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SYSTEMATIC REVIEW

The Role of Trunk Muscle Strength for Physical Fitness and Athletic Performance in Trained Individuals: A Systematic Review and Meta-Analysis

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Abstract

Background The importance of trunk muscle strength (TMS) for physical fitness and athletic performance has been demonstrated by studies reporting significant correlations between those capacities. However, evidence-based knowledge regarding the magnitude of correlations between TMS and proxies of physical fitness and athletic performance as well as potential effects of core strength training (CST) on TMS, physical fitness and athletic performance variables is currently lacking for trained individuals.

Objective The aims of this systematic review and meta-analysis were to quantify associations between variables of TMS, physical fitness and athletic performance and effects of CST on these measures in healthy trained individuals.

Data Sources PubMed, Web of Science, and SPORTDiscus were systematically screened from January 1984 to March 2015.

Study Eligibility Criteria Studies were included that investigated healthy trained individuals aged 16–44 years and tested at least one measure of TMS, muscle strength, muscle power, balance, and/or athletic performance.

Study Appraisal and Synthesis Methods Z-transformed Pearson's correlation coefficients between measures of TMS and physical performance were aggregated and back-transformed to r values. Further, to quantify the effects of CST, weighted standardized mean differences (SMDs) of TMS and physical performance were calculated using random effects models. The methodological quality of CST studies was assessed by the Physiotherapy Evidence Database (PEDro) scale.

Results Small-sized relationships of TMS with physical performance measures ($-0.05 \leq r \leq 0.18$) were found in 15 correlation studies. Sixteen intervention studies revealed large effects of CST on measures of TMS (SMD = 1.07) but small-to-medium-sized effects on proxies of physical performance ($0 \leq \text{SMD} \leq 0.71$) compared with no training or regular training only. The methodological quality of CST studies was low (median PEDro score = 4).

Conclusions Our findings indicate that TMS plays only a minor role for physical fitness and athletic performance in trained individuals. In fact, CST appears to be an effective means to increase TMS and was associated with only limited gains in physical fitness and athletic performance measures when compared with no or only regular training.

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Key Points

The present systematic review and meta-analysis characterized and quantified associations between measures of trunk muscle strength (TMS), physical fitness, and athletic performance and investigated the effects of core strength training (CST) versus no training, regular training only or alternative training on fitness and performance measures in healthy trained individuals.

Irrespective of the athletes' expertise level, our analyses revealed small-sized correlations for TMS with lower limb muscle strength, muscle power, balance, and athletic performance.

When compared with no training or regular training only, CST induced large effects on TMS but small to medium effects on physical fitness and athletic performance measures in trained individuals. However, small effects were detected for CST as compared with alternative training.

Our findings indicate that TMS plays only a minor role in physical fitness and athletic performance in trained individuals. Further, it appears that CST is an effective means to increase TMS but is associated with only limited gains in physical fitness as well as athletic performance and that CST is not superior to alternative training regimens.

1 Introduction

In many sports, adequate levels of physical fitness (e.g., muscle strength/power, endurance) are necessary to successfully perform sport-specific tasks. For instance, during competition in team sports, athletes need high levels of aerobic capacity, speed, and agility, as well as maximal and explosive muscle strength to outperform their opponents [1, 2]. In addition, it has been shown that elite athletes from team (e.g., soccer) and individual (e.g., gymnastics, rowing) sports are superior to sub-elite or recreational trained individuals regarding physical fitness measures such as muscular strength and/or sprint time [3–5].

It is well-known that improvements in athletes' physical performance can be achieved by means of strength training [6–8]. One specific strengthening method that has recently received a lot of attention, particularly in the lay literature, is core strength training (CST), because the core appears to play a crucial role during performance of everyday [9] and sports-related activities [10]. According to Akuthota et al. [11], the core refers to a muscular box consisting of the abdominals in the front, paraspinals and gluteals in the back, the diaphragm as the roof, and the pelvic floor and hip girdle muscles as the bottom. Functionally, these muscles are centrally located in almost all kinetic chains and important for stabilizing the spine and pelvis, providing proximal stability for distal mobility and function of the limbs during everyday and sports activities [12]. In a recent systematic review, Granacher et al. [13] observed significant associations between measures of trunk muscle strength (TMS), balance, and functional performance in seniors and argued that TMS is important for the successful performance of activities of daily living in older adults. Moreover, it was found that CST programs can be used in addition or even as an alternative to traditional balance and/or strength training programs in order to improve variables of muscle strength, balance, and/or functional performance in old age [13]. Similarly, researchers attempted to elucidate the importance of the trunk for performance measures in athletic populations as well, particularly during the last 2 decades. For instance, Blache and Monteil [14] recently showed in a simulation study with young athletes (25 ± 4 years) that vertical jump height was significantly lower if activity of the spinal erector muscle was excluded from the statistical model. Another study examined rowing performance in elite oarsmen and observed that trunk muscles appear to make the second greatest contribution (following lower leg muscles) to the total linear oar velocity during on-water and ergometer rowing [15]. Taking these findings into account, it seems reasonable to argue that there is a link between performance levels in measures of TMS and sport-specific tasks (e.g., jump height, rowing time) in athletes. Based on this intuitive association of TMS with physical fitness and athletic performance variables, we hypothesize that training-induced improvements in activation of trunk muscles may even improve measures of physical fitness and athletic performance as a result of enhanced TMS. In support of this assumption, Andersson et al. [16] reported significantly higher peak torque values for isokinetic TMS in young male elite athletes (18–22 years) from different sports (e.g., soccer, tennis) compared with male subjects from the normal population (i.e., conscripts). Interestingly, Miltner et al. [17] found significantly higher values of TMS (i.e., isometric ventral and lateral trunk flexion) in elite but not sub-elite athletes, when compared with healthy untrained individuals. Athletes' expertise level may thus be an important factor in trained individuals that has an impact on both the magnitude of associations between TMS and proxies of physical fitness and athletic performance and the magnitude of training-induced effects of CST on TMS, physical fitness, and athletic performance measures. However, to the best of our knowledge, there is no systematic review and meta-analysis available that provides high-level evidence regarding the effects of CST on physical fitness and athletic performance in trained individuals. The already published review articles are limited in terms of their evidence level (i.e., narrative reviews [12, 18–20]) and the applied training protocols (i.e., CST integrated in more comprehensive training programs [21]).

Therefore, the objectives of this systematic review and meta-analysis are to (a) characterize and quantify associations between TMS and measures of physical fitness and athletic performance, and (b) determine general effects of CST on measures of TMS, physical fitness, and athletic performance in trained individuals. With reference to the relevant literature [12–16], we expected (a) large-sized associations between TMS, physical fitness, and athletic performance, and (b) physical fitness and athletic performance enhancements following CST in trained individuals. Further, we hypothesized that these findings are modulated by the athletes' expertise level.

2 Methods

The present systematic review and meta-analysis was conducted in accordance with the recommendations of the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) [22].

2.1 Literature Search

Two computerized systematic literature reviews were performed in the databases PubMed, Web of Science, and SPORTDiscus from January 1984 to March 2015; one for correlation and one for intervention studies. The following search terms were included in Boolean search strategies: ("core strength" OR "trunk muscle strength" OR "trunk strength" OR "core stability" OR "torso strength") AND "performance" AND ("relationship" OR "association*" OR "correlation") for correlation studies and ("core strength" OR "trunk muscle strength" OR "trunk strength" OR "core stability" OR "torso strength") AND "performance" AND ("training" OR "intervention") for intervention studies. By using filter criteria of the respective databases, the search was limited to full-text availability, publication dates (i.e., 1984/01/01 to 2015/03/31), human species, ages (i.e., 16–44 years), and English language. Further, the reference lists of the included studies as well as relevant review articles were screened for titles in order to identify additional suitable studies for inclusion in this meta-analysis.

2.2 Selection Criteria

Studies were included in the present systematic review and meta-analysis if they provided relevant information with regards to the PICOS approach. This structured question approach addresses five review components: patient population or disease (P), interventions or exposure of interest (I), comparators (C), main outcome or endpoint of interest (O), and study design (S) [22]. The following criteria and specific experimental characteristics were required: (a) population: healthy trained individuals (i.e., recreational, sub-elite, elite athletes) with mean ages ranging from 16 to 44 years; (b) intervention: CST containing a description of at least one training modality (e.g., training frequency); (c) comparator: passive (i.e., no training), active (e.g., regular training), and/or alternative training (e.g., lower body strength training) control group; (d) outcome: at least one measure of TMS, physical fitness, and/or athletic performance; and (e) study design: controlled study. In this regard, CST was defined as a training program incorporating specific resistance exercises (e.g., machine-based, body weight, Pilates training) with the primary goal to strengthen trunk muscles of the ventral, dorsal, lateral, and rotational chain. Given that most included studies analyzed TMS using measures of trunk muscle endurance, this meta-analysis primarily quantified TMS by variables of muscular endurance of the trunk in the frontal, sagittal, and/or horizontal plane (e.g., holding time during isometric plank tests). In addition, measures of maximal muscle strength of the trunk were used to determine TMS (e.g., peak torque during maximal isokinetic trunk muscle testing). In accordance with Caspersen et al. [23], we included tests for the assessment of health- (e.g., muscle strength) and skill-related (e.g., balance, muscle power) components of physical fitness. For example, muscle strength of lower/upper limbs was tested using, e.g., the squat/bench press one repetition maximum (1 RM), muscle power was assessed, e.g., by means of vertical jump height, and balance was tested, e.g., using the star excursion balance test. Proxies of athletic performance included sport-specific performance measures such as swimming or running times.

Studies were excluded if they (a) examined young healthy individuals that were not classified as physically active on a regular basis; (b) had no control group and/or CST groups only (e.g., performed on different surfaces); (c) did not meet the minimum requirements regarding the description of training modalities (e.g., period, frequency); and (d) did not report results adequately (i.e., correlation coefficients, means and standard deviations/errors) or if respective authors did not reply to our inquiries sent by email. Based on the defined inclusion and exclusion criteria, two independent reviewers (O.P., T.M.) screened potentially relevant papers by analyzing titles, abstracts, and full texts of respective articles to elucidate their eligibility.

2.3 Coding of Studies

Each study was coded for the following variables: number of participants, sex, age, expertise level, and sport pursued by the subjects. The expertise level of the participants was classified as elite (national/international top-level athletes), sub-elite (competitive athletes, e.g., third division or varsity), and recreational athletes [24]. Additionally, in terms of training studies, CST programs were coded for the following modalities: training type, period, frequency, and volume (i.e., number of sets per exercise, number of repetitions per set). Our analyses focused on measures of TMS, muscle strength, muscle power, balance, and athletic performance. Prone plank tests were preferentially used for the category TMS, 1 RM of leg extensors for muscle strength, the countermovement jump test for muscle power, the star excursion balance test for balance, and running/swimming/rowing times for athletic performance. Several authors were helpful and responded to our requests by sending missing data. Further, data from two studies were included in which the pre- and post-testing means and standard deviations were estimated from the published figures [25, 26].

2.4 Assessment of Methodological Quality

Given that there is no consensus regarding reliable and valid instruments for the assessment of methodological quality of correlation studies [27], no rating of studies was conducted. For intervention studies, the Physiotherapy Evidence Database (PEDro) scale was used to quantify the quality of the included studies on a scale from 0 to 10 points, with $\geq$6 points representing a cut-off score for high-quality studies [28]. Two independent reviewers (O.P., T.M.) performed quality assessments of the included studies. When disagreement between raters occurred, a consensus meeting was performed and an additional rating was obtained from a third assessor (U.G.) to achieve consensus.

2.5 Statistical Analyses

Associations between variables of TMS, physical fitness, and athletic performance were assessed using the Pearson product-moment correlation coefficient (r value). To pool correlation coefficients derived from different studies, z-transformed r values (i.e., r_z values) were calculated according to the formula $r_z = \frac{1}{2}[\ln(1 + r) - \ln(1 - r)]$ where ln is the natural logarithm [29]. Further, to determine the effects of CST on outcome measures, the between-subject standardized mean differences (SMDs) were calculated according to the following equation: $\mathrm{SMD} = \frac{m_1 - m_2}{s_{\mathrm{pooled}}}$ where m_1 stands for the mean post-value of the CST group, m_2 stands for the mean post-value of the control group, and s_{pooled} stands for the pooled standard deviation. In accordance with Hedges and Olkin [30], the SMD was adjusted for the respective sample size by using the factor $\left(1 - \frac{3}{4N-9}\right)$ with N representing the total sample size. The meta-analysis was conducted using Review Manager 5.3 (Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark). By doing so, the included studies were finally weighted according to the magnitude of the respective standard error using a random effects model. In order to improve readability, we consistently reported positive outcomes (r_z, SMD) if benefits of TMS or superiority of CST compared with control or alternative training group were indicated.

Weighted mean r_z values were calculated and subsequently back-transformed to Pearson's r to classify and interpret the correlation sizes as well as the explained variance (r^2). Based on the recommendations of Vincent and Weir [31], values of $0 \leq r < 0.70$ indicate small, $0.70 \leq r < 0.90$ medium, and $r \geq 0.90$ large sizes of correlation. In addition, a statistical analysis was conducted to calculate differences between the mean r values by expertise level (e.g., elite vs. sub-elite). The corresponding formula is as follows: $z = (r_{z1} - r_{z2})/\sqrt{(1/(n_1 - 3) + 1/(n_2 - 3))}$. Further, the calculation of weighted mean SMDs allows for a quantitative evaluation of the effects of CST on different measures of physical fitness and athletic performance, and it helps to determine whether a difference is of practical concern. According to Cohen [32], effect size values of SMD <0.50 indicate small, $0.50 \leq \mathrm{SMD} < 0.80$ indicate medium, and SMD ≥ 0.80 indicate large effects. The level of significance was set at $p < 0.05$.

3 Results

3.1 Study Characteristics

In terms of potentially relevant journal articles, the flow chart in Fig. 1 displays the process of the systematic review through different phases. A total of 419 studies (i.e., $n = 141$ correlation studies, $n = 278$ intervention studies) were initially identified from the literature searches. Finally, 15 correlation studies (Table 1) and 16 intervention studies (Table 2) with a total of 955 healthy trained participants (i.e., 443 in correlation and 512 in intervention

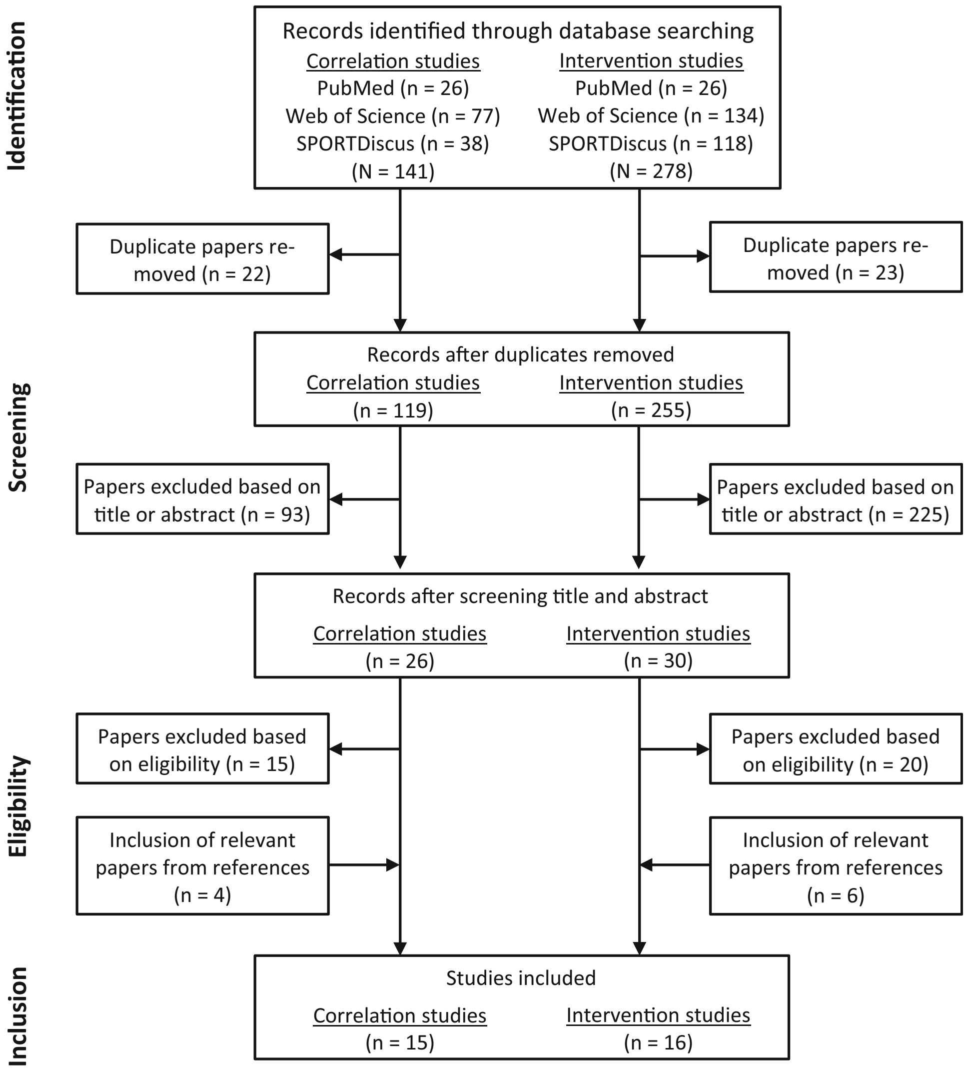


Fig. 1 Flow chart illustrating the different phases of the search and study selection

studies) from different sport disciplines (e.g., athletics, football, golf, swimming) were included in the present review and meta-analysis.

Regarding correlation studies, four studies investigated elite athletes, eight studies used sub-elite athletes, and recreational athletes participated in three studies, according to the classification provided by Lesinski et al. [24]. Further, only seven out of 15 correlation studies [33–39] used maximal trunk muscle testing (e.g., maximal isokinetic strength) instead of trunk muscle endurance testing in order to assess TMS.

In the intervention studies, elite athletes were identified in two studies, sub-elite athletes in ten studies, and recreational athletes in four studies. Three out of 16 intervention studies [26, 40, 41] used maximal trunk muscle testing (e.g., maximal isometric strength, 3 RM) in order to assess TMS, whereas five studies did not assess TMS at all [42–46]. Further, three intervention studies compared the effects of CST versus alternative training programs on measures of physical fitness and athletic performance [40, 42, 47]. Training protocols comprised frontal, dorsal, and lateral CST exercises as well as Pilates exercises under different surface conditions (e.g., stable floor, Swiss ball, sling trainer) and with different activation strategies (e.g., static, dynamic combined with enhanced inspiratory load). The intervention periods lasted for 6–12 weeks, including 2–4 sessions/week.

In terms of quality assessment using the PEDro scale, the results of the analysis are illustrated in Table 3. The median quality score for intervention studies was 4 points (95 % confidence interval 3.5–5), which can be interpreted as low methodological quality. Only two studies reached the pre-determined cut-off score of ≥ 6 points [42, 47].

Table 1 Studies examining associations between measures of trunk muscle strength and physical performance tests (i.e., muscle strength, muscle power, balance, and/or athletic performance) in healthy trained individuals

Study	No. of subjects			Age, years (mean ± SD or range)	Sport activity	Expertise level	Trunk muscle strength tests	Performance tests
	All	M	F					
Ambegaonkar et al. [53]	40	0	40	20 ± 1	Lacrosse, soccer	Sub-elite	Trunk extension/flexion endurance; lateral trunk muscle endurance	Isometric hip strength; Y balance test
Clayton et al. [33]	29	29	0	20 ± 2	Baseball	Sub-elite	Trunk extension/flexion endurance; lateral trunk muscle endurance; MIKS of trunk flexors/extensors/rotators	CMJ; hang clean 1 RM; backward overhead medicine ball throw
Gordon et al. [39]	45	0	45	16 ± 6	Lacrosse	Sub-elite	Bent knee double leg lowering test	Star excursion balance test
Hoppe et al. [49]	10	10	0	24 ± 5	Hockey	Elite	Trunk extension/flexion endurance; lateral trunk muscle endurance	Bench press, squat 1 RM; 20-m sprint; 22-m agility test; incremental endurance test; CMJ
Keogh et al. [48]	30	30	0	18–35	Resistance training	Recreational	Trunk extension/flexion endurance; lateral trunk muscle endurance	Instability strength level (i.e., ratio of performances on unstable vs. stable surfaces) during dumbbell shoulder press
Lin et al. [54]	61	61	0	17 ± 1	Baseball	Sub-elite	Static/dynamic trunk extension/flexion endurance	Bat swing velocity
McKean and Burkett [34]	29	15	14	25 ± 5	Kayak	Elite	Double leg lowering	Bench press and pull up 1 RM; bench pull test; kayak race performance (i.e., 500 m, 1000 m)
Nesser et al. [50]	29	29	0	18–23	Football	Sub-elite	Trunk extension/flexion endurance; lateral trunk muscle endurance	Bench press, squat and power clean 1 RM; 20-yd and 40-yd sprint; shuttle run; CMJ
Nesser and Lee [51]	16	0	16	18–23	Football	Sub-elite	Trunk extension/flexion endurance; lateral trunk muscle endurance	Bench press, squat 1 RM; 40-yd sprint; shuttle run; CMJ
Okada et al. [52]	28	16	12	24 ± 4	Mixed	Recreational	Trunk extension/flexion endurance; lateral trunk muscle endurance	Backward overhead medicine ball throw; T-run agility test; repetitions in single-leg squat
Prieske et al. [35]	29	14	15	23 ± 3	Mixed	Recreational	MIKS of trunk flexors/extensors	Vertical drop jump (stable/unstable surface)
Sharrock et al. [36]	35	20	15	18–22	Mixed (e.g., basketball, swimming, tennis)	Sub-elite	Double leg lowering	T-run agility test; 40-yd sprint; medicine ball throw; CMJ
Shinkle et al. [37]	25	25	0	19 ± 1	Football	Sub-elite	Static/dynamic forward/backward medicine ball throws	Bench press, squat 1 RM; 40-yd sprint; shuttle run; CMJ
Vanlandewijck et al. [38]	13	10	3	26 ± 7	Track (wheelchair)	Elite	MIS of trunk flexors	Wheelchair acceleration on track/ergometer
Wells et al. [55]	24	15	9	23 ± 5	Golf	Elite	Trunk flexion endurance; lateral trunk muscle endurance	Golf ball speed; golf ball carry distance; golf performance statistics (e.g., mean score, average putt distance after a chip shot)

1 RM one repetition maximum, *CMJ* countermovement jump, *F* female, *M* male, *MIKS* maximal isokinetic strength, *MIS* maximal isometric strength, *SD* standard deviation

Table 2 Studies examining the effects of CST on measures of trunk muscle strength and performance tests (i.e., muscle strength, muscle power, balance, and/or athletic performance) in healthy trained individuals

Study	No. of subjects			Age, years (mean ± SD or range)	Sport activity	Expertise level	Trunk muscle strength tests	Performance tests	Interventions
	All	M	F						
Aggarwal et al. [42]	30	15	15	24 ± 1	Outdoor sports	Recreational	NT	Stork balance test, SEBT, multiple single-leg hopping stabilization	Core stability training with exercises enhancing activation of local stabilizers (CST) vs. balance training with single stands on stable and unstable surfaces, etc. (INT) vs. passive CON; 6 weeks, 3×/week, 40–50 min
Amorim et al. [43]	15	3	12	16 ± 1	Dancing	Sub-elite	NT	Muscular endurance in isometric dance techniques (i.e., penché, developpé); flexibility in dance techniques (e.g., arabesque, cambré)	Pilates training using mat-based exercises (e.g., Hundred, Scissors, Side Bend) (CST) vs. active CON; 11 weeks; 2×/week, 60 min
Butcher et al. [40]	55	20	35	23 ± 3	Mixed (e.g., basketball, dancing, athletics)	Sub-elite	Double leg lowering	Leg press 1 RM; CMJ	Core stabilization training with back extension, leg lowering, side support on knees, etc. (CST) vs. leg strength training with seated leg extensions, seated knee extensions, and prone leg curl (INT1) vs. combined core stabilization and leg strength training (INT2) vs. passive CON; 9 weeks, 3×/week
Durall et al. [56]	30	0	30	20 ± 1	Gymnastics	Sub-elite	Muscular endurance of trunk flexors/extensors/lateral trunk flexors right and left	NT	Core training with frontal, dorsal, and lateral strengthening exercises (CST) vs. passive CON; 10 weeks, 2×/week, 15 min
Jamison et al. [47]	36	36	0	20 ± 1	Football	Sub-elite	MIS of trunk flexors, trunk extensors, lateral trunk flexors dominant side/non-dominant side; muscular endurance of trunk flexors, trunk extensors, lateral trunk flexors right	Deadlift 1 RM; 3-cone test, 20-yd shuttle run, standing long jump	Combined core stabilization (e.g., planks, curl ups) and reduced strength training (e.g., bench press, deadlifts) program (CST) vs. whole-body strength training (INT); 6 weeks, 3×/week, 60 min
Kim [41]	17	0	17	22 ± 4	Golf	Sub-elite	Back extension 1 RM, lower back MIS	Squat 1 RM, driver performance (clubhead speed, ball speed, carry distance)	Core training with core strengthening (e.g., crunches) and flexibility exercises (e.g., trunk stretching) conducted at home and during training (CST) vs. active CON; 12 weeks, 3×/week, 90 min

Table 2 continued

Study	No. of subjects			Age, years (mean ± SD or range)	Sport activity	Expertise level	Trunk muscle strength tests	Performance tests	Interventions
	All	M	F						
Lust et al. [57]	40	ND	ND	20 ± 2	Baseball	Sub-elite	Muscular endurance of trunk flexors, trunk extensors, lateral trunk flexors right/left	Functional throwing performance	Combined core strengthening (e.g., partial sit-ups, bridging) and open/closed kinetic chain (e.g., bench press, step ups) program (CST) vs. combined open/closed kinetic chain and plyometric program (CON); 6 weeks, 3×/week, 30–45 min
Mills et al. [44]	30	0	30	18–23	Mixed (volleyball, basketball)	Sub-elite	NT	T agility test, squat jump, static balance	Global core strengthening program with frontal, rotational, and lateral core exercises (CST) vs. stability training (INT) to voluntarily activate local stabilizing muscles (e.g., transversus abdominis, pelvic floor muscles) in several positions (quadruped, supine, sitting, etc.) vs. CON; 10 weeks, 4×/week, 1–4 sets of 5–40 reps/10–30 s
Saeterbakken et al. [45]	24	0	24	17 ± 0	Handball	Sub-elite	NT	Throwing velocity	Core instability strength training with 6 core and rotational exercises using adjustable sling (CST) vs. active CON; 6 weeks, 2×/week, 75 min
Sato and Mokha [46]	28	10	18	37 ± 9	Running	Recreational, sub-elite	NT	SEBT score, 5000-m run, running kinetics	Core strengthening program with frontal, dorsal, rotational, and lateral core exercises incorporating Swiss ball (CST) vs. active CON; 6 weeks, 4×/week, 2–3 sets of 10–15 reps
Stanforth et al. [58]	55	0	55	20-40	Mixed (aerobic, walking, dance)	Recreational	Double leg lowering, muscular endurance of trunk flexors/extensors	NT	Traditional core training on floor with, e.g., crunches and back extensions (CST1) vs. core training on Swiss ball with, e.g., crunches and back extensions (CST2) vs. passive CON; 10 weeks, 2×/week, 2 sets of 10–50 reps
Stanton et al. [59]	22	22	0	16 ± 1	Mixed (basketball, football)	Sub-elite	Muscular endurance of trunk flexors	VO_{2max}, running economy	Core instability strength training using Swiss ball-based exercises (e.g., supine Russian twist, alternating superman) (CST) vs. active CON; 6 weeks, 2×/week, 25 min

Table 2 continued

Study	No. of subjects			Age, years (mean ± SD or range)	Sport activity	Expertise level	Trunk muscle strength tests	Performance tests	Interventions
	All	M	F						
Szymanski et al. [26]	49	49	0	14–18	Baseball	Sub-elite	Trunk rotation 3 RM	Squat 3 RM, bench press 3 RM, hitter's throw test	Whole-body strength and bat swing training combined with rotational medicine ball exercises (CST) vs. whole-body strength and bat swing training (CON); 12 weeks, 3×/week, 2 sets of 6–10 reps
Tong et al. [60]	16	12	4	23 ± 4	Running	Recreational	Muscular endurance of trunk flexors	Running economy	Functional core training (e.g., bridge, dynamic bird dog) combined with enhanced inspiratory load (CST) vs. active CON; 6 weeks (+4 weeks inspiratory muscle training prior to intervention), 3–4×/week; 2–3 sets of 10–15 reps
Tse et al. [25]	45	45	0	21 ± 1	Rowing	Sub-elite	Muscular endurance of trunk flexors/extensors/lateral trunk flexors right and left	CMJ, standing long jump, overhead medicine ball throw, shuttle run, 40-m sprint, 2000-m ergometer rowing	Core stabilization training with static-dynamic and mobility exercises for the trunk muscles and circuit strength training for each major muscle group (CST) vs. active CON; 8 weeks, 2×/week, 30–40 min
Weston et al. [61]	20	10	10	16 ± 1	Swimming	Elite	Muscular endurance of trunk flexors	Pull down 1 RM, 50-m swimming	Core strengthening program with prone bridge, bird-dog, etc. (CST) vs. active CON; 12 weeks, 3×/week, 30 min

1 RM/3 RM one/three repetition maximum, *CMJ* countermovement jump, *CON* control group, *CST* core strength training group, *F* female, *INT* intervention group, *M* male, *MIS* maximal isometric strength, *ND* not defined, *NT* not tested, *reps* repetitions, *SD* standard deviation, *SEBT* star excursion balance test, VO_{2max} maximal oxygen uptake

Table 3 Physiotherapy Evidence Database (PEDro) score of the included longitudinal studies

Study	Eligibility criteria	Randomized allocation	Blinded allocation	Group homogeneity	Blinded subjects	Blinded therapists	Blinded assessor	Drop out <15 %	Intention-to-treat analysis	Between-group comparison	Point estimates and variability	PEDro score
Aggarwal et al. [42]	●	●	●	●	○	○	○	●	○	●	●	6
Amorim et al. [43]	○	○	○	●	○	○	○	○	○	●	●	3
Butcher et al. [40]	●	●	○	●	○	○	○	○	○	●	●	4
Durall et al. [56]	○	○	○	●	○	○	○	●	○	●	●	4
Jamison et al. [47]	○	●	○	●	○	○	●	○	●	●	●	6
Kim [41]	○	○	○	●	○	○	○	●	○	●	●	4
Lust et al. [57]	●	●	○	●	○	○	○	○	○	●	●	4
Mills et al. [44]	●	●	○	●	○	○	○	●	○	●	●	5
Saeterbakken et al. [45]	●	○	○	●	○	○	○	●	○	●	●	4
Sato and Mokha [46]	○	●	○	○	○	○	○	○	○	●	●	3
Stanforth et al. [58]	○	○	○	●	○	○	○	○	○	●	●	3
Stanton et al. [59]	○	○	○	●	○	○	○	●	●	●	●	5
Szymanski et al. [26]	○	●	○	●	○	○	○	●	○	●	●	5
Tong et al. [60]	○	●	○	●	○	○	○	○	●	●	●	5
Tse et al. [25]	○	○	○	●	○	○	○	○	○	●	●	3
Weston et al. [61]	○	○	○	○	○	○	○	●	●	●	●	4

● indicates a "yes" score; ○ indicates a "no" score. The eligibility criteria criterion has to be excluded for calculation of the total PEDro score

3.2 Associations Between Measures of Trunk Muscle Strength and Physical Performance

3.2.1 *Muscle Strength*

Nine studies investigated associations between variables of TMS and muscle strength (e.g., squat 1 RM) [33, 34, 37, 48–53]. The calculation of mean r_z yielded a value of 0.18 ($I^2 = 42$ %, $\chi^2 = 13.74$, $df = 8$, $p = 0.09$) (Fig. 2). The back-transformed r value of 0.18 ($r^2 = 3.2$ %) indicates small-sized correlations.

3.2.2 *Muscle Power*

Associations between variables of TMS and muscle power (e.g., countermovement jump) were investigated in nine studies [34–37, 49–52, 54]. The mean r_z value amounted to 0.02 ($I^2 = 68$ %, $\chi^2 = 25.00$, $df = 8$, $p = 0.002$) (Fig. 3). The back-transformed r value of 0.02 ($r^2 < 0.1$ %) indicates small-sized correlations.

3.2.3 *Balance*

Only two studies investigated potential associations between variables of TMS and balance (e.g., Y-balance test) [39, 53]. The mean r_z value was −0.05 ($I^2 = 50$ %, $\chi^2 = 2.00$, $df = 1$, $p = 0.16$). The corresponding back-transformed r value of −0.05 ($r^2 = 0.3$ %) is indicative of small-sized correlations.

3.2.4 *Athletic Performance*

Nine studies were included in our analyses that investigated associations between measures of TMS and athletic performance (e.g., kayak race time) [34, 36–38, 49–52, 55]. The analyses revealed a mean r_z of 0.18 ($I^2 = 60$ %, $\chi^2 = 20.10$, $df = 8, p = 0.01$) (Fig. 4). The back-transformed r value of 0.16 ($r^2 = 2.6$ %) is indicative of small-sized correlations.

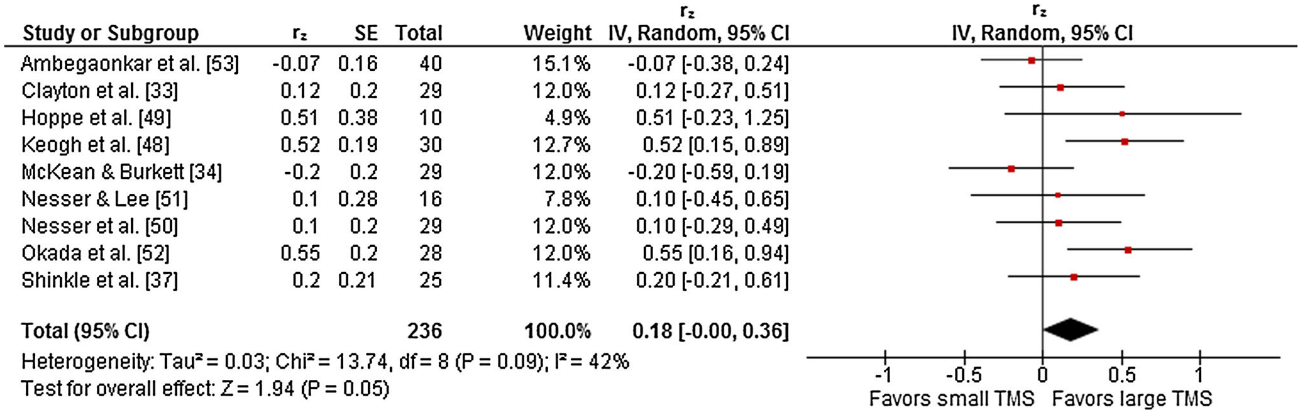
3.2.5 *Differences in Associations by Expertise Level*

Table 4 shows the comparison of correlation coefficients between elite (four studies), sub-elite (six studies), and recreational (three studies) athletes. Statistically significant differences between expertise levels were obtained for the associations of TMS with muscle strength only. More precisely, the back-transformed r value in recreational athletes [$r = 0.49$ ($r^2 = 24.0$ %)] was significantly higher than that found in elite [$r = 0.08$ ($r^2 = 0.6$ %), $z = -2.13$, $p = 0.017$] and sub-elite [$r = 0.07$ ($r^2 = 0.5$ %), $z = -2.92$, $p = 0.002$] athletes. No significant differences were found between elite and sub-elite athletes.

3.3 Effects of Core Strength Training on Physical Performance

3.3.1 *Trunk Muscle Strength*

Nine studies were eligible for inclusion in our systematic review and meta-analysis that determined the effects of CST on measures of TMS compared with no or only regular training [25, 40, 41, 56–61]. The analysis revealed a mean SMD of 1.07 ($I^2 = 83$ %, $\chi^2 = 47.47$, $df = 8$, $p < 0.001$), which is indicative of a large effect in favor of CST (Fig. 5). Further, two studies investigated the effects of CST on measures of TMS compared with alternative training (i.e., whole-body strength training [40, 47]). The respective mean SMD amounted to 0.16 ($I^2 = 57$ %, $\chi^2 = 2.35$, $df = 1$, $p < 0.13$), which is indicative of a small-sized effect in favor of CST.

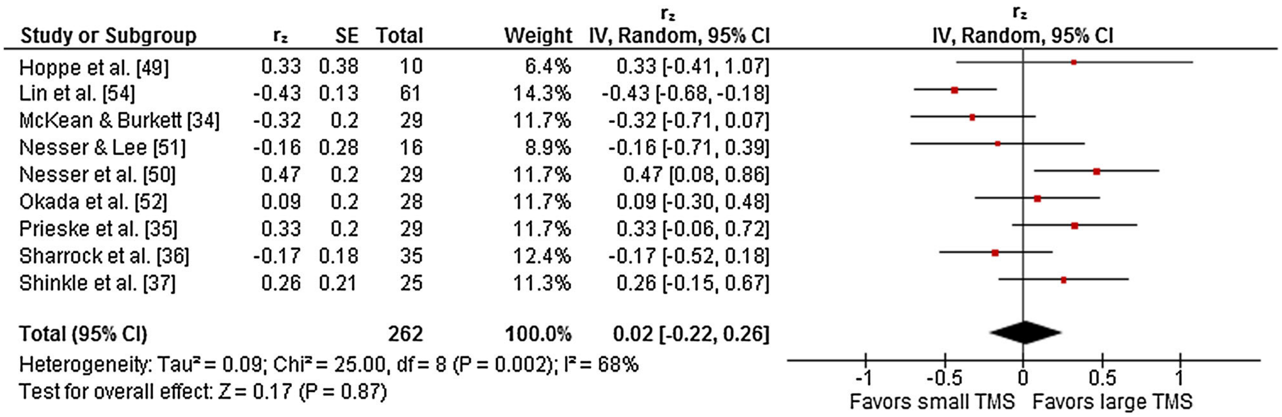


Study or Subgroup	r_z	SE	Total	Weight	r_z IV, Random, 95% CI
Ambegaonkar et al. [53]	-0.07	0.16	40	15.1%	-0.07 [-0.38, 0.24]
Clayton et al. [33]	0.12	0.2	29	12.0%	0.12 [-0.27, 0.51]
Hoppe et al. [49]	0.51	0.38	10	4.9%	0.51 [-0.23, 1.25]
Keogh et al. [48]	0.52	0.19	30	12.7%	0.52 [0.15, 0.89]
McKean & Burkett [34]	-0.2	0.2	29	12.0%	-0.20 [-0.59, 0.19]
Nesser & Lee [51]	0.1	0.28	16	7.8%	0.10 [-0.45, 0.65]
Nesser et al. [50]	0.1	0.2	29	12.0%	0.10 [-0.29, 0.49]
Okada et al. [52]	0.55	0.2	28	12.0%	0.55 [0.16, 0.94]
Shinkle et al. [37]	0.2	0.21	25	11.4%	0.20 [-0.21, 0.61]
Total (95% CI)			**236**	**100.0%**	**0.18 [-0.00, 0.36]**

Heterogeneity: Tau² = 0.03; Chi² = 13.74, df = 8 (P = 0.09); I² = 42%

Test for overall effect: Z = 1.94 (P = 0.05)

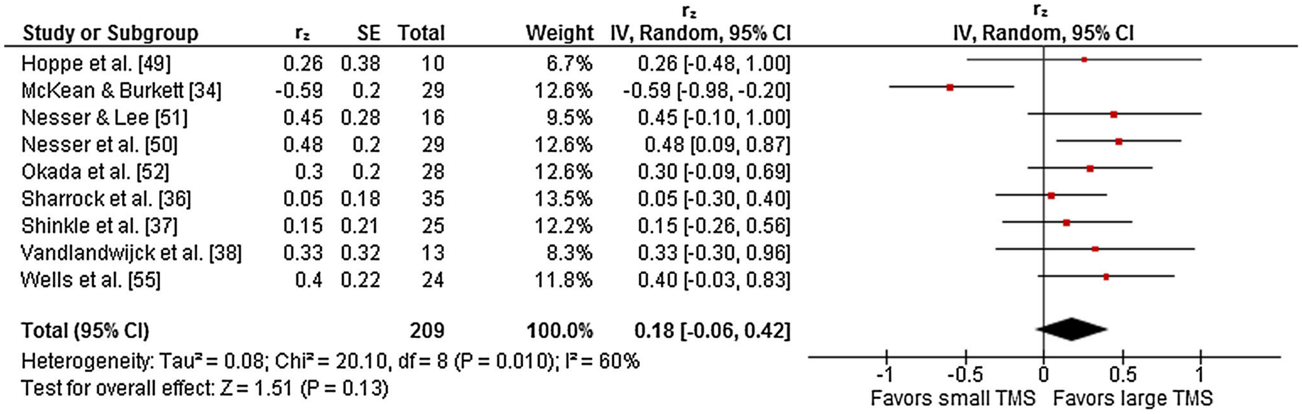
Fig. 2 Z-transformed Pearson's r values (r_z) for associations between variables of TMS (e.g., time in plank test) and muscle strength (e.g., one repetition maximum) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *TMS* trunk muscle strength



Study or Subgroup	r_z	SE	Total	Weight	r_z IV, Random, 95% CI
Hoppe et al. [49]	0.33	0.38	10	6.4%	0.33 [-0.41, 1.07]
Lin et al. [54]	-0.43	0.13	61	14.3%	-0.43 [-0.68, -0.18]
McKean & Burkett [34]	-0.32	0.2	29	11.7%	-0.32 [-0.71, 0.07]
Nesser & Lee [51]	-0.16	0.28	16	8.9%	-0.16 [-0.71, 0.39]
Nesser et al. [50]	0.47	0.2	29	11.7%	0.47 [0.08, 0.86]
Okada et al. [52]	0.09	0.2	28	11.7%	0.09 [-0.30, 0.48]
Prieske et al. [35]	0.33	0.2	29	11.7%	0.33 [-0.06, 0.72]
Sharrock et al. [36]	-0.17	0.18	35	12.4%	-0.17 [-0.52, 0.18]
Shinkle et al. [37]	0.26	0.21	25	11.3%	0.26 [-0.15, 0.67]
Total (95% CI)			**262**	**100.0%**	**0.02 [-0.22, 0.26]**

Heterogeneity: Tau² = 0.09; Chi² = 25.00, df = 8 (P = 0.002); I² = 68%
Test for overall effect: Z = 0.17 (P = 0.87)

Fig. 3 Z-transformed Pearson's *r* values (r_z) for associations between variables of TMS (e.g., time in plank test) and muscle power (e.g., countermovement jump height) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *TMS* trunk muscle strength



Study or Subgroup	r_z	SE	Total	Weight	r_z IV, Random, 95% CI
Hoppe et al. [49]	0.26	0.38	10	6.7%	0.26 [-0.48, 1.00]
McKean & Burkett [34]	-0.59	0.2	29	12.6%	-0.59 [-0.98, -0.20]
Nesser & Lee [51]	0.45	0.28	16	9.5%	0.45 [-0.10, 1.00]
Nesser et al. [50]	0.48	0.2	29	12.6%	0.48 [0.09, 0.87]
Okada et al. [52]	0.3	0.2	28	12.6%	0.30 [-0.09, 0.69]
Sharrock et al. [36]	0.05	0.18	35	13.5%	0.05 [-0.30, 0.40]
Shinkle et al. [37]	0.15	0.21	25	12.2%	0.15 [-0.26, 0.56]
Vandlandwijck et al. [38]	0.33	0.32	13	8.3%	0.33 [-0.30, 0.96]
Wells et al. [55]	0.4	0.22	24	11.8%	0.40 [-0.03, 0.83]
Total (95% CI)			**209**	**100.0%**	**0.18 [-0.06, 0.42]**

Heterogeneity: Tau² = 0.08; Chi² = 20.10, df = 8 (P = 0.010); I² = 60%
Test for overall effect: Z = 1.51 (P = 0.13)

Fig. 4 Z-transformed Pearson's *r* values (r_z) for associations between variables of TMS (e.g., time in plank test) and athletic performance (e.g., kayak race time) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *TMS* trunk muscle strength

3.3.2 Muscle Strength

Five studies were eligible for inclusion in this work that determined the effects of CST on measures of muscle strength (e.g., squat 1 RM) compared with no or only regular training [26, 40, 41, 43, 61]. The mean SMD of 0.25 ($I^2 = 31$ %, $\chi^2 = 5.77$, $df = 4$, $p < 0.22$) indicates small effects in favor of CST groups (Fig. 6). Further, two studies were included comparing the effects of CST on measures of muscle strength compared with alternative training (i.e., whole-body/lower-body strength training [40, 47]). The analysis revealed a mean SMD of 0.19 ($I^2 = 46$ %, $\chi^2 = 1.58$, $df = 1$, $p < 0.17$), which is indicative of small-sized effects in favor of CST.

3.3.3 Muscle Power

Six studies investigated the effects of CST on muscle power output (e.g., countermovement jump) compared with no or only regular training [25, 26, 40, 41, 44, 45]. The analysis revealed a mean SMD of 0.71 ($I^2 = 82$ %, $\chi^2 = 27.47$, $df = 5$, $p < 0.001$), which is indicative of medium-sized effects in favor of CST groups (Fig. 7). Two studies were eligible for inclusion that determined the effects of CST on measures of muscle power output compared with alternative training (i.e., whole-body/leg strength training [40, 47]). The mean SMD was 0.49 ($I^2 = 21$ %, $\chi^2 = 1.27$, $df = 1$, $p = 0.26$), indicating small effects in favor of CST groups.

Table 4 Comparison of correlation coefficients (mean back-transformed Pearson's *r*) between trunk muscle strength and performance measures in elite, sub-elite, and recreational athletes

Performance category	Elite	Sub-elite	Recreational
Muscle strength	0.08	0.07	0.49*
Muscle power	−0.08	−0.02	0.21
Balance	NA	NA	NA
Athletic performance	0.07	0.24	0.29

NA not available

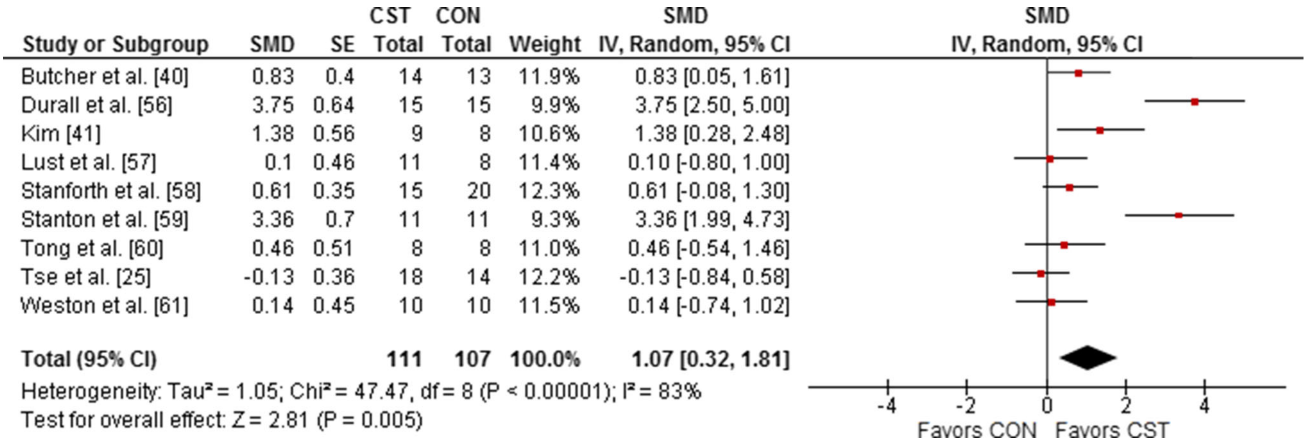
* Significantly different from elite and sub-elite athletes ($p < 0.05$)

3.3.4 Balance

Three studies were included in this review and meta-analysis that determined the effects of CST on measures of balance (e.g., star excursion balance test) compared with no or only regular training [42, 44, 46]. The mean SMD amounted to 0.40 ($I^2 = 0$ %, $\chi^2 = 0.17$, $df = 2$, $p = 0.92$), which indicates small effects in favor of CST (Fig. 8). Only one study investigated the effects of CST on measures of balance compared with an alternative training program (i.e., balance training [42]). The respective SMD was −0.17, which is indicative of a small-sized effect in favor of alternative training programs.

3.3.5 Athletic Performance

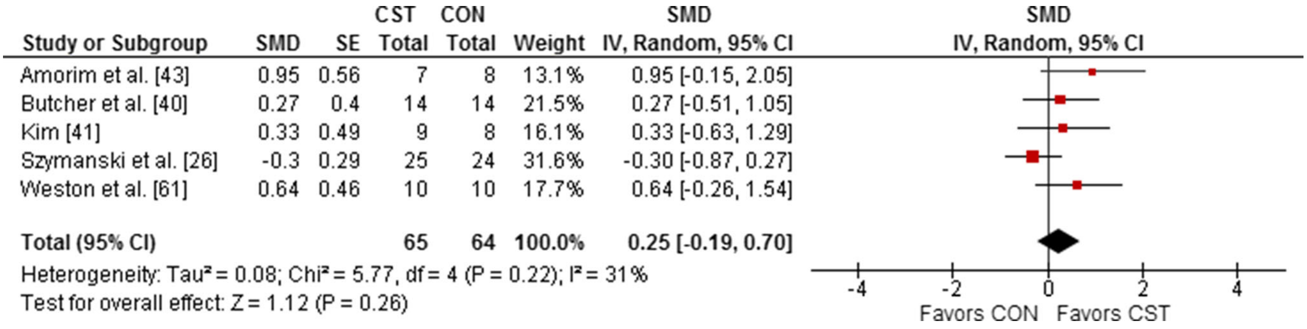
Effects of CST on measures of athletic performance (e.g., 5000-m run time) compared with no or only regular training were determined in eight studies [25, 42–44, 46, 57, 60, 61]. The analysis showed a mean SMD of 0 ($I^2 = 62$ %, $\chi^2 = 18.31$, $df = 7$, $p = 0.01$), which is indicative of small effects in favor of CST (Fig. 9). Further, two studies were included comparing the effects of CST on measures of athletic performance compared with alternative training (e.g., whole-body strength training [42, 47]). The corresponding mean SMD was −0.12 ($I^2 = 19$ %,



Study or Subgroup	SMD	SE	CST Total	CON Total	Weight	SMD IV, Random, 95% CI
Butcher et al. [40]	0.83	0.4	14	13	11.9%	0.83 [0.05, 1.61]
Durall et al. [56]	3.75	0.64	15	15	9.9%	3.75 [2.50, 5.00]
Kim [41]	1.38	0.56	9	8	10.6%	1.38 [0.28, 2.48]
Lust et al. [57]	0.1	0.46	11	8	11.4%	0.10 [-0.80, 1.00]
Stanforth et al. [58]	0.61	0.35	15	20	12.3%	0.61 [-0.08, 1.30]
Stanton et al. [59]	3.36	0.7	11	11	9.3%	3.36 [1.99, 4.73]
Tong et al. [60]	0.46	0.51	8	8	11.0%	0.46 [-0.54, 1.46]
Tse et al. [25]	-0.13	0.36	18	14	12.2%	-0.13 [-0.84, 0.58]
Weston et al. [61]	0.14	0.45	10	10	11.5%	0.14 [-0.74, 1.02]
Total (95% CI)			**111**	**107**	**100.0%**	**1.07 [0.32, 1.81]**

Heterogeneity: Tau² = 1.05; Chi² = 47.47, df = 8 (P < 0.00001); I² = 83%
Test for overall effect: Z = 2.81 (P = 0.005)

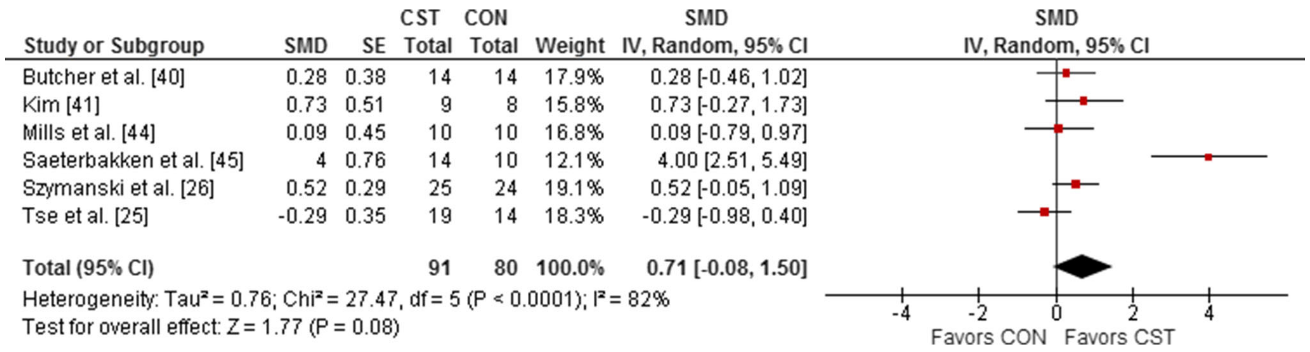
Fig. 5 Effects of core strength training (CST) compared with a control group (CON) on measures of trunk muscle strength (e.g., time in plank test) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *SMD* standardized mean difference



Study or Subgroup	SMD	SE	CST Total	CON Total	Weight	SMD IV, Random, 95% CI
Amorim et al. [43]	0.95	0.56	7	8	13.1%	0.95 [-0.15, 2.05]
Butcher et al. [40]	0.27	0.4	14	14	21.5%	0.27 [-0.51, 1.05]
Kim [41]	0.33	0.49	9	8	16.1%	0.33 [-0.63, 1.29]
Szymanski et al. [26]	-0.3	0.29	25	24	31.6%	-0.30 [-0.87, 0.27]
Weston et al. [61]	0.64	0.46	10	10	17.7%	0.64 [-0.26, 1.54]
Total (95% CI)			**65**	**64**	**100.0%**	**0.25 [-0.19, 0.70]**

Heterogeneity: Tau² = 0.08; Chi² = 5.77, df = 4 (P = 0.22); I² = 31%
Test for overall effect: Z = 1.12 (P = 0.26)

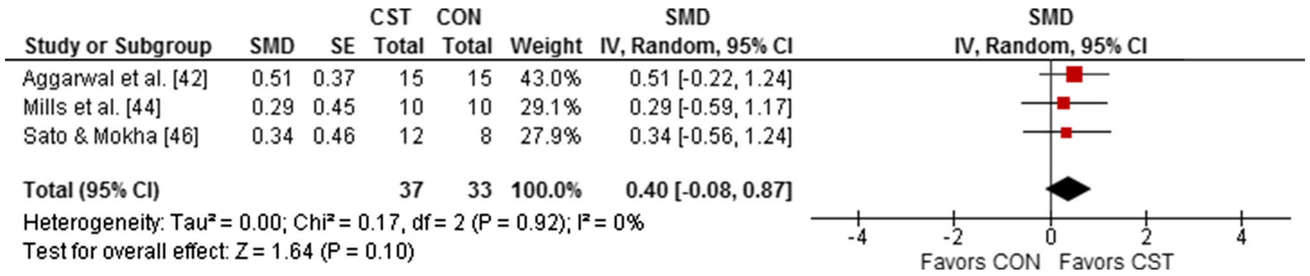
Fig. 6 Effects of core strength training (CST) compared with a control group (CON) on measures of muscle strength (e.g., leg press one repetition maximum) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *SMD* standardized mean difference



Study or Subgroup	SMD	SE	CST Total	CON Total	Weight	SMD IV, Random, 95% CI
Butcher et al. [40]	0.28	0.38	14	14	17.9%	0.28 [-0.46, 1.02]
Kim [41]	0.73	0.51	9	8	15.8%	0.73 [-0.27, 1.73]
Mills et al. [44]	0.09	0.45	10	10	16.8%	0.09 [-0.79, 0.97]
Saeterbakken et al. [45]	4	0.76	14	10	12.1%	4.00 [2.51, 5.49]
Szymanski et al. [26]	0.52	0.29	25	24	19.1%	0.52 [-0.05, 1.09]
Tse et al. [25]	-0.29	0.35	19	14	18.3%	-0.29 [-0.98, 0.40]
Total (95% CI)			**91**	**80**	**100.0%**	**0.71 [-0.08, 1.50]**

Heterogeneity: $Tau^2 = 0.76; Chi^2 = 27.47, df = 5 (P < 0.0001); I^2 = 82\%$
Test for overall effect: Z = 1.77 (P = 0.08)

Fig. 7 Effects of core strength training (CST) compared with a control group (CON) on measures of muscle power (e.g., countermovement jump height) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *SMD* standardized mean difference



Study or Subgroup	SMD	SE	CST Total	CON Total	Weight	SMD IV, Random, 95% CI
Aggarwal et al. [42]	0.51	0.37	15	15	43.0%	0.51 [-0.22, 1.24]
Mills et al. [44]	0.29	0.45	10	10	29.1%	0.29 [-0.59, 1.17]
Sato & Mokha [46]	0.34	0.46	12	8	27.9%	0.34 [-0.56, 1.24]
Total (95% CI)			**37**	**33**	**100.0%**	**0.40 [-0.08, 0.87]**

Heterogeneity: $Tau^2 = 0.00; Chi^2 = 0.17, df = 2 (P = 0.92); I^2 = 0\%$
Test for overall effect: Z = 1.64 (P = 0.10)

Fig. 8 Effects of core strength training (CST) compared with a control group (CON) on measures of balance (e.g., star excursion balance test) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *SMD* standardized mean difference

$\chi^2 = 1.23$, $df = 1$, $p = 0.27$) and indicated small effects in favor of alternative training groups.

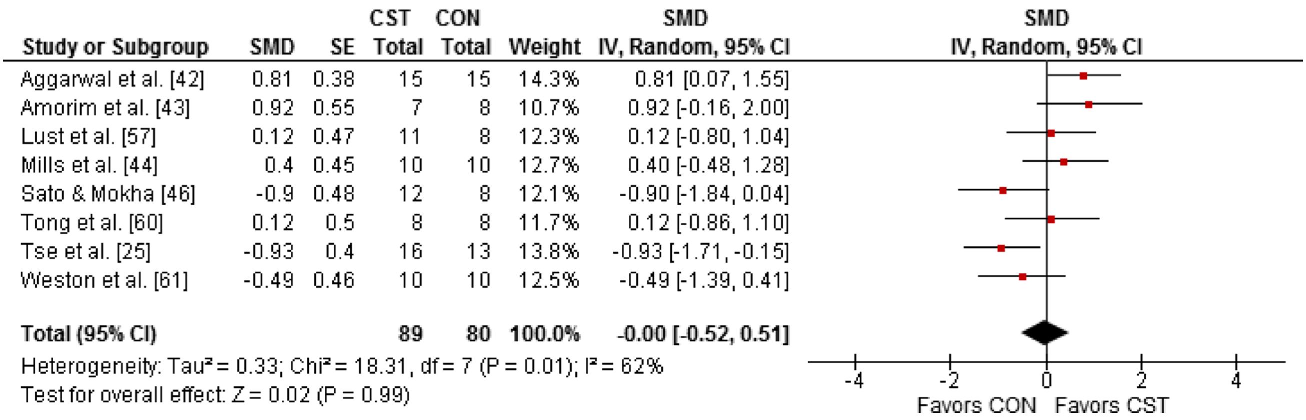
3.3.6 Differences by Expertise Level

Table 5 shows the comparison of SMDs between elite (one study), sub-elite (eleven studies), and recreational (four studies) athletes. Subgroup analyses revealed no statistically significant differences in SMDs between trained individuals of different expertise levels ($p \geq 0.48$).

4 Discussion

The present systematic review and meta-analysis characterized and quantified associations between TMS and proxies of physical fitness and athletic performance as well as general effects of CST on those measures in trained individuals. Our analyses revealed only small-sized associations between variables of TMS and measures of physical fitness and athletic performance irrespective of expertise level. However, significantly larger correlations of TMS and muscle strength were observed in recreational compared with elite and sub-elite athletes. Additionally, CST resulted in large effects in TMS, but predominantly small effects in physical fitness and athletic performance when compared with no or only regular training, and overall small effects when compared with alternative training.

In this regard, it is crucial to know that the quality of the included intervention studies of the present systematic review and meta-analysis is rather low (Table 3). In fact, only two studies reached the pre-determined PEDro cut-off score of ≥6 points [42, 47]. Similarly, a recent systematic review highlighted the low methodological quality of literature for the treatment of low back pain in athletes from different sports (e.g., field hockey, cricket, gymnastics) [62]. Despite the methodological limitations of the available studies, CST training has been propagated for various cohorts and purposes during the last 2 decades [9, 10, 12, 63]. Obviously, there is a significant difference between practitioners and scientists in rating the relevance of CST programs. Interestingly, when including only high-quality studies (i.e., PEDro score of ≥6 points) in our analyses, SMDs for instance indicate medium (SMD = 0.51) and large (SMD = 0.81) effects of CST compared with a passive control group on measures of physical fitness (i.e., balance) and athletic performance (e.g., multiple single-leg hopping). Additionally, when comparing the effects of CST with other training programs (e.g., balance training), SMDs



Study or Subgroup	SMD	SE	CST Total	CON Total	Weight	SMD IV, Random, 95% CI
Aggarwal et al. [42]	0.81	0.38	15	15	14.3%	0.81 [0.07, 1.55]
Amorim et al. [43]	0.92	0.55	7	8	10.7%	0.92 [-0.16, 2.00]
Lust et al. [57]	0.12	0.47	11	8	12.3%	0.12 [-0.80, 1.04]
Mills et al. [44]	0.4	0.45	10	10	12.7%	0.40 [-0.48, 1.28]
Sato & Mokha [46]	-0.9	0.48	12	8	12.1%	-0.90 [-1.84, 0.04]
Tong et al. [60]	0.12	0.5	8	8	11.7%	0.12 [-0.86, 1.10]
Tse et al. [25]	-0.93	0.4	16	13	13.8%	-0.93 [-1.71, -0.15]
Weston et al. [61]	-0.49	0.46	10	10	12.5%	-0.49 [-1.39, 0.41]
Total (95% CI)			**89**	**80**	**100.0%**	**-0.00 [-0.52, 0.51]**

Heterogeneity: Tau² = 0.33; Chi² = 18.31, df = 7 (P = 0.01); I² = 62%
Test for overall effect: Z = 0.02 (P = 0.99)

Fig. 9 Effects of core strength training (CST) compared with a control group (CON) on measures of athletic performance (e.g., 5000-m run time) in healthy trained individuals. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Random* random effects model, *SE* standard error, *SMD* standardized mean difference

Table 5 Comparison of weighted mean standardized differences of performance measures in elite, sub-elite, and recreational athletes

Performance category	Elite	Sub-elite	Recreational	*p* value
Trunk muscle strength	0.72	1.50	0.56	0.48
Muscle strength	0.49	0.18	NA	0.52
Muscle power	0.73	0.73	NA	1.00
Balance	NA	0.29	0.44	0.77
Athletic performance	−0.04	−0.01	0.04	0.99

NA not available

of the studies of Aggarwal et al. [42] and Jamison et al. [47] indicate medium (SMD = 0.62) and large (SMD = 0.86) effects for variables of muscle strength and muscle power in favor of CST. This is partly in contrast to the findings of small- to medium-sized effects of CST on physical fitness and athletic performance compared with no or regular training only or alternative training programs. In order to scientifically contribute to this research field, further high-quality studies [i.e., Randomized Controlled Trials (RCTs)] are needed to determine the effects of CST on specific measures of physical fitness and athletic performance.

4.1 Associations Between Measures of Trunk Muscle Strength and Physical Performance

In contrast to our hypothesis, the finding of small-sized associations of the included correlation studies indicate that TMS plays only a minor role in measures of physical fitness and athletic performance in trained individuals. More precisely, it can be concluded that the athletes with higher values of TMS are not necessarily those athletes with larger performance outputs. A possible explanation for the observed findings may be that the tests used for TMS assessment do not adequately indicate the importance of trunk muscles for physical fitness and athletic performance. In fact, several studies applied trunk muscle endurance tests comprising submaximal isometric muscle actions (e.g., prone plank test) that differ significantly from the movement patterns and characteristics during maximal and explosive force production in sports-related activities (e.g., jumping, throwing [48–55]). Nevertheless, even when related to maximal dynamic TMS tests, associations between measures of TMS, physical fitness and athletic performance remain small. For instance, Clayton et al. [33] reported small-sized associations between peak torque of the trunk flexors/extensors and vertical countermovement jump height ($-0.18 < r < 0.10$) in collegiate baseball players (20 ± 2 years). Thus, other factors than test condition may even have a larger impact on the present findings.

In this regard, it can be speculated that physical fitness and athletic performance appear to be affected rather by well-timed activation of agonistic and synergistic muscle groups, but not maximal trunk muscle activation during the respective movement task. For instance, Prieske et al. [35] found only small associations between trunk and leg muscle activation levels during drop jumps on different surfaces (i.e., firm force plate, compliant balance pad on top of a force plate), indicating that higher trunk muscle activities will not necessarily be transferred to the activation levels of the prime movers (i.e., leg muscles) during jumping tasks. However, athletic function is often produced by kinetic chains which require a coordinated activation of body segments in order to place optimum velocity with the optimum timing for the desired athletic task [12]. In fact, Hodges and Richardson [64] showed shorter reaction time intervals during voluntary hip flexion, abduction, and extension tasks from visual stimulus to onset of electromyographic activity in several trunk muscles as compared with respective prime movers. This indicates that trunk muscles were activated well ahead of the prime movers in each of the abovementioned movement directions. Thus, it can be speculated that the role of the core for physical fitness and athletic performance is rather a matter of quality (i.e., intermuscular coordination) than of quantity of trunk muscle activation/force production during movement tasks. Chaudhari et al. [65] supported this assumption by showing that better lumbopelvic control during single-leg stance tasks as a measure of intermuscular coordination was associated with higher in-game pitching performance in professional baseball players (23 ± 2 years).

In terms of expertise level, significantly larger associations between measures of TMS and muscle strength have been found in recreational trained individuals (mean $r = 0.49$) compared with elite (mean $r = 0.08$) and sub-elite (mean $r = 0.07$) athletes. Based on these correlation studies, it can be concluded that TMS becomes even less important for strength performances of the limb muscles in individuals who train at higher athletic levels. It seems plausible to assume that this finding can be attributed to the individual strength training programs depending on the subjects' training status. According to the general-to-specific model of strength training progression [66], novices are recommended to start with a general strength training design, whereas more specific designs should be conducted with higher levels of training. In other words, recreational athletes are used to training both trunk and limb muscle strength by performing unspecific strengthening programs (e.g., whole-body strength training). As a consequence, recreationally trained individuals may experience gains in trunk as well as limb muscle strength which is reflected in higher correlation coefficients between these two capacities. However, more specific strength training programs (e.g., plyometric training) in elite and sub-elite athletes may lead to increased strength output only in selected muscle groups (e.g., lower limb muscles) crucial for success in the respective sport. Thus, athletes with higher levels of limb muscle strength do not necessarily represent those athletes with large TMS and/or vice versa, which, in turn, is reflected in smaller associations. Nevertheless, according to Vincent and Weir [31], the correlation coefficients in recreational athletes can still be classified as small.

4.2 Effects of Core Strength Training on Physical Performance

In support of the results of the correlation studies, large effects on TMS but predominantly small effects on variables of physical fitness and athletic performance were observed in trained individuals following CST programs as compared with no or regular training. However, the results of our meta-analysis are in contrast to the findings of a systematic review of Granacher et al. [13], who found improved variables of strength, balance, and/or functional performance following CST in old age. In particular, the effect sizes of training-induced performance changes calculated in their review article can be classified as medium to large ($0.52 \leq$ mean SMD ≤ 0.99). It seems plausible to argue that the participants' characteristics of the included studies may have contributed to the inconsistent findings. Indeed, Granacher and colleagues [13] analyzed studies in sedentary/community-dwelling old adults (≥60 years). In contrast, the present systematic review and meta-analysis included studies in healthy young trained individuals (16–44 years) without any reported impairments/injuries. Thus, it seems plausible to argue that the investigated seniors in the review article of Granacher et al. [13] may have preferentially improved their functional performance by specific gains in postural alignment following CST programs.

Notably, according to the concept of training specificity [67], the training must attempt to closely mimic the demands of the respective sport-specific activity. In this regard, physical performance in sports predominantly comprises explosive dynamic muscle actions in an upright position (e.g., jumping, throwing a ball). However, core strengthening exercises of the included training studies were preferentially performed under isometric conditions and/or in vertical directions while lying in horizontal positions (e.g., prone planks, crunches). Consequently, it can be argued that the training-induced increases in TMS may not transfer to physical fitness and athletic performance because of insufficient comparability of exercises during CST with sport-specific activities. Future studies have to elucidate whether CST programs utilizing exercises in an upright standing position (e.g., Romanian deadlift) may be more effective in transferring increases in TMS to proxies of physical fitness and athletic performance in trained individuals. On the other hand, it might be speculated that exercise instructions were inappropriate to allow adaptations following CST. In this regard, Bressel et al. [68] showed that verbal instruction is even more effective to increase trunk muscle activation during lower limb resistance exercises (i.e., squats) as compared with higher training loads in resistance-trained males. Appropriate exercise instructions may therefore be considered an important prerequisite for inducing sufficient and adequate CST stimuli in healthy athletes.

Further, the findings of small-sized effects of CST on physical fitness and athletic performance outcomes were not affected by the athletes' expertise level (i.e., elite, sub-elite, recreational) or the comparison of treatments (i.e., CST vs. no/regular training, CST vs. alternative training). In terms of expertise level, this is in support of the calculated predominantly small-sized associations between measures of TMS and proxies of physical fitness and athletic performance in elite, sub-elite, and recreational athletes and indicates that increases in TMS may have only limited effects on physical performance measures in trained individuals, irrespective of training status. With respect to the comparison of treatments, only small effects were found when comparing CST to alternative training. This implies that CST is not superior to, but is at least as effective as, more "traditional" training programs for enhancing physical fitness and athletic performance variables. However, it has to be noted that only one (i.e., balance) and two (i.e., TMS, muscle strength, muscle power, athletic performance) studies using various alternative training programs have been identified for calculating the respective SMDs. For instance, Butcher et al. [40] compared CST with lower limb strength training, whereas Aggarwal et al. [42] used balance training in comparison to CST. Notably, lower limb strength training and balance training differentially affected performance measures such as muscle strength (i.e., maximal isometric leg press), muscle power (i.e., drop jump, squat jump), and balance (i.e., single-leg stance) [69]. Thus, it seems reasonable to argue that the findings of small-sized effects of CST versus alternative training on variables of physical fitness and athletic performance are impaired by heterogeneity of the included studies.

4.3 Limitations

Several studies investigated the relationship between variables of TMS and proxies of physical fitness and athletic performance to determine the importance of core strengthening for the respective sport discipline. Notably, the analysis of correlative studies representing cross-sectional designs has substantial limitations because the outcomes do not permit the identification of cause-and-effect relations. Accordingly, intervention studies were analyzed as well in order to detect cause-and-effect relations. Referring to this, only three out of 16 intervention studies [40, 42, 47] investigated training-related changes in CST groups as compared with alternative training groups with a large heterogeneity of alternative training programs (e.g., balance training, lower limb strength training). In addition, the included studies were heterogeneous in terms of surface conditions (e.g., stable floor vs. Swiss ball) and activation strategies (e.g., static vs. dynamic combined with enhanced inspiratory load). Thus, there is a need for more high-quality studies to explicitly identify the relevance of CST for physical fitness and athletic performance. Given the relatively low methodological quality in the literature, the present systematic review and meta-analysis primarily included intervention studies with an appropriate description of the applied exercises rather than the included training modalities. Future studies should comprehensively describe intervention characteristics (i.e., training modalities in terms of training period, training frequency, number of sets and/or repetitions) thereby allowing for the analysis of potential dose–response relationships.

5 Conclusions

The present systematic review and meta-analysis revealed predominately small-sized correlations between measures of TMS and physical fitness and athletic performance in recreational, sub-elite, and elite athletes. Irrespective of the potential impact of the athletes' expertise level on the association between TMS and muscle strength (i.e., larger *r* value in recreational compared with elite and sub-elite athletes), the findings indicate that TMS plays only a minor role in measures of physical fitness and athletic performance. Additionally, analyses showed that CST when compared with no or regular training has large effects on TMS but predominantly small effects on proxies of physical fitness and athletic performance in trained individuals irrespective of athletes' expertise level. These analyses are based on findings of methodologically limited studies. Therefore, we conclude that CST with the goal to increase TMS has only limited effects on physical fitness and athletic performance measures in trained individuals. Yet, the comparison of CST versus an alternative training regimen revealed small effects on TMS, physical fitness and athletic performance variables. From this, CST seems to have only limited extra effects in trained individuals. Due to the fact that the included intervention studies were predominantly low in methodological quality, further high-quality studies (i.e., RCTs) are needed to determine whether there are transfer effects of CST to specific measures of physical fitness and athletic performance in trained individuals.

Compliance with Ethical Standards

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