showing a small positive effect (SMD = 0.33, 95% CI [− 0.31, 0.97]), while [73] reported a significant negative effect (SMD = − 1.25, 95% CI [− 1.93, − 0.57]). Notably, four studies [52, 56, 62, 66] showed minimal or negative effects with SMDs ranging from − 0.21 to 0.33. The 95% prediction interval [− 1.53, 0.97] suggests considerable uncertainty in the true effect of core training on speed performance (see Table 4 and Appendix 3c).

Maximal strength

The analysis of maximal strength outcomes encompassed 7 studies with 190 participants (95 experimental, 95 control), evaluating the effects of core training interventions on maximal strength performance. The forest plot reveals notable heterogeneity in effect sizes, ranging from moderate to very large improvements. One study [50] demonstrated the most substantial effect (SMD = 49.27, 95% CI [34.01, 64.54]), followed by [71] (SMD = 8.16, 95% CI [6.18, 10.14]). More moderate effects were observed in [70] (SMD = 1.67, 95% CI [0.83, 2.52]) and [61] (SMD = 1.18, 95% CI [0.22, 2.15]). The pooled effect estimate indicated a substantial but non-significant improvement (SMD = 7.57, 95% CI [− 7.75, 22.89], P = 0.27), with high heterogeneity (I^2 = 100%). The wide prediction interval [− 32.16, 47.30] suggests considerable uncertainty in the true effect across different contexts (see Table 4 and Appendix 3d).

Flexibility

The meta-analysis examining flexibility outcomes incorporated 4 studies with 198 total participants (99 experimental, 99 control). The results demonstrated a non-significant effect of core training on flexibility measures (SMD = 0.48, 95% CI [− 0.76, 1.73], P = 0.30) with high heterogeneity (I^2 = 83). Individual study effects showed considerable variation, with [70] reporting the largest positive effect (SMD = 1.44, 95% CI [0.62, 2.25]) and [52] showing a moderate improvement (SMD = 0.73, 95% CI [0.05, 1.41]). In contrast, [58] demonstrated a small negative effect (SMD = − 0.42, 95% CI [− 0.82, − 0.03]), while [57] reported a non-significant positive effect (SMD = 0.40, 95% CI [− 0.34, 1.14]). The wide prediction interval [− 2.12, 3.09] indicates substantial uncertainty in the true effect of core training on flexibility across different contexts (see Table 4 and Appendix 3e).

Change of direction

Analysis of change of direction (COD) performance encompassed 5 studies with 138 total participants (71 experimental, 67 control). The meta-analysis revealed a minimal, non-significant effect of core training on COD performance (SMD = 0.10, 95% CI [− 0.56, 0.76], P = 0.69) with moderate heterogeneity (I^2 = 37%). Effect sizes demonstrated relatively consistent patterns across studies, though with varying magnitudes. Three studies reported small positive effects [48, 52, 57] with SMDs ranging from 0.34 to 0.55, while [63] showed a moderate negative effect (SMD = − 0.90, 95% CI [− 1.83, 0.03]). Notably, [66] demonstrated no effect (SMD = 0.00, 95% CI [− 0.63, 0.63]). The relatively narrow prediction interval [− 0.96, 1.16] suggests moderate consistency in potential effects across different context (see Table 4 and Appendix 3f).

Technical skill performance

The meta-analysis of technical skill performance incorporated 9 studies with 213 total participants (110 experimental, 103 control). The analysis revealed a non-significant overall effect of core training on technical skill measures (SMD = 0.71, 95% CI [− 4.38, 5.81], P = 0.75) with high heterogeneity (I^2 = 99%). Individual study effects demonstrated high variability, with [67] reporting the largest positive effect (SMD = 11.45, 95% CI [6.34, 16.56]) and [66] showing a substantial negative effect (SMD = − 15.03, 95% CI [− 18.61, − 11.46]). Moderate positive effects were observed in studies by [57] (SMD = 3.86, 95% CI [2.56, 5.15]) and [49] (SMD = 2.39, 95% CI [1.21, 3.56]). Several studies reported smaller positive effects, including [51, 60, 64] with SMDs ranging from 0.73 to 1.59. The wide prediction interval [− 14.70, 16.13] indicates substantial uncertainty in the true effect of core training on technical skill performance across different contexts (see Table 4 and Appendix 3g).

Throwing velocity/distance

Meta-analysis of throwing velocity performance encompassed 6 studies with 164 participants (86 experimental, 78 control). The results demonstrated high heterogeneity in training responses (I^2 = 93%), with a positive but non-significant overall effect (SMD = 1.52, 95% CI [− 0.43, 3.48], P = 0.10). The magnitude of effects varied substantially across studies, with [59] reporting the largest improvement (SMD = 5.25, 95% CI [3.23, 7.26]), followed by [51] (SMD = 2.73, 95% CI [1.43, 4.04]). More modest effects were observed by [64] (SMD = 1.12, 95% CI [0.16, 2.08]), while [54]demonstrated minimal improvement (SMD =0.18, 95% CI [− 0.48, 0.85]). [65] and [75] showed small positive effects with SMDs of 0.25 and 0.61 respectively. The wide prediction interval [− 3.18, 6.23] suggests considerable uncertainty in the true effect across different throwing contexts (see Table 4 and Appendix 3h).

Vertical jump velocity

Analysis of vertical jump performance included 8 studies with 226 total participants (116 experimental, 110 control). The meta-analysis revealed insignificant effect (SMD =0.90, 95% CI [− 0.23, 2.03], $P= 0.10$) with high heterogeneity ($I^2= 90\%$). Individual study effects demonstrated considerable variation, with [73] reporting the largest improvement (SMD =4.29, 95% CI [3.12, 5.46]), followed by [53] showing moderate positive effects (SMD =1.29, 95% CI [0.25, 2.34]). Several studies reported small to moderate positive effects, including [57, 61, 64], with SMDs ranging from 0.23 to 0.39. Notably, [52] demonstrated minimal effect (SMD =0.04, 95% CI [− 0.61, 0.70]). The wide prediction interval [− 2.22, 4.02] indicates substantial uncertainty in the true effect of core training on vertical jump performance across different contexts (see Table 4 and Appendix 3i).

Sensitivity analyses

Sensitivity analyses using the"one study removed"approach demonstrated varying degrees of robustness across different outcome measures (see Appendix 4). For core endurance, removal of individual studies yielded standardized mean differences (SMD) ranging from 1.09 to 1.49, compared to the original pooled estimate of 1.32 (95% CI [0.57, 2.08]). The removal of [57] produced the largest reduction in effect size (SMD =1.09, 95% CI [0.43, 1.76]), while excluding [51] resulted in the highest increase (SMD =1.49, 95% CI [0.73, 2.25]). Statistical significance remained consistent (all $p< 0.001$) regardless of which study was removed, indicating robust evidence for a positive effect of core training on core endurance. For balance outcomes, removal of individual studies produced SMDs ranging from 0.84 to 1.07 (original SMD =0.99, 95% CI [0.29, 1.69]). The removal of [67] resulted in the greatest decrease in effect size (SMD =0.84, 95% CI [0.28, 1.39]), while excluding [74] yielded the largest increase (SMD =1.07, 95% CI [0.19, 1.95]). All analyses maintained statistical significance ($p < 0.05$), suggesting robust evidence for positive effects of core training on balance.

The SMDs for speed performance ranged from − 0.42 to − 0.07 after individual study removal (original SMD =− 0.28, 95% CI [− 0.86, 0.31]). The removal of [73] substantially changed the effect estimate to − 0.07 (95% CI [− 0.44, 0.30]) and statistical significance ($p = 0.63$), indicating that results for speed performance were not robust and heavily influenced by this single study. For maximal strength outcomes, systematic removal of individual studies produced more variable results, with SMDs ranging from 1.99 to 9.05 (original SMD =7.57, 95% CI [− 7.75, 22.89]). The elimination of [50] decreased the effect size considerably (SMD =1.99, 95% CI [− 1.07, 5.05]), suggesting this study had substantial influence on the original pooled estimate. Statistical significance varied depending on which study was removed (p-values ranging from 0.16 to 0.35), further confirming limited robustness of findings for maximal strength. For technical skill performance, sensitivity analyses revealed substantial variability, with SMDs ranging from 0.32 to 1.92 after study removal (original SMD =0.71, 95% CI [− 4.38, 5.81]). Removal of [57] and [66] notably affected both the magnitude and statistical significance of findings, indicating low robustness for this outcome.

For flexibility outcomes, removal of individual studies produced SMDs ranging from 0.19 to 0.83 compared to the original SMD of 0.48 (95% CI [− 0.76, 1.73]). Excluding [70] led to the largest decrease in effect size (SMD =0.19, 95% CI [− 1.34, 1.71]), while removing [52] resulted in the most substantial increase (SMD =0.83, 95% CI [− 0.44, 2.10]). Statistical significance remained non-significant across all iterations (p-values ranging from 0.11 to 0.65), confirming the original finding that core training demonstrates no significant effect on flexibility. For change of direction performance, sensitivity analyses yielded SMDs ranging from − 0.02 to 0.28 after individual study removal (original SMD =0.10, 95% CI [− 0.56, 0.76]). The removal of [63] resulted in the most substantial effect reduction (SMD =− 0.02, 95% CI [− 0.88, 0.84]), while excluding [57] produced the largest increase (SMD =0.28, 95% CI [− 0.12, 0.67]). All analyses maintained statistical non-significance (all $p> 0.05$), confirming the limited effect of core training on change of direction performance.

For throwing velocity/distance, removal of individual studies resulted in SMDs ranging from 0.86 to 1.83 (original SMD =1.52, 95% CI [− 0.43, 3.48]). Excluding [59] led to the most notable decrease (SMD =0.86, 95% CI [− 0.34, 2.06]), while removing [54] produced the largest increase (SMD =1.83, 95% CI [− 0.60, 4.26]). Statistical significance was notably affected by study removal, with p-values ranging from 0.10 to 0.15, suggesting borderline significance and limited robustness of findings for this outcome. For vertical jump height, removal of individual studies yielded SMDs ranging from 0.40 to 1.03 (original SMD =0.90, 95% CI [− 0.23, 2.03]). Excluding [73] substantially reduced the effect size (SMD =0.40, 95% CI [0.09, 0.70]) but notably increased statistical significance ($p = 0.02$). Removing [52] produced the largest effect estimate (SMD = 1.03, 95% CI [− 0.28, 2.34]) with reduced statistical significance (p = 0.10). These inconsistent patterns in both effect size and significance after study removal indicate moderate stability of findings for vertical jump performance.

Subgroup analysis

The subgroup analysis examining competitive level effects on balance performance encompassed 7 studies with 222 total participants (112 experimental, 110 control). The analysis revealed distinct patterns across four competitive levels, with high heterogeneity between subgroups (I^2 = 77.6%). Amateur level athletes, represented by a single study [67], demonstrated the largest effect (SMD = 2.94, 95% CI [1.28, 4.59], P = 0.0005). Professional athletes, also represented by one study [74], showed substantial improvements (SMD = 1.73, 95% CI [0.77, 2.69], P = 0.0004). The semi-professional category, comprising three studies [47, 55, 64], exhibited consistent positive effects (SMD = 0.93, 95% CI [0.46, 1.41], P < 0.00001) with notably low heterogeneity (I^2 = 0%). Youth competitive athletes, analysed in two studies [52, 63], showed the smallest improvement (SMD = 0.29, 95% CI [− 3.30, 3.87], P = 0.31) with low heterogeneity (I^2 = 7%) (Fig. 5).

The analysis of moderating factors in core training effectiveness encountered several methodological constraints. While the study identified seven key moderators (competition level, sport type, intervention duration, training frequency, session duration, gender, and age group), the uneven distribution of studies across these variables precluded comprehensive analysis of all factors. This methodological limitation is particularly evident in the examination of competition level effects on balance performance, where the seven included studies were distributed unevenly across four competitive levels:

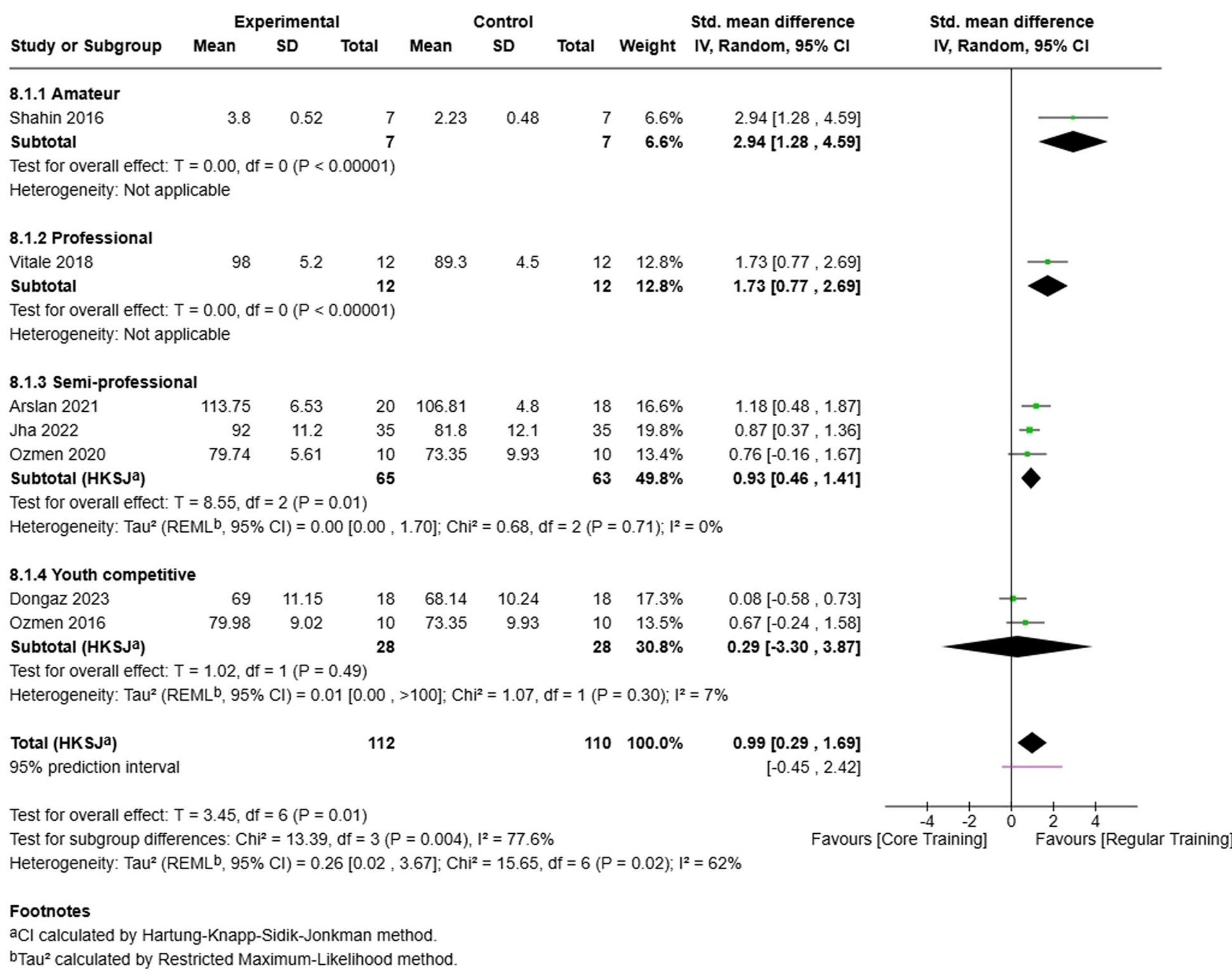

Fig. 5 Competition level as a moderator of balance performance. Subgroup analysis examining the influence of competition level on balance performance improvements. Results stratified by professional (n = 1), semi-professional (n = 3), amateur (n = 1), and youth competitive (n = 2) levels. Effect sizes and confidence intervals displayed for each competitive level

professional (n = 1), amateur (n = 1), semi-professional (n = 3), and youth competitive (n = 2). The concentration of studies within certain competitive levels while having minimal representation in others reflects a common challenge in sports science research, where intervention complexity and population availability often result in imbalanced study distributions. This distribution pattern, while limiting certain statistical comparisons, provides focused insights into specific competitive levels while highlighting areas requiring additional research.

Discussion

This meta-analysis provides several key insights beyond previous reviews. The participant age range (15–23 years) spans critical developmental periods, encompassing peak motor skill development, enhanced trainability of core stability, and optimal performance enhancement potential [77, 78]. This comprehensive age distribution strengthens the ecological validity of the study's findings. The diverse competitive levels represented offer broader insights than previous analyses focused on single populations [5, 76]. While the low heterogeneity in amateur (I2 =0%) and youth competitive (I2 =0%) categories might suggest more consistent training responses across these groups, the limited number of studies in each category necessitates caution in interpretation. The higher heterogeneity in semi-professional categories (I2 =75%) indicates more variable adaptations at advanced levels, highlighting the context-dependent nature of core training responses.

The variety of sports categories examined extends beyond previous meta-analyses of single sports [4–6]. While low heterogeneity in team sports (I^2= 0%) might suggest more consistent core training responses in these contexts, the higher heterogeneity in individual sports (I^2= 67%) indicates more variable adaptations. This variability suggests that core training effects may be sport-specific rather than universally applicable across all athletic contexts. The standardized approach to control conditions, maintaining regular training volumes and intensities [59, 65], strengthens the validity of intervention effects. This systematic categorization of control activities provides a robust foundation for interpreting performance outcomes. The comprehensive measurement of multiple performance outcomes through varied assessment methods allows for thorough evaluation of core training effects. This multi-faceted approach provides practitioners with evidence-based insights for implementing core training across different sports and competitive levels while maintaining methodological rigor through RCT-only inclusion.

The comprehensive funnel plot analysis revealed varying degrees of publication bias across different performance measures. General athletic performance outcomes (balance, core endurance) showed more consistent reporting patterns compared to sport-specific measures, which demonstrated greater asymmetry and potential selective reporting. This pattern aligns with but shows more nuanced bias patterns than previous meta-analyses in the field [4, 5]. The observed asymmetries suggest the need for more comprehensive reporting of null and negative findings, particularly in sport-specific performance measures. These findings highlight the importance of considering publication bias when interpreting the overall effects of core training on athletic performance.

Core training and athlete performance

Core endurance and balance

The findings of the effects of core training on core endurance align with but show stronger effects than those reported in previous meta-analyses. For instance, [4] found only moderate effects on core endurance (SMD =0.90, 95% CI [0.54, 1.26]) in their analysis of sport-specific performance outcomes. The higher effect size in the study's results (SMD =1.32, 95% CI [0.57, 2.08], $P<$ 0.004), combined with the high heterogeneity (I^2= 77%), suggests that while core training may improve endurance, the magnitude of improvement varies considerably across different populations and training protocols. This high heterogeneity indicates that effects are likely context-dependent rather than universal. This variability was also noted by [6], though they focused more on sport-specific performance measures than core endurance specifically.

Comparative analysis of the study's results on the effects of curtaining on balance with existing literature reveals consistency in the positive direction of effects, though with varying magnitudes. Rodríguez-Perea et al. (2023) reported a large effect on balance (SMD =1.17, p= 0.001) with notably moderate heterogeneity (I^2= 66%), while Dong et al. (2023) similarly found substantial improvements (SMD =0.81, 95% CI [0.34, 1.27], I^2= 0%). The current analysis demonstrates stronger effects than these previous meta-analyses (SMD =0.99, 95% CI [0.29, 1.69], P= 0.01), potentially due to the inclusion of more recent studies and diverse athletic populations. The observed moderate heterogeneity (I^2= 62%) aligns with the theoretical framework suggesting that balance adaptations may be influenced by multiple factors including training protocol specificity, athlete characteristics, and sport-specific demands. This interpretation is supported by [5], who identified significant balance improvements in sport-specific contexts, emphasizing the need for targeted core training interventions.

The results indicate that core training improves core endurance, although the magnitude of improvement varies considerably across different populations and training protocols, as evidenced by the high heterogeneity. Similarly, balance performance showed significant enhancements following core training interventions, but with moderate heterogeneity, suggesting that the effectiveness may depend on factors such as training specificity and athlete characteristics. This finding suggests that core training may reliably improve relative strength measures, although more research is needed to confirm this across a broader range of contexts. Overall, these findings support the effectiveness of core training for enhancing general athletic performance qualities, particularly core endurance and balance. However, the observed heterogeneity highlights the need for careful consideration of individual athlete characteristics and training protocols when implementing core training interventions.

Sport-specific outcomes

The results of the effects of core training on speed (SMD = − 0.28, 95% CI [− 0.86, 0.31], P = 0.28) align with the results reported by [4], who similarly found non-significant effects on speed performance (SMD = − 0.32, 95% CI [− 1.05, 0.40]) in their analysis. The observed variability in outcomes supports [6] conclusion that core training may have limited direct transfer to speed capabilities. This study analysis extends these findings by demonstrating consistent non-significant effects across a broader range of athletic populations and training protocols. The moderate heterogeneity observed suggests that factors such as training specificity and athlete characteristics may influence the relationship between core training and speed performance. This interpretation is particularly relevant given the contrasting findings between team sport athletes [47, 66] and individual sport athletes [56, 62] in the analysis.

The high heterogeneity observed in the analysis extends beyond previous findings in the literature (SMD = 7.57, 95% CI [− 7.75, 22.89], P = 0.27; I^2 = 100%). While [6] reported moderate effects on strength measures, their analysis showed more consistent effects across studies. These findings reveal more dramatic variations in training responses, particularly evident in the contrast between [50] and [71] large effect sizes versus the more modest improvements reported by [59] and [52]. This variability may reflect differences in measurement approaches and training protocols across studies, a limitation also noted by [4] in their meta-analysis. This high variability and non-significant overall effect suggest that core training cannot be reliably expected to enhance maximal strength across different contexts. The variability likely reflects differences in measurement approaches and training protocols across studies, a limitation also noted by [76] in their sport-specific analysis.

The analysis reported nonsignificant effects of core training on flexibility but with high heterogeneity (SMD = 0.48, 95% CI [− 0.76, 1.73], P = 0.30; (I^2 = 83%) denoting a significant finding in the context of existing literature. While [5] identified flexibility as a critical research gap in their sport-specific review of badminton performance, this analysis provides empirical evidence of the variable effects of core training on flexibility outcomes. The contrasting results between studies suggest that flexibility adaptations may be highly specific to the training protocol and athlete population. This interpretation aligns with [6] observations regarding the importance of training specificity, though they did not explicitly analyze flexibility outcomes. The significant variation in effect sizes, particularly evident in the contrast between [70] positive findings and [58] negative results, suggests that the relationship between core training and flexibility development may be moderated by factors such as training protocol design and sport-specific requirements.

The findings on the effects of core training ion change of direction (SMD = 0.10, 95% CI [− 0.56, 0.76], P = 0.69, I^2 = 37%) align with but provide better insights than previous analyses in the literature [6] reported moderate effects on agility measures, a finding this study's analysis partially challenges through more specific examination of COD performance. The lower heterogeneity observed in this analysis (I^2 = 37%) compared to other performance measures suggests more consistent training responses for COD ability. This observation is particularly noteworthy given the diverse athlete populations represented, from youth athletes [57] to elite performers [66]. The neutral to slightly positive effects demonstrated in most studies indicate that while core training may contribute to COD performance, its impact is likely secondary to other training factors. This interpretation is supported by [4], who similarly found limited transfer of core training benefits to dynamic performance measures.

The findings on effects of core training on technical skill performance revealed nonsignificant effect (SMD = 0.71, 95% CI [− 4.38, 5.81], P = 0.75) with high heterogeneity (I^2 = 99%), contradicting claims of universal benefits to sport-specific skills. These findings diverge from those reported by [4], who found more consistent effects on sport-specific performance measures. The dramatic contrast in outcomes, especially evident between [67] and [66], suggests that technical skill adaptations to core training are highly inconsistent and likely contingent on specific combinations of sport type, athlete characteristics, and assessment methods employed rather than representing a reliable training effect. This interpretation aligns with [6] observations regarding the importance of training specificity, though they reported more modest variations in effect sizes. The substantial positive effects demonstrated in combat sports [57] and individual sports [49] compared to team sports contexts suggests that the relationship between core training and technical skill development may be moderated by sport-specific demands and movement patterns. The high heterogeneity (I^2= 99%) underscores the complexity of this relationship and the potential influence of factors such as skill level, training protocol design, and assessment methodology.

Our findings further extend the current understanding of core training's impact on throwing performance beyond previous analyses. [6] reported more modest effects on throwing velocity (ES =0.30), while the analysis reveals potentially larger but more variable improvements (SMD =1.52, 95% CI [− 0.43, 3.48], P= 0.10; I^2= 93%). The high heterogeneity observed may reflect the diverse throwing demands across different sports, from handball [59] to wrestling-specific movements [51]. This interpretation is supported by the contrast between the large effects in combat sports and the more moderate improvements in team sports contexts. The variation in effect sizes aligns with [4]observations regarding the sport-specific nature of core training adaptations, though the analysis suggests greater potential for throwing velocity enhancement in certain contexts. The high heterogeneity (I^2= 93%) underscores the importance of considering sport-specific movement patterns and technical requirements when implementing core training for throwing performance enhancement.

The findings of the effects of core training on vertical velocity also extend beyond previous research while highlighting important methodological considerations. [6] reported more consistent effects on vertical jump performance (ES =0.69), whereas the analysis reveals greater variability in training responses effect (SMD =0.90, 95% CI [− 0.23, 2.03], P= 0.10). The stark contrast between outcomes, particularly evident in the comparison between [73] and [52], suggests that jump performance adaptations may be influenced by factors beyond core training alone. The high heterogeneity observed (I^2= 90%) aligns with [4] observations regarding the sport-specific nature of performance adaptations, though the analysis indicates potentially larger effects in certain contexts. The trend toward significance (P = 0.05) despite substantial between-study variation suggests that core training may contribute to vertical jump performance enhancement, though the magnitude of improvement likely depends on training protocol design and athlete characteristics.

The meta-analysis results reveal a complex and largely inconsistent relationship between core training and sport-specific performance measures. While some outcomes, such as maximal strength and throwing velocity, showed potentially large but statistically non-significant improvements, the wider confidence intervals and high heterogeneity (I^2= 93–100%) indicate that these effects are highly unreliable. Speed, flexibility, change of direction, and technical skill performance all demonstrated limited or non-significant improvements following core training interventions, challenging the common assumption that core training directly enhances sport-specific performance capabilities. These findings suggest that the transfer of core training adaptations to sport-specific skills may be highly context-dependent, influenced by factors such as training protocol specificity, athlete characteristics, and sport-specific demands. The contrast in effects between different sports and skill categories highlights the importance of considering these contextual factors when implementing core training programs. The high heterogeneity observed in several outcomes, particularly technical skill performance and maximal strength, underscores the complexity of the relationship between core training and sport-specific performance enhancement.

Sensitivity analysis implications

The sensitivity analyses conducted across multiple outcome domains revealed critical patterns that warrant careful interpretation. For general athletic performance measures, particularly core endurance and balance, the findings demonstrated remarkable stability against the systematic removal of individual studies. Effect magnitudes remained consistently large, and statistical significance was preserved throughout all iterations. This stability substantially strengthens confidence in the conclusion that core training effectively enhances these foundational athletic qualities. In contrast, sport-specific performance measures exhibited considerably greater sensitivity to individual study influence. Speed performance results were particularly unstable, with both effect magnitude and statistical significance shifting substantially upon removal of single studies, notably [73]. Similarly, maximal strength outcomes varied dramatically in response to study removal, with effect sizes fluctuating between 1.99 and 9.05 depending on which study was excluded. This extensive variability undermines confidence in the robustness of these findings.

The observed differential patterns align with theoretical expectations about the specificity of training adaptations. The sensitivity analysis reveals a systematic pattern whereby general athletic qualities show robust improvements across various study contexts, while sport-specific performance enhancements appear more contingent on particular methodological approaches, populations, or intervention characteristics. This aligns with the principle that transfer effects become increasingly variable as performance measures become more specialized and complex [79, 80]. These findings carry important implications for practice. The stable positive effects on core endurance and balance suggest these adaptations are reliable outcomes of core training across diverse contexts. Conversely, the variable findings for sport-specific outcomes indicate that practitioners should maintain measured expectations regarding direct performance enhancement in specialized athletic tasks. This pattern reinforces the recommendation that core training should be conceptualized primarily as developing foundational athletic qualities that may indirectly support sport performance rather than as a direct enhancer of specialized sport skills.

Subgroup analysis

The differential effects observed across competitive levels as observed from the subgroup analysis provide important insights into the relationship between training status and core training adaptations. The overall effect (SMD $=0.99$, 95% CI [0.29, 1.69], $P< 0.01$) suggests a generally positive impact of core training on balance performance, though with considerable variation between competitive levels ($I^2= 62\%$). The stronger effects observed in amateur and professional athletes, compared to youth competitive athletes, align with [6] findings regarding training experience and adaptation potential. However, the notably consistent effects among semi-professional athletes ($I^2= 0\%$) suggest that this population may represent an optimal balance between training experience and adaptation potential. The moderate overall heterogeneity ($I^2= 62\%$) indicates that while competitive level significantly moderates training responses, other factors likely contribute to the observed variations in effectiveness.

The subgroup analysis findings, while promising, must be interpreted with considerable caution. The reliance on single studies for professional and amateur levels limits the ability to distinguish true level-specific effects from study-specific factors. The wide confidence intervals, particularly in the youth competitive category (SMD $=0.29$, 95% CI [− 3.30, 3.89]), indicate substantial uncertainty in the true magnitude of effects. Furthermore, the moderate heterogeneity ($I^2= 62\%$) suggests that other factors beyond the competitive level may influence training effectiveness. According to [5, 6, 52, 76, 81], the dispersion of studies across multiple moderators and outcomes often resulted in insufficient data for meaningful statistical comparisons. This fragmentation represents a critical gap in the understanding of how various factors influence core training effectiveness and highlights the need for more systematic research approaches.

Limitations

Several notable limitations should be considered when interpreting the results of this meta-analysis. The methodological quality of the included studies was moderate, with an average PEDro score of 5.65, and a high risk of bias particularly in intervention implementation and blinding procedures. A significant methodological limitation was the inability to statistically assess publication bias using Egger's test, as none of the outcome categories included the minimum recommended 10 studies. This constraint necessitated reliance on visual inspection of funnel plots alone, which has recognized subjective limitations and reduced reliability for detecting true publication bias. High heterogeneity across studies in training duration protocols, including varying durations (4–24 weeks), frequencies (1–5 sessions/week), and intensities, made it challenging to determine optimal training parameters. The included studies showed uneven distribution across competitive levels and limited representation of female athletes, restricting generalizability across different athletic populations. Outcome measurements lacked standardization, with different testing methods and success criteria used across studies, potentially affecting the reliability of between-study comparisons. Statistical limitations included high heterogeneity ($I^2> 75\%$) in many outcome measures and insufficient data for comprehensive moderator analysis comparisons [5, 6, 52, 76, 81]. The analysis of sport-specific adaptations was limited by the varying relevance of core training to different sports and insufficient sport-specific data. Additionally, most studies lacked long-term follow-up data, leaving questions about the sustainability of observed improvements unanswered. The varying types of control group activities and inconsistent reporting of control protocols further complicated interpretation. These limitations highlight the need for more standardized, high-quality research in this area, particularly focusing on long-term effects and sport-specific applications of core training.

The challenges encountered in the moderator analyses have important implications for future research. First, they emphasize the need for more studies examining core training effects within specific competitive levels and other moderator categories. Second, they highlight the importance of standardized reporting of potential moderating variables and training duration protocols. Finally, they suggest the value of focused research programs examining specific moderator effects rather than attempting to address multiple factors simultaneously. Despite these limitations, the analysis provides valuable insights into the complexity of core training effectiveness and its potential dependence on athlete characteristics and training parameters comparisons [5, 6, 52, 76, 81]. The stronger effects observed at higher competitive levels suggest that training experience or athletic capability may influence the benefits derived from core training interventions. However, the limited evidence base prevents definitive conclusions about these relationships.

Looking forward, advancing the understanding of core training effectiveness requires addressing these methodological challenges. Future research should prioritize replication within specific moderator categories, standardize outcome measures across studies, and provide comprehensive reporting of potential moderating variables. This approach would facilitate a more robust meta-analytic synthesis and enable stronger conclusions about how various factors influence training effectiveness. While the analysis suggests that factors such as competition level may moderate core training effectiveness, the current state of evidence allows only preliminary conclusions. The limitations encountered in analysing moderating effects highlight both the complexity of training intervention research and the need for more systematic approaches to examining these relationships. Future research addressing these limitations will be crucial for developing more nuanced and evidence-based recommendations for core training implementation across different athletic populations.

Conclusion

This comprehensive meta-analysis examining the effects of core training on athletic performance reveals a complex and nuanced picture of its effectiveness across different performance domains. The findings suggest that core training may have positive effects on certain general athletic performance measures, particularly core endurance and balance, though with substantial heterogeneity ($I^2 = 62–77\%$) indicating context-dependent rather than universal benefits. Its impact on sport-specific performance measures, however, shows even greater variability and generally smaller, non-significant effects. Despite common claims in practice, core training did not demonstrate significant improvements in maximal strength, and showed only near-significant effects on vertical jump performance while demonstrating limited or non-significant effects on speed, flexibility, change of direction, technical skills, and throwing performance. The high heterogeneity observed across most outcomes suggests that training responses vary considerably depending on factors such as training duration protocol, athlete characteristics, and sports context. These findings have important practical implications for coaches and practitioners. Core training should be viewed as a valuable component of athletic development programs, particularly for enhancing foundational athletic qualities. However, it should not be relied upon as a primary intervention for developing sport-specific capabilities. Instead, core training should be integrated with other training methods specifically targeted at desired performance outcomes. Future research should address the limitations identified in this analysis by implementing more standardized protocols, examining long-term training effects, and investigating the influence of moderating factors such as competitive level, age, and gender. Additionally, sport-specific applications of core training warrant further investigation to optimize its integration into different athletic contexts. In conclusion, while core training has clear benefits for general athletic performance, its application should be carefully considered within the broader context of athletic development programs, with attention to sport-specific requirements and individual athlete needs.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

YTW was responsible for the overall design and coordination of the study. He led the data analysis and was involved in interpreting the results and drafting the manuscript. XYX was in charge of the execution of the experiments and preliminary data processing in the study. He also contributed to writing the methods section of the manuscript. ZZJ participated in data collection and analysis and assisted in writing the results section of the manuscript. SYS Assist with the organization of images and adjustments to formatting, and conduct a review and polish the wording throughout the entire text. ZJH Assisted in paper revision and data collation, and adjusted the scale of forest plots. DCW as the corresponding author, was responsible for the final review of the manuscript and ensuring the academic integrity of the research. He also participated in the study design and discussion of the results.

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Data availability

All data comes from references and is publicly available.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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