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Effectiveness of maximum, explosive, and combined strength training on endurance runners performance indicators: a systematic review and meta-analysis

Efectividad del entrenamiento de fuerza máxima, explosiva y de ambas combinada en los indicadores de rendimiento de corredores de resistencia: una revisión sistemática con meta-análisis

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Abstract. Objective: This study aimed to analyze the effect of practicing maximum strength (MAX), explosive strength (EXP), or both combined (COMB) on seven runners' performance indicators: vertical jump (VJ), one-repetition maximum squat (1RM), peak velocity/peak running speed (PV), lactate threshold (LT), middle-distance time trial (TT), maximum oxygen consumption ($VO2_{max}$), and running economy (RE). Methods: A systematic review (Scopus, Web of Science, Sports Discuss, PubMed) with meta-analysis was conducted following PRISMA standards. Inclusion criteria (PICOS) were: Recreational or well-trained athletes aged 18-45 performing concurrent training for at least five weeks. The search terms used were related to different types of strength/endurance and participants' age and sports modality. Twenty manuscripts were selected, and quality assessed with PEDro. Results: MAX training is more effective than EXP and COMB in improving VJ, 1RM, and PV, while COMB is more effective than MAX and EXP to enhance TT. MAX is more effective than EXP in improving LT. Concurrent workouts do not provide additional benefits to $VO2_{max}$. It is unknown which strength modality (MAX, EXP, or COMB) is more effective in improving RE. Conclusion: Concurrent training is more effective than single-mode endurance training for enhancing specific performance variables in adult endurance runners. Middle- and long-distance runners may consider incorporating MAX training to target specific goals (i.e., improving VJ, 1RM, LT, PV) while utilizing COMB training to enhance TT. Certain variables may benefit from EXP. New randomized controlled trials are required to confirm these findings.
Keywords: endurance, running, concurrent training, maximum strength, explosive strength

Resumen. Objetivo: Este estudio analizó el efecto de la fuerza máxima (MAX), la fuerza explosiva (EXP) o una combinación de ambas (COMB) en siete indicadores de rendimiento en fondistas: salto vertical (VJ), test de una repetición máxima en sentadilla (1RM), velocidad pico/máxima de carrera (PV), umbral de lactato (LT), carrera sobre la distancia de competición (TT), consumo máximo de oxígeno ($VO2_{máx}$) y economía de carrera (RE). Métodos: Se realizó una revisión sistemática (Scopus, Web of Science, Sports Discuss, PubMed) con metaanálisis siguiendo los estándares PRISMA. Los criterios de inclusión (PICOS) fueron: atletas recreativos o bien entrenados de 18 a 45 años que realizasen entrenamientos concurrentes durante al menos cinco días a la semana. Los términos de búsqueda utilizados estaban relacionados con diferentes tipos de fuerza/resistencia, edad de los participantes y modalidad deportiva. Se seleccionaron 20 manuscritos, cuya calidad fue evaluada con la escala PEDro. Resultados: MAX es más efectivo que EXP y COMB para mejorar VJ, 1RM, PV, mientras que COMB es más efectivo que MAX y EXP para mejorar TT. MAX es más efectivo que EXP para mejorar LT. Las sesiones de entrenamiento concurrente no proporcionan beneficios adicionales para la mejora de $VO2_{máx}$. Se desconoce qué modalidad de fuerza (MAX, EXP o COMB) es más efectiva para mejorar RE. Conclusión: El entrenamiento concurrente es más efectivo que el entrenamiento exclusivo de resistencia para mejorar variables de rendimiento específicas en fondistas adultos. Los corredores de media y larga distancia pueden incorporar el entrenamiento MAX para alcanzar objetivos específicos, como mejorar su VJ, 1RM, LT, PV, y usar COMB para mejorar su TT. Ciertas variables podrían mejorar mediante el entrenamiento de EXP. Se necesitan nuevos ensayos controlados aleatorizados para confirmar estos hallazgos.
Palabras clave: resistencia, carrera, entrenamiento concurrente, fuerza máxima, fuerza explosiva

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Introduction

The objective of middle- and long-distance running is to enhance athletic performance. Traditionally, the critical factors believed to determine endurance performance have included maximum oxygen uptake ($VO2_{max}$), running economy (RE), and lactate threshold (LT) (Fernandez Rodriguez et al., 2019; Li et al., 2019; Mikkola et al., 2011). However, in recent years, regular improvements in endurance performance have been observed without a proportional increase in $VO2_{max}$ (Flores-Zamora et al., 2017), and weak correlations have been found between $VO2_{max}$ and endurance performance in experienced athletes (Beattie et al., 2017). Furthermore, modern endurance runners exhibit $VO2_{max}$ and LT values similar to those seen in the past (Beattie et al., 2014; Li et al., 2019). Therefore, the current approach uses RE, velocity at $VO2_{max}$ ($vVO2_{max}$), and endurance-specific muscle power as key indicators of endurance performance (Beattie et al., 2014). Similarly, Jones et al. (2021) also note that while individual factors like VO2peak, oxygen cost of running, and lactate-related metrics lack significant correlations with marathon performance, combining these variables can predict marathon times effectively (Jones et al., 2021). Additionally, some authors argue that peripheral factors such as enhanced neuromuscular function, increases in motor neuron excitability, and musculotendinous stiffness are crucial for sustaining high running speeds when a greater contribution of the anaerobic system is required, particularly in the final phases of the race or end-spurt (Damasceno et al., 2015; Duffield et al., 2005; Li et al., 2019).

Therefore, adding strength training to the endurance training programs of middle- and long-distance runners —known as concurrent training (Coffey & Hawley, 2017)— plays an essential role. When endurance athletes incorporate strength training, they can achieve several important adaptations as described in the literature (Flores-Zamora et al., 2017; Beattie et al., 2017; Blagrove et al., 2017; Blagrove et al., 2018; Gäbler et al., 2018a; Rønnestad & Mujika, 2014; Trowell et al., 2020; Yamamoto et al., 2008). These adaptations include reducing the required force for the same workload, resulting in energy conservation and delayed onset of fatigue. Additionally, they included enhanced neuro-muscular function, characterized by improved motor unit recruitment and synchronization, activation frequency, intermuscular coordination, neural inhibition, and rate coding. At the muscle-tendon level, there is a delayed activation of type IIa fibers due to the prolonged utilization of type I fibers. This may result in a potential transformation of fast-twitch fibers into intermediate fibers (IIa), an improved muscle stretch-shortening cycle, enhanced muscle-tendon stiffness, and an increased cross-sectional area of the Achilles tendon (Machado et al., 2022).

Furthermore, strength training increases muscle glycogen availability and augmented anaerobic enzyme activity. These combined improvements can lead to enhanced performance across key indicators such as LT, RE (Flores-Zamora et al., 2017; Beattie et al., 2014), and particularly $vVO2_{max}$, an essential performance parameter that combines $VO2_{max}$ and running economy, and allows the identification of aerobic differences among runners, which cannot be attained with $VO2_{max}$ or RE alone (Billat & Koralsztein, 1996)

However, successfully combining strength and endurance represents one of the greatest challenges in training prescription for coaches due to its complexity (Coffey & Hawley, 2017). Indeed, strength and endurance events have traditionally been categorized as activities of opposing nature when considering performance duration and energy metabolism (Berryman et al., 2018a), and the potential endurance and strength adaptations obtained may be attenuated. This phenomenon is called interference or concurrent training effect (Flores-Zamora et al., 2017; Taipale et al., 2014). Thus, it must be considered that while endurance training increases the capillary luminal diameter and number, increases mitochondrial density, and decreases the muscle fiber size (Hendrickse et al., 2021), strength training generates the opposite effects (Berryman et al., 2018a; Blagrove et al., 2020).

While there is support for the beneficial effects of incorporating strength training into endurance programs, there is also evidence of potential interference effects. Consistent with this, some studies have found that strength programs improved endurance athletes′ performance (Aagaard & Andersen, 2010; Flores-Zamora et al., 2017), whereas others have not (Ferrauti et al., 2010; García-Manso, 2013; Vikmoen et al., 2016). The discrepancies found between studies could be related to the following aspects: Developing different types of strength, using different training methods (Berryman et al., 2018a; Berryman et al., 2018b; Blagrove et al., 2017), athletes' training history, modality of aerobic training, intervention duration (Leveritt et al., 1999), and difficulties to transfer strength gains to running technique (Støren et al., 2008; Trowell et al., 2020).

Thus, there is a lack of consensus on the types of strength training suitable for concurrent programs in endurance athletes. Maximum strength (MAX), explosive strength (EXP), or a combination of both (COMB) are commonly used in concurrent training protocols. Maximum strength refers to the highest force exerted during a single lift or an isometric contraction (Lum et al., 2022), and explosive strength is the result of the relationship between the force produced and the needed time for its application (González Badillo & Ribas, 2002).

Some previous studies concluded that EXP could yield better results than maximum strength (Ambrosini et al., 2021), while other research reported the opposite (Eihara et al., 2022). However, due to limited research, it was not possible to determine yet which type of strength enhances further endurance performance (Yamamoto et al., 2008). Moreover, there are also studies recommending a combination of MAX and EXP with endurance training to obtain better results (Berryman et al., 2010; Li et al., 2019). Therefore, further research is needed (Beattie et al., 2014; Li et al., 2019). New research should include adequate training protocols and assessments, and the interventions should be longer than in the current publications (Beattie et al., 2014). New studies could also be useful to clarify the effects of adding COMB training to endurance training (Li et al., 2019).

Furthermore, it is also necessary to conduct new systematic reviews since recent randomized controlled studies have not been included yet. Also, some systematic reviews included different sports despite the existing differences between activities such as cross-country skiing, cycling, and running (Blagrove et al., 2017). Moreover, some reviews have exclusively focused on RE (Denadai et al., 2017; Yamamoto et al., 2008). As a result, it is necessary to examine the effect of concurrent training programs on a comprehensive range of endurance performance parameters and to compare the effect of adding MAX or EXP strength, or COMB, to endurance training. Thus, on the one hand, it could be expected MAX training enhances endurance athletes′ performance by improving agonist-antagonist muscle coactivation, intra- and intermuscular coordination, and running technique. Additionally, MAX training may reduce the relative workload due to increased strength (Barnes et al., 2013; Latash, 2018). On the other hand, EXP could enhance endurance athletes' performance by improving motor unit synchronization, increasing muscle power and elastic return, and improving muscle-tendon rigidity (Barnes et al., 2013; Spurrs et al., 2003). Finally, combining COMB training with endurance training protocols could provide the benefits of both regimens (MAX and EXP) and might be useful in promoting a post-activation potentiation response (Carter & Greenwood, 2014).

Therefore, this study aims to systematically review the literature and conduct a meta-analysis to determine the effect of MAX, EXP, or COMB on various performance indicators of endurance runners. Specifically, we aimed to compare the effects of these three strength regimes on vertical jump (VJ), one-repetition maximum (1RM) squat, peak velocity or peak running speed (PV), LT (measured in incremental test protocols), middle-distance time trial (TT), $VO2_{max}$, and RE. We hypothesized that concurrent training combining endurance and MAX, EXP, or COMB strength training would improve specific performance parameters of adult endurance runners compared to single-mode endurance training. We further hypothesized that concurrent training would not confer an advantage in improving $VO2_{max}$. Finally, we hypothesized that adding COMB to resistance training would be more effective than adding only MAX or EXP.

Materials and Methods

Protocol and registration

A systematic review with meta-analysis was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist and statement. The study was registered under the following code PSU IRB-2022-11-0134 at Prince Sultan University's Institutional Review Board.

Eligibility criteria

The PICOS (Population, Intervention, Comparison, Outcomes, Study design) tool for quality systematic reviews was used to elaborate with rigor and accuracy the inclusion and exclusion criteria applied in the selection of the manuscripts finally included in the present study (table 1) (Amir-Behghadami & Janati, 2020).

Table 1.
PICOS strategy for the inclusion and exclusion criteria.

Category	Inclusion criteria	Exclusion criteria
Population	Endurance runners (18-45 years, both sexes)	Athletes under 18 or over 45, non-runners, and individuals with injuries or medical conditions.
Intervention	Concurrent strength (MAX, EXP, COMB) and endurance training for at least five weeks.	Concurrent training or cohorts in muscular endurance, body weight, or isometric sessions. Strength interventions with electrical muscle stimulation or vibratory plates. Training protocols of less than five weeks.
Comparison	Research with at least two groups: one experimental and one control, or two experimental groups.	Studies lacking at least two groups: one experimental and one control, or two experimental groups. Studies where different experimental groups perform concurrent training at different times or days. Studies involving ergogenic aids.
Outcomes	Studies reporting at least one performance parameter (e.g., $VO2_{max}$, running economy, lactate threshold).	Studies that did not report any performance parameters, and efforts to obtain such data from the authors were unsuccessful
Study design	Randomized and nonrandomized controlled studies	Cross-sectional studies and interventions published in grey literature sources, such as reports, conference proceedings without peer review, or publications not issued by commercial publishers

Information sources

For the screening process, the following electronic databases were searched: PubMed, SPORT Discus, Web of Science, and Scopus. The period screened was until November 30, 2023.

Search

The search process involved an examination of the title, abstract, and full-text fields of the manuscripts. Each of these sections was evaluated according to predetermined inclusion and exclusion criteria. The search algorithm used in the previously mentioned databases was: (adult OR middle-aged OR college-aged) AND (concurrent OR concomitant OR combined OR added OR complex) AND (maximum strength OR explosive strength OR resistance OR plyometric OR reactive strength) AND (performance OR running OR function OR effect OR gain OR improvement OR adaptation OR indicator OR parameter OR variable OR response OR race OR running economy OR energy cost) AND (runner OR endurance athlete OR middle-distance OR long-distance) NOT (youth OR elderly OR adolescent OR patient OR disease OR syndrome OR injury OR sedentary OR obese OR supplementation OR animal).

Study selection

The screening was limited to articles published in English or Spanish. The search and selection process of the articles was conducted by two of the main researchers of this study, using the double-blind method (P.P.-G. & J.S-I.) Possible discrepancies between both researches were solved consensually by another researcher (F.H.Y.). The flow diagram of the study selection is shown in Figure 1.

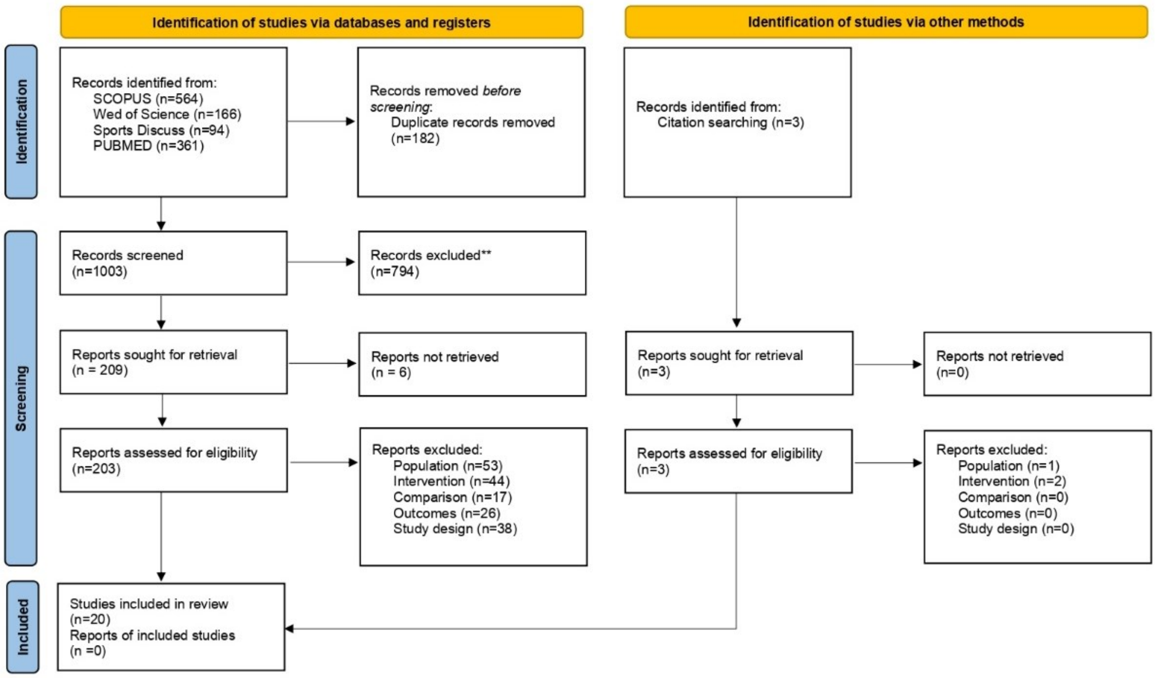

Figure 1. Flowchart of the study search, identification, screening, selection and inclusion.

Data collection process

Regarding the data collection process from the selected studies, the means and standard deviations before and after the implementation of the training protocols were recorded (pre- and post-test). This information was obtained directly from the tables provided in the articles. In those publications where the data were not available, the authors of the articles were contacted to request this information. When the authors did not respond, means and standard deviations were obtained using the GetData Graph Digitizer and Plot Digitizer programs. When the information was flagged or incomplete, it was not included in the meta-analysis. In the cases where more than one measurement of the same variable was provided, we chose the test with the highest validity and reliability index, according to the age and characteristics of the subjects included in the present study.

Data items

The variables analyzed in the meta-analysis of the present study were seven: Vertical jump (VJ),1RM, RE, VO_{2max}, TT, LT (measured in incremental test protocols), and PV.

Study risk of bias assessment

The PEDro (Physiotherapy Evidence Database) scale was utilized to examine the internal validity, risk of bias, and methodological quality of the studies selected for this research (Maher et al., 2003). Two investigators carried out this evaluation process independently, and once completed, the inter-rater reliability was calculated. PEDro scale is composed of 11 dichotomous items. The first is not evaluable, while the remaining 10 are scored with 0 or 1. Therefore, the final result is between 0 and 10. A higher score indicates high methodological quality, and a lower score, risk of bias. PEDro scores were interpreted as follows: 0-3: poor quality, 4-5: fair quality, 6-8: good quality, 9-10: excellent quality (Cashin & McAuley, 2020).

Additional analysis

All analyses were performed using the Comprehensive Meta-Analysis software, version 2 (Biostat Inc.,) (www.metaanalysis.com). Hedges' g effect size (ES) —a variation of Cohen's d— was used to correct for sampling bias, considering the small sample size. The values of 0.2, 0.5, 0.8, or 1.2 for ES indicate small, medium, large, or very large overall effects, respectively (Cohen, 1988). ES values and their 95% confidence intervals [CI] were calculated using the mean from study groups and pre- and post-test trials, standard deviation, and total sample size. Between-group comparisons were performed when the same variable (i.e., VO_{2max}, RE) was reported at least in two different studies for each group (CON, MAX, EXP, or COMB). The heterogeneity was determined by examining the Q test and the I^2 value. The heterogeneity represents the percentage of variance due to between-study factors rather than sampling error. Therefore, it was calculated as I^2 (Vassos et al., 2014). The heterogeneity (I^2) values of 25%, 50%, and 75% were used for the small, medium, and large levels[48]. The fixed effects model was used when there was no significant heterogeneity between studies, and the random effects model was applied when significant heterogeneity was found (DerSimonian & Laird, 1986). The significance level was set as $p < 0.05$.

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Results

Study selection

In the initial search, a total of 1185 articles were identified. Furthermore, three studies were included as they were identified in previously published articles (systematic reviews and primary research). Subsequently, 182 duplicate articles were removed. The publications were then filtered based on title (n=137) and abstract (n=691) and further refined by population (n=53), intervention (n=44), comparison (n=17), outcomes (n=26), and study design (n=38). Consequently, an additional 178 articles were excluded. Thus, the final number of articles included in the present study was 20 (see Figure 1). The interrater reliability (IRR) was estimated at 95.1%, and the Cohen's kappa was 0.89.

Study characteristics

As explained in Table 1, only the experimental groups that performed MAX, EXP, or COMB interventions were included in the meta-analysis. The total number of subjects included in the study was 451 (342 males and 109 females). All of them were middle- or long-distance runners (recreational or well-trained), aged between 18 and 45 (See table 2).

Table 2.
Descriptive characteristics of the subjects and the studies included in the present research.

Authors	n	Age (years)	Level	Intervention	Randomized	Duration (weeks)	PEDro score
Johnston et al. (1997)	12F	30.30	Endurance runners	I: MAX+END CON: END	Yes	10	6
Støren et al. (2008)	17(9M,8F)	29.18	Well-trained endurance runners	I: MAX+END CON: END	Yes	8	6
Ferrauti et al. (2010)	22(16M,6F)	40	Recreational runners	I: MAX+END CON: END	Yes	8	6
Damasceno et al. (2015)	19M	33.50	Recreational endurance runners	I: MAX+END CON: END	Yes	8	6
Vikmoen et al. (2016)	19F	32.93	Well-training endurance athletes	I: MAX+END CON: END	Yes	11	6
Li et al. (2019)	28M	20.71	Well-trained endurance runners	I_1: MAX+END I_2:COMB+END CON: END	Yes	8	6
Paavolainen et al. (1999)	18M	23.44	Elite cross-country runners	I: EXP+END CON: END	Yes	9	6
Spurrs et al. (2003)	17M	25	Endurance runners	I: EXP+END CON: END	Yes	6	6
Saunders et al. (2006)	15M	24.20	Highly-trained endurance runners	I: EXP+END CON: END	Yes	9	6
Ramírez-Campillo et al. (2014)	36(22M,14F)	22.10	Highly competitive endurance runners	I: EXP+END CON: END	Yes	6	6
Pellegrino et al. (2016)	22(14M,8F)	33.35	Experienced endurance runners	I: EXP+END CON: END	Yes	6	6
Berryman et al. (2010)	28M	29.85	Moderately to well-trained endurance runners	I_1:EXP+END I_2:MAX+END CON: END	Yes	8	6
Taipale et al. (2010)	28M	35.37	Recreational endurance runners	I_1:EXP+END I_2:MAX +END	Yes	8	6
Mikkola et al. (2011)	27M	35.55	Recreational endurance runners	I_1:EXP+END I_2:MAX +END	Yes	8	6
Barnes et al. (2013)	42(23M,19F)	19.72	Cross-country runners	I1: MAX+END I2: COMB+END	Yes	10	6
Taipale et al. (2013)	30M	34.57	Recreational endurance runners	I1: MAX+END I2: EXP+END I3: COMB+END CON: END	Yes	8	6
Lum et al. (2022)	26(18M,8F)	26	Endurance runners	I1:EXP+END CON: END	Yes	6	6
Sedano et al. (2013)	18M	23.70	Well-training runners	I1:COMB+END CON: END	Yes	12	6
Taipale at al. (2014)	34(16M,18F)	32.14	Recreational endurance runners	I: COMB+END CON: END	Yes	8	6
Beattie et al. (2017)	20M	28.55	Competitive distance runners	I: COMB+END CON: END	No	40	5

Legend: n: sample size; F: Female; M male; I intervention group; CON: Control group; MAX maximum strength; EXP Explosive strength; END: Endurance; COMB: Combined maximum and explosive strength.

Moreover, the strength and endurance training programs the groups underwent are shown in table 3. Of all the studies selected, 11 included experimental groups that performed MAX training (Barnes et al., 2013; Berryman et al., 2010.; Damasceno et al., 2015; Ferrauti et al., 2010; Johnston et al., 1997; Li et al., 2019; Rønnestad & Mujika, 2014; Støren et al., 2008; Taipale et al., 2010; Taipale et al., 2013; Vikmoen et al., 2016), 10 EXP training (Berryman et al., 2010.; Lum et al., 2022; Mikkola et al., 2011; Paavolainen et al., 1999; Pellegrino et al., 2016; Ramírez-Campillo et al., 2014; Saunders et al., 2006; Spurrs et al., 2003; Taipale et al., 2010; Taipale et al., 2013), and six studies included experimental groups performing COMB training (Li et al., 2019; Barnes et al., 2013; Beattie et al., 2017; Sedano et al., 2013; Taipale et al., 2013; Taipale et al., 2014). The duration of the intervention periods in 19 of the 20 studies was between 6 and 12 weeks, whereas, in the remaining research, the intervention lasted 40 weeks (Beattie et al., 2017). MAX groups performed non-running specific strength training exercises, focusing mainly on lower extremities, except in four studies (Barnes et al., 2013; Ferrauti et al., 2010; Johnston et al., 1997; Taipale et al., 2013), where some trunk and upper body exercises were also practiced. In most studies, both multi- and single-joint exercises were used, except in two studies where only half-squat was performed (Berryman et al., 2010.; Støren et al., 2008). Regarding the resistance used, in some studies, more emphasis was placed on the neural factors of strength (Damasceno et al., 2015; Ferrauti et al., 2010; Mikkola et al., 2011; Støren et al., 2008), in two studies on metabolic factors (Li et al., 2019, Berryman et al., 2010.), and in other articles, the resistance applied was suitable to attained both neural and metabolic adaptations (Barnes et al., 2013; Johnston et al., 1997; Taipale et al., 2010; Taipale et al 2013; Vikmoen et al., 2016). EXP training protocols included —in some cases — only exercises performed with one's own body, such as jumping, bounding, and hopping (Berryman et al., 2010.; Lum et al., 2022; Pellegrino et al., 2016; Ramírez-Campillo et al., 2014). In contrast, in other interventions, weight-training machines were also used in addition to the previously mentioned exercises (Paavolainen et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Taipale et al., 2010; Taipale et al. 2013). Most protocols consisted of performing between two and four sets and between five and 10 repetitions. Finally, the groups that underwent COMB training performed strength sessions where MAX exercises (mainly multi-joint) were combined with EXP exercises (i.e., horizontal or vertical jumps, hops, and bounds). As for endurance training, many of the study participants included in the 20 selected studies were required to continue their regular endurance training (see table 3).

Table 3.
Study characteristics and training programs undergone by the different experimental groups.

Study	Duration// Frequency	Training parameters	Exercises
Johnston et al. (1997)	10 weeks// ST:3/wk; E:4-5/wk	ST: (MAXG) 2x20/2′ (bent-leg heel raise); 2x12/2′ (straight-leg heel raise); 2x15/2′ (sit-up, abdominal curl); 3x8/2′ (Leg extension, leg curl, seated row, lat pulldown; 3x6/2′ (squat, lunge, bench press, seated press, hammer curl) ET:20-30km/week at steady pace	Squat, knee flexion, knee extension, seated press, lat pulldown, hummer curl, sit-up, lunge, heel raise, bench press
Støren et al. (2008)	8 weeks// ST:3/wk	ST: (MAXG) 4x4RM/3′ ET: Continue with their normal endurance training (60-95%HR_{max})	Half-squat
Ferrauti et al. (2010)	8 weeks// ST:2/wk	ST: (MAXG) 4x3-5RM/3′ (leg press, leg extension, leg curl, ankle extension, hip extension); 3x20-25RM/90′′ (bench press, lateral flexion, trunk flexion, trunk extension, trunk rotation, reverse fly). ET: 240(121) min/wk	Leg press, leg extension, leg curl, hip extension, ankle extension, reverse fly bench press, trunk flexion, trunk extension, lateral flexion, trunk rotation
Damasceno et al. (2015)	8 weeks// ST:2/wk	ST: (MAXG) Wks 1–2: 3x8–10RM/3′; wks 3–4: 3x6–8 RM/3′; wks 5–6: 3x4–6 RM/3′; wks 7–8: 2x3–5 RM/3′ ET: Maintained their endurance training program on different days than ST	Half-squat, leg-press, plantar flexion, and knee extension
Vikmoen et al. (2016)	11 weeks// ST:3/wk; ET: 6/wk	ST: (MAXG) Wks 1–3: 3x10RM and 6RM; wks 4–6: 3x8RM and 5RM; wks 7–11: 3x6RM and 4RM ET: Weekly training: 1:3.7(1.6) h at 60%-82% $HR_{max;}$ 1.1(0.5) h at 83%-87%, 3:0.8(0.5) h; 88%-100% of maximal HR	Half squat, leg press, standing one-legged hip flexion, ankle plantar flexion
Li et al. (2019)	8 weeks// ST:3/wk	ST: MAXG: 5x5(80-85%1RM)/3′; COMBG: 3x5(80-85%1RM)/4′ (Back squat, Bulgarian squat, Romanian deadlift); 3x6/4’ (drop jump, single leg hop, double leg hurdle hop) ET: Continuous training (70-85%HR_{max}), and interval training (90-95% HR_{max}). Total distance: 77.25(2.33) km/wk	MAXG: Back squat, Bulgarian squat, Romanian deadlift COMBG: Back squat, drop jump, Bulgarian squat, single leg hop, Romanian deadlift, double leg hurdle hop
Paavolainen et al. (1999)	9 weeks	ST: (EXPG) Alternative jumps, bilateral countermovement, drop and hurdle jumps, and 1-legged 5-jump, leg-press, leg extension, leg curl without additional weight or with the barbell on the shoulders. Leg-press, leg extension, leg curl: 5-20reps(0-40%1RM) ET: 30-120′ at <84%HR_{max}	Alternative jumps, bilateral countermovement, drop and hurdle jumps, and 1-legged 5-jump, leg-press, leg extension, leg curl
Spurrs et al. (2003)	6 weeks// ST:2/wk the first 3 wks, and 3/wk the last 3 wks	ST: (EXPG) 2x10 (Squat jump); 2x10-12 (split scissor jump); 2-3x10-12 (double leg bound); 2-3x10-15 (alternate leg bound, single leg forward hop); 2-3x6-10 (depth jump); 2-3x10 (double leg hurdle jump, single	Squat jump, split scissor jump, double leg bound, alternate leg bound, single leg forward hop, depth jump, double leg hurdle

		leg hurdle hop) ET: 60-80km/wk	jump, single leg hurdle hop
Saunders et al. (2006)	9 weeks// ST:3/wk	ST: (EXPG) 1-2x15 (back extension); 2-5x6-8 (leg press); 1-3x6 (countermovement jumps); 1-3x20 (knee lifts); 1-3x10 (ankle jumps); 1-3x10 (hamstring curls); 4-6x10m (alternate-leg bounds); 1-5x20-30m (skip for height); 1-4x20 (single-leg ankle jumps); 5x5 (continuous hurdle jumps); 5x8 (scissor jumps for height) ET: 107(43) km/wk including continuous training and interval training	Back extension, leg press, countermovement jumps, knee lifts, ankle jumps, hamstring curls, alternate-leg bounds, skip for height, single-leg ankle jumps, continuous hurdle jumps, scissor jumps for height
Ramírez-Campillo et al. (2014)	6 weeks// ST:2/wk	ST: (EXPG) 2x10/2′ from a 20cm box; 2x10/2′ from a 40cm box; 2x10/2′ from a 60 cm box ET: 67.2(18.9) km/wk	Bounce drop jumps
Pellegrino et al. (2016)	6 weeks// ST:15sessions/6wks	ST: (EXPG) 60-228 jumps/session	Deep and box jumps
Berryman et al. (2010)	8 weeks// ST:1/wk; ET:3/wk	ST: MAXG: 3x8/3′; EXPG: Drop jumps from 20, 40, or 60 cm boxes ET: Session 1: 10-6x200-800m at 96-105% of peak treadmill speed; session: 6-1x5-30min at 70-80% of peak treadmill speed; session 3: 30-60min at 70% peak treadmill speed	MAXG: Concentric half-squat; EXPG: drop jumps
Taipale et al. (2010)	8 weeks// ST:2/wk; ET: in non-strength training days	ST: MAXG: 3x4-6 (80-85%1RM) (squat and leg press) and 2x12-15 (50-60%1RM) (calf exercise); EXPG group: 3x6 (30-40%1RM) (explosive squats and leg press); 2-3x10 (20kg) (scissor jump); 2-3x5 (maximal individual squat jumps); 2-3x5 (20kg between wks 4-8) (maximal squat jumps) ET: Wks 0-4: 20(5)-26(4.6) km/wk; wks 4-8: 29.8(7.8)-38.3(4.8) km/wk	MAXG: squat, leg press, calf exercise; EXPG: explosive squats, scissor jump, maximal individual squat jumps, maximal squat jumps
Mikkola et al. (2011)	8 weeks// ST:2/wk	ST: MAXG: Wks 1-4: 3x6/2-3′; wks 5-8: 3x4/2-3′. EXPG group: 3x6/2-3′ (squat and leg press); 2x5/2-3′ (squat jumps (singles and non-stop)); 2x10/2-3′ (scissor jumps) ET: Most of the endurance training (>95%) was of low intensity and was performed below the lactate aerobic threshold	MAXG: Squat and leg press; EXPG: squat, leg press, squat jumps (singles and non-stop), scissor jumps
Barnes et al. (2013)	10 weeks// ST:1-2/wk; ET: 6/wk	ST: MAXG: 2-4x6-20; COMBG: 1-4x6-20	MAXG: Back squat, calf raise, dumb bell military press, glute/hamstring raise, lateral pull down, box step-up, dead lift, calf raise, dumb bell incline bench press, resisted monster walk, pull-up, Bulgarian split squat. COMBG: Same exercises as MAXG plus: forward hop, countermovement jump, alternate leg bound, tuck jump, box jump, side shuffle, scissor jump
Taipale et al. (2013)	8 weeks// ST:1-2/wk; ET: On non-strength training days	ST: MAXG: 3x4–6(80–85%1RM)/2′ (squat and leg press); 2x12–15(50–60%1RM)/2′ (calf exercise); 3x20-30(body weight)/2′ (Sit-ups, back-extension); EXP+END: 3x6(30-40%1RM)/2′ (squat and leg press); 2–3x10sec (20kg) (scissor jump); 2-3x5 (body weight)/2′ (maximal squat jump); 3x20-30 (body weight)/2′ (Sit-ups, back-extension); COMBG: wks 0-4: 2x6RM/2′ (squat and leg press); wks 4-8: 3x4RM/2′ (squat/leg press); 2-3x8-10/2′ (box jumps, vertical jumps); 3x20-30 (body weight)/2′ (Sit-ups, back-extension) ET: 5:38(0:56) h per week below lactate threshold	MAXG: Squat, leg press, calf exercise, sit-ups, back-extension. EXPG: Leg press, scissor jump, maximal squat jump, single body weight, maximal squat jump, sit-ups, back-extension. COMBG: Squat and leg press, box jumps, vertical jumps, sit-ups, back-extension
Lum et al. (2022)	6 weeks// ST:2/wk	ST (EXPG): 2-4x5/3′	Depth jump, single leg bounding, side split jump
Sedano et al. (2013)	12 weeks// ST: 2/wk; ET: 6/wk	ST (COMBG): 3x7 reps (70 %1RM) + 10 reps/5′ ET: cross-country or road running (0.5-1.5h), fartlek (0.5-1.5h), and interval training.	Barbell squat + Vertical jumps over hurdles (40 cm); Lying leg curl + Horizontal jumps; Seated calf raises + Vertical jumps over hurdles (40cm); leg extension + horizontal jumps
Taipale at al. (2014)	8 weeks// ST:1-2/wk; ET:2-4/wk	ST (COMBG): Wks 1-4: 2x6RM/3′ (squat and leg press); 2X8/2-3′ (box jumps, vertical jumps), 3x20-30/2′ (sit-ups and back extension). Wks 5-8: 2x4RM/3′ (squat and leg press); 2X10/2-3′ (box jumps, vertical jumps), 3x20-30/2′ (sit-ups and back extension) ET: M: 18(11) km/wk; F: 23(13) km/wk	Squat, leg press, box jumps, vertical jumps, sit-ups, back extension
Beattie et al. (2017)	40 weeks// ST:2/wk	ST (COMBG): Wks 1-12: 2-3x3-6 (pogo jumps); 2-3x3-8 (back squat); 2-3x6-12 (Romanian deadlift); 1-3x6-12 (split squat). Wks 13-20: 3x5-6 (drop jump); 2-3x3-8 (back squat); 1-3x5-12 (Romanian deadlift); 1-3x5-10 (split squat). Wks 21-32: 1-5x4-5 (drop jump); 1-3x3 (jump squat); 1-3x3-5 (back squat); 1-3x5-8 (single leg Romanian deadlift); 1x8 (single leg squat). Wks 33-40: 1-3x4-5 (drop jump); 1-3x3 (jump squat); 1-3x3-5 (back squat); 1-3x5-8 (single leg Romanian deadlift); 1x8 (single leg squat)	Pogo jumps, back squat, Romanian deadlift, split squat, drop jump, countermovement jump, reverse lunge, skater squat, jump squat,

Legend: n: sample size; F: Female; M: Male; I intervention group; C: control group; MAXG: experimental group that underwent a concurrent training of maximum strength and endurance; EXPG: experimental group that underwent a concurrent training of explosive strength and endurance; COMBG: experimental group that underwent a concurrent training of maximum and explosive strength and endurance; ET: endurance training; HRmax: maximum heart rate; 1RM: one-repetition maximum squat; Wk: week.

Risk of bias within studies

No studies were excluded based on PEDro score. In 19 of the studies included, the PEDro scored obtained was 6, which reflects good quality, whereas, in one study, the score assigned was 5, which indicates fair quality (see table 2). Therefore, the average PEDro score was 5.95±0.21. Moreover, the inter-rater reliability obtained was IRR=96.66%, while Cohen's kappa was k = 0.933.

Synthesis of results

No significant differences were found at baseline for any parameters included in the meta-analysis. The results of the post-test are detailed below.

3.4.1. Vertical Jump (VJ)

In the meta-analysis, it was found that MAX presented significantly better results than CON in the post-test: Hedges g [95%CI] = -0.504 [-0.972 - -0.036]; ES = 0.239; p = 0.035; Q = 4.097; I2 = 26.775) (Figure 2). The ES and level of heterogeneity were small. Similarly, EXP marks were significantly better than those of CON (Hedges g [95%CI] = -0.365 [-0.715- -0.016]; ES = 0.178; p = 0.041; Q = 8.469; I2 = 40.96%) being the ES very small, and the heterogeneity small (Figure 2). No significant differences were found between CON and COMB (Figure 3), between MAX and EXP (Figure 3), and between MAX and COMB (Figure 4).

Moreover, of the 20 studies included in the meta-analysis, MAX (Berryman et al., 2010.; Li et al., 2019; Mikkola et al., 2011; Taipale et al., 2010; Taipale et al., 2013; Vikmoen et al., 2016) and COMB (Li et al., 2019; Beattie et al., 2017; Sedano et al., 2013; Taipale et al., 2013; Taipale et al., 2014) training significantly improved VJ in all studies where those training regimes were applied, and VJ was assessed. In contrast, EXP training provided improvements in seven out of nine studies (Mikkola et al., 2011; Berryman et al., 2010.; Lum et al., 2022; Pellegrino et al., 2016; Ramírez-Campillo et al., 2014; Spurrs et al., 2003; Taipale et al., 2010; Taipale et al., 2013). Additionally, in one study, it was observed that the effect size of the improvement was larger in MAX than in EXP (Mikkola et al., 2011). And in another research, VJ improved significantly only during the preparatory period (Taipale et al., 2010).

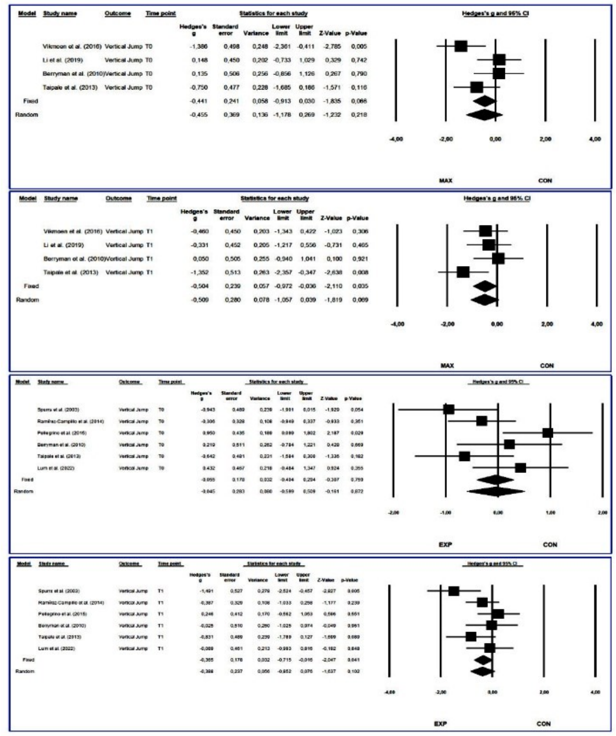

Figure 2. Forest plot comparison between MAX vs. CON and EXP vs. CON groups. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

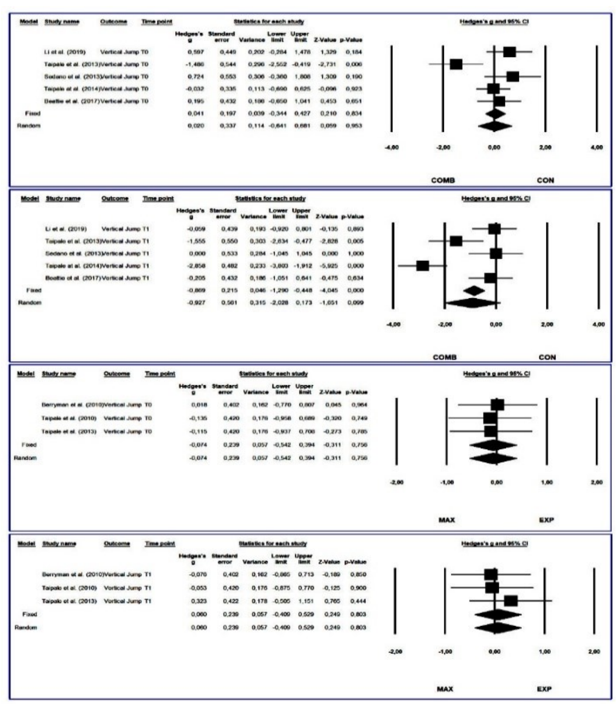

Figure 3. Forest plot comparison between COMB vs. CON and MAX vs. EXP groups. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

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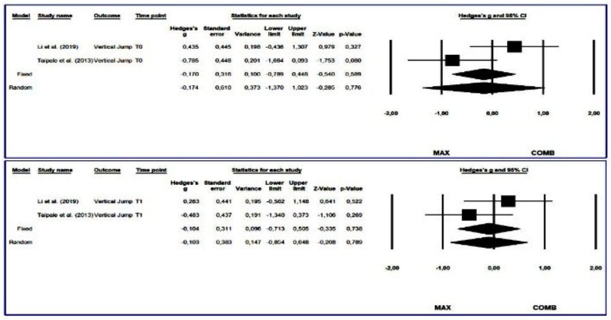

Figure 4. Forest plot comparison between MAX vs. COMB groups. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

One-repetition maximum (1RM) squat

In the meta-analysis, we observed that MAX results were significantly better than those of CON in the post-test (Hedges g [95%CI] = -1.102 [-1.857 - -0.346]; p = 0.004; Q = 16.506; I2 = 69.708), being the effect size large and the level of heterogeneity medium (Figure 5). COMB marks were also significantly better than CON results (Hedges g [95%CI] = -0.653 [-1.043] - -0.263]; p = 0.001); Q = 4.967; I2 = 19.46%) with a medium effect size and low level of heterogeneity (Figure 6). Finally, there were also significant differences between MAX and EXP in favor of the first group (Hedges g [95%CI] = 1.108 (0.589 – 1.628); p < 0.001; Q = 3.331, I2 = 39.955), with a small effect size and low heterogeneity (Figure 6). No significant differences were reported between EXP and CON (Figure 5) and MAX and COMB (Figure 7).

Furthermore, in all the studies included in the meta-analysis where the experimental groups performed MAX, and 1RM was assessed (Mikkola et al., 2011; Li et al., 2019; Li et al., 2019; Barnes et al., 2013; Damasceno et al., 2015; Ferrauti et al., 2010; Johnston et al., 1997; Støren et al., 2008; Taipale et al., 2013; Vikmoen et al., 2016), the subjects obtained significant improvements in 1RM. In one study, performing MAX produced greater improvements than EXP (Mikkola et al., 2011). Another study also observed that performing MAX training provided larger improvements than COMB training (Barnes et al., 2013). Likewise, significant improvements were observed in all studies where COMB training was performed, and 1RM assessed (Li et al., 2019; Barnes et al., 2013; Beattie et al., 2017; Sedano et al., 2013; Taipale et al., 2013; Taipale et al., 2014). In contrast, in the case of EXP, significant improvements were found in three out of four studies (Mikkola et al., 2011; Saunders et al., 2006; Taipale et al., 2010; Taipale et al., 2013).

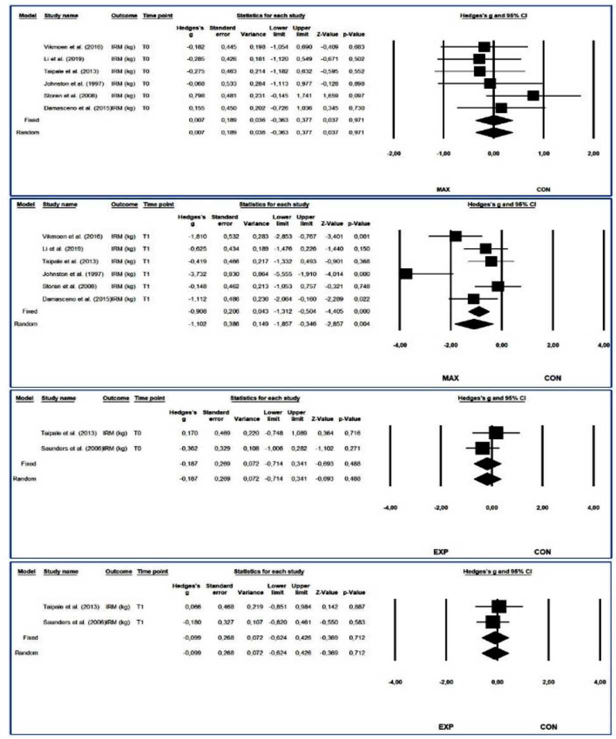

Figure 5. Forest plot comparison between MAX vs. CON and EXP vs. CON groups. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

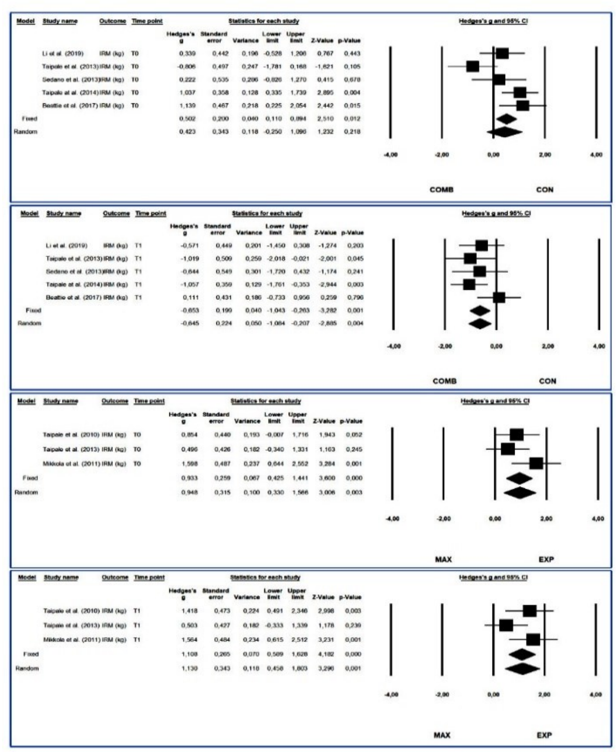

Figure 6. Forest plot comparison between COMB vs. CON and MAX vs. EXP groups in the pre- and post-measurements in 1RM. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

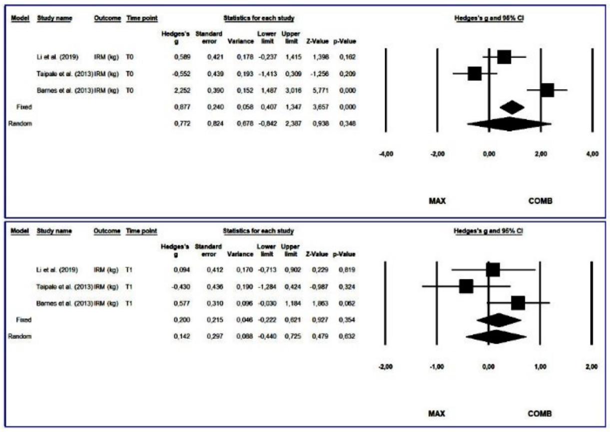

Figure 7. Forest plot comparison between MAX vs. COMB groups in the pre- and post-measurements in 1RM. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

Running economy

No significant differences were found in the meta-analysis between CON and the three experimental groups (MAX, EXP, and COMB) ($p > 0.05$). Similarly, no significant differences were found between the three experimental groups ($p > 0.05$) (Figures 8, 9, and 10).

Furthermore, 10 of the 20 studies selected for the current meta-analysis included experimental groups that underwent MAX training, and RE was assessed (Barnes et al., 2013; Berryman et al., 2010.; Damasceno et al., 2015; Ferrauti et al., 2010; Johnston et al., 1997; Li et al., 2019; Mikkola et al., 2011; Støren et al., 2008; Taipale et al., 2010; Vikmoen et al., 2016). In six of them, MAX training produced significant improvements in RE. EXP training generated improvements in five of the seven studies in which this training protocol was applied (Berryman et al., 2010; Lum et al., 2022; Mikkola et al., 2011; Pellegrino et al., 2016; Saunders et al., 2006; Spurrs et al., 2003; Taipale et al., 2010), and RE was evaluated. Finally, COMB training generated improvements in RE in three of the four studies wherein this training methodology was applied and RE was measured (Barnes et al., 2013; Beattie et al., 2017; Li et al., 2019; Sedano et al., 2013). However, Barnes et al. (2013) found that MAX training was significantly better than COMB in improving RE (Barnes et al., 2013), and Berryman et al. (2010) ascertained that EXP was significantly better than MAX (Berryman et al., 2010.) in enhancing RE.

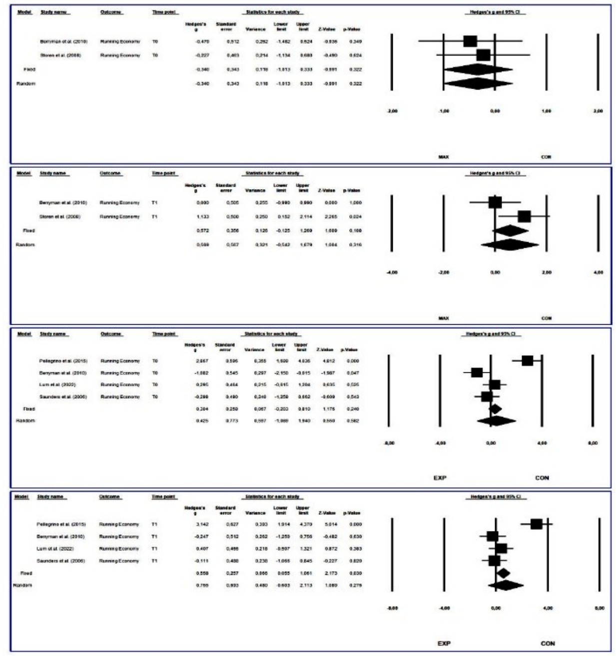

Figure 8. Forest plot comparison between MAX vs. CON and EXP vs. CON groups in the pre- and post-measurements in running economy. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

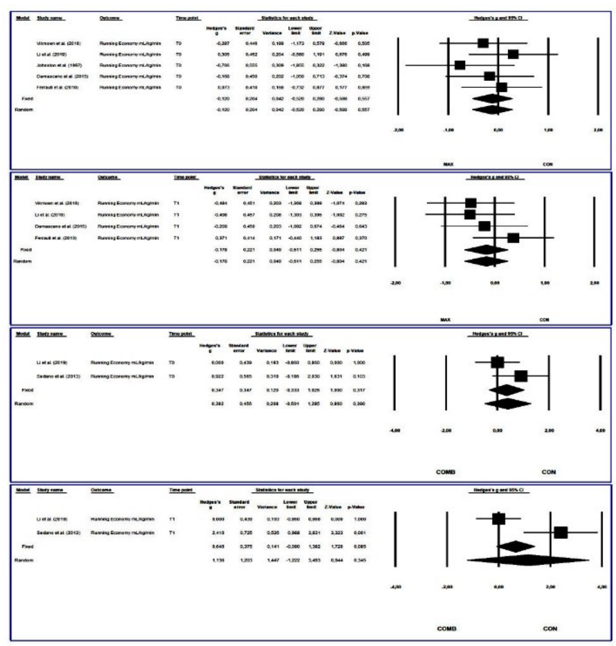

Figure 9. Forest plot comparison between MAX vs. CON and COMB vs. CON groups in the pre- and post-measurements in running economy mL/kg/min. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

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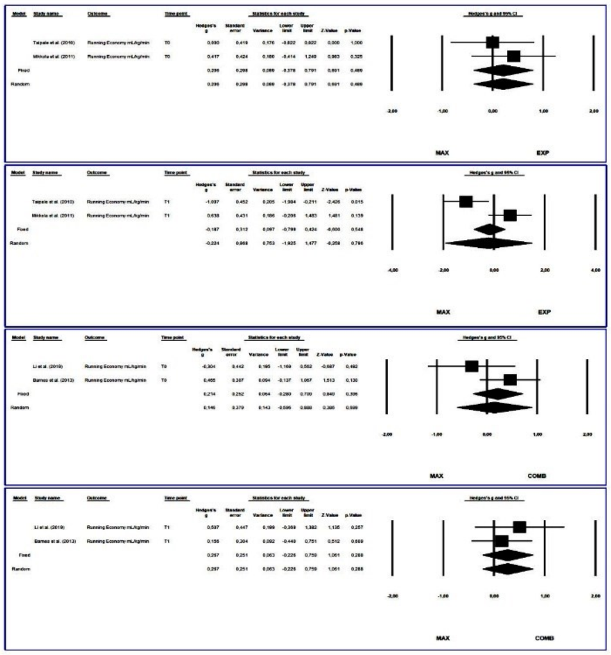

Figure 10. Forest plot comparison between MAX-EXP, and MAX vs. COMB groups in the pre- and post-measurements in running economy mL/kg/min. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

Furthermore, 10 of the 20 studies selected for the current meta-analysis included experimental groups that underwent MAX training and RE was assessed (Mikkola et al., 2011; Li et al., 2019; Damasceno et al., 2015; Ferrauti et al., 2010; Vikmoen et al., 2016; Støren et al., 2008; Berryman et al., 2010; Barnes et al., 2013; Johnston et al., 1997; Taipale et al., 2010). In six of them, MAX training produced significant improvements in RE. EXP training generated improvements in RE in five of the seven studies in which this training protocol was applied (Mikkola et al., 2011; Lum et al., 2023; Berryman et al., 2010; Spurrs et al., 2003; Taipale et al., 2010; Saunders et al., 2006; Pellegrino et al., 2016), and RE was evaluated. Finally, COMB training generated improvements in RE in three of the four studies wherein this training methodology was applied and RE was measured (Li et al., 2019; Beattie et al., 2017; Barnes et al., 2013; Sedano et al., 2013). However, Barnes et al. (2013) found that MAX training improved RE significantly better than COMB. Berryman et al. (2010) ascertained that EXP was significantly better than MAX in enhancing RE.

3.4.4. Maximum oxygen consumption

The meta-analysis showed no significant differences in VO_{2max} between study protocols (CON vs. MAX, CON vs. EXP, CON vs. COMB, MAX vs. EXP and MAX vs. COMB; p>0.05; Figures 11, 12 and 13).

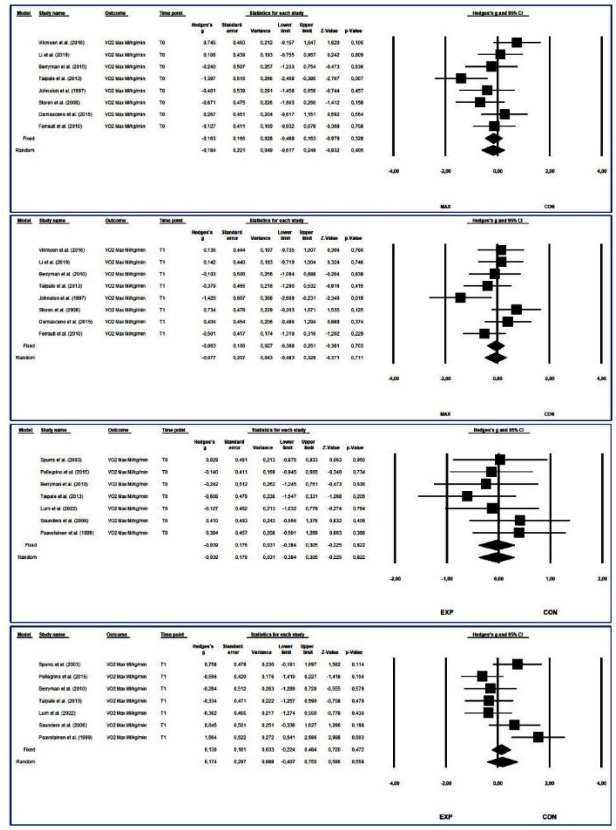

Figure 11. Forest plot comparison between MAX vs. CON and EXP vs. CON groups in the pre- and post-measurements in VO_{2max}. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

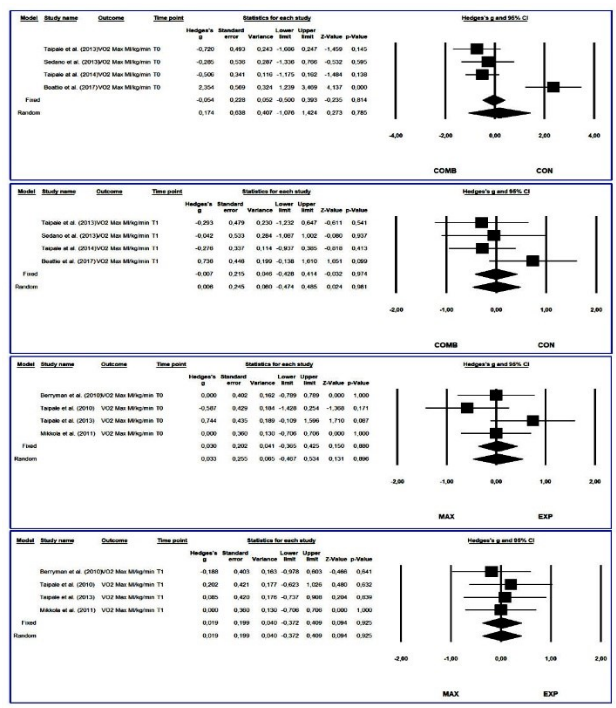

Figure 12. Forest plot comparison between COMB vs. CON and MAX vs. EXP groups in the pre- and post-measurements in VO_{2max}. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and

whiskers for ES; T0: pre-test; T1: post-test.

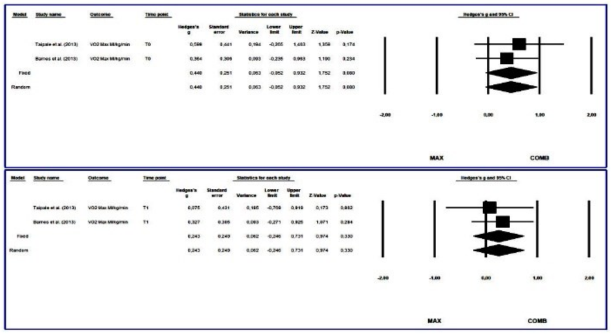

Figure 13. *Forest plot comparison between MAX vs. COMB groups in the pre- and post-measurements in VO_{2max}. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.*

Time trial

On the one hand, the meta-analysis revealed that MAX and EXP training protocols did not generate significant improvements ($p > 0.05$) (Figure 14). However, COMB training produced significant improvements (Hedges g [95%CI] = 3.072 [0.585: 5.56] ES = 1.269; p = 0.015; Q = 4.589; I2 = 78.208) with a very large effect side and high heterogeneity (Figure 15). On the other hand, in all studies where EXP (Berryman et al., 2010.; Lum et al., 2022; Paavolainen et al., 1999; Pellegrino et al., 2016; Ramírez-Campillo et al., 2014; Spurrs et al., 2003) and COMB (Li et al., 2019; Sedano et al., 2013) training protocols were applied, and TT was measured, significant improvements were observed in this variable. In the case of MAX training, such improvements were observed in two out of three studies (Berryman et al., 2010.; Li et al., 2019; Vikmoen et al., 2016).

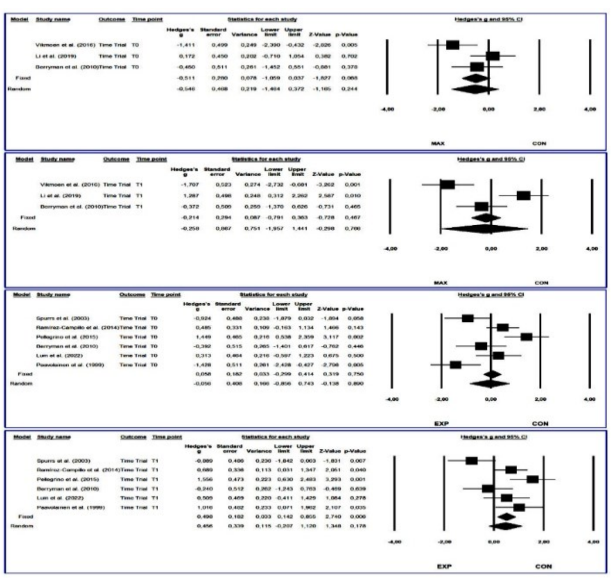

Figure 14. Forest plot comparison between MAX vs. CON and EXP vs. CON groups in the pre- and post-measurements in TT. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

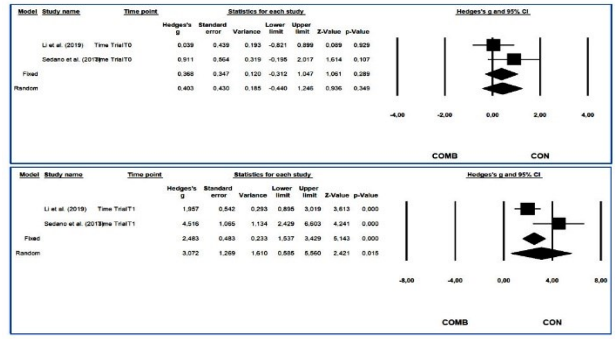

Figure 15. Forest plot comparison between COMB vs. CON groups in the pre- and post-measurements in TT. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

Peak velocity

In the meta-analysis, it was observed that MAX, EXP and COMB training did not produce significant improvements compared to CON ($p > 0.05$). In addition, no significant differences were found between MAX, EXP, and COMB in PV ($p > 0.05$) (Figures 16, 17, 18). In addition, in all the studies where MAX (Barnes et al., 2013; Berryman et al., 2010.; Damasceno et al., 2015; Taipale et al., 2013), EXP (Berryman et al., 2010.; Taipale et al., 2013), and COMB (Barnes et al., 2013; Sedano et al., 2013; Taipale et al., 2013; Taipale et al., 2014), training protocols were used, and PV was measured, significant improvements in this parameter were observed. Likewise, in the study conducted by Barnes et al. (2013), the improvements attained by the MAX group were higher than those of the COMB group.

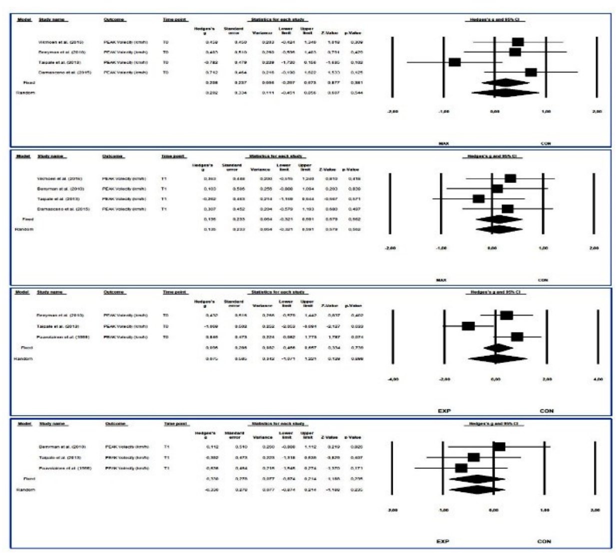

Figure 16. Forest plot comparison between MAX vs. CON and EXP vs. CON groups in the pre- and post-measurements in PV. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

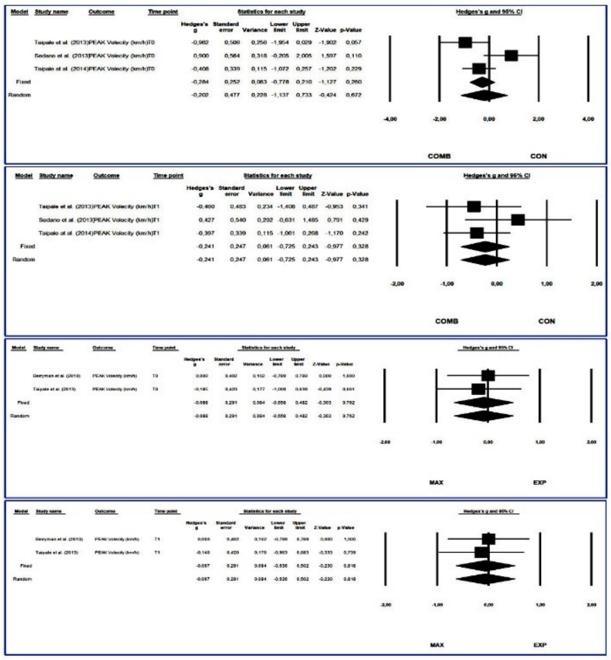

Figure 17. Forest plot comparison between COMB vs. CON and MAX vs. EXP groups in the pre- and post-measurements in PV. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

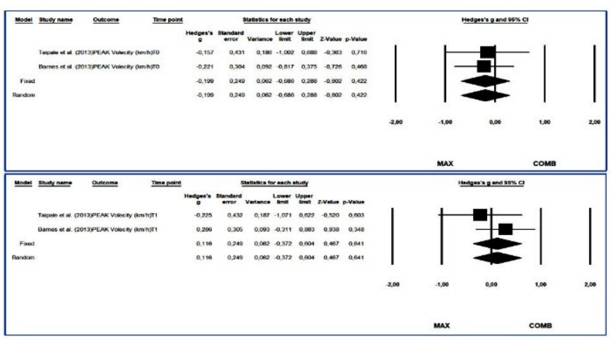

Figure 18. Forest plot comparison between MAX vs. COMB groups in the pre- and post-measurements in PV. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

Lactate threshold

The meta-analysis showed that MAX and EXP training protocols did not significantly improved this variable ($p > 0.05$) (Figure 19). Moreover, MAX training significantly improved LT in those studies where this training protocol was applied and LT was assessed (Ferrauti et al., 2010; Mikkola et al., 2011; Støren et al., 2008). In contrast, EXP training only improved LT in one out of three studies (Mikkola et al., 2011; Paavolainen et al., 1999; Spurrs et al., 2003). Likewise, one study reported improvements in LT in CON (Ferrauti et al., 2010).

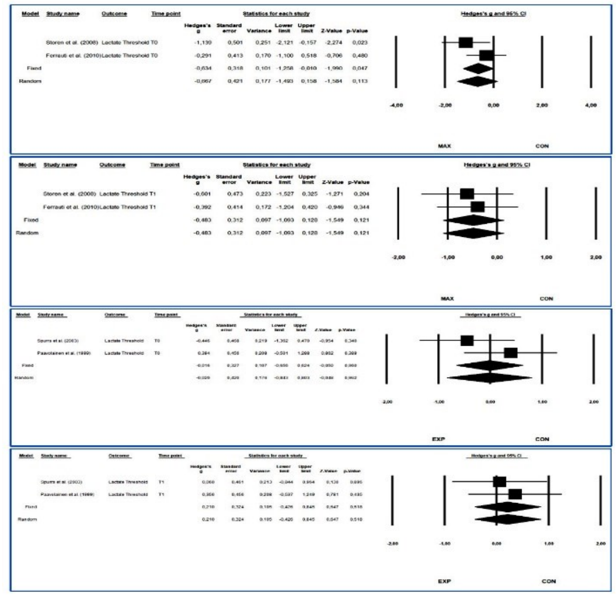

Figure 19. Forest plot comparison between MAX vs. CON and EXP vs. CON groups in the pre- and post-measurements in LT. Data are reported as Hedges' g with effect sizes (ES) and 95% confidence interval (CI). The diamond at the bottom shows the overall effect. The drawn squares show their 95% CI for ES and whiskers for ES; T0: pre-test; T1: post-test.

Discussion

Based on the results, MAX could be more effective than EXP and COMB in enhancing VJ. This may seem surprising as some of the EXP groups included in the meta-analysis did not show significant improvements in VJ, despite performing exercises such as deep jumps or squat jumps (Pellegrino et al., 2016; Taipale et al., 2010). However, evidence indicates that explosive strength training improves VJ (Ciacci & Bartolomei, 2018). One possible explanation for the lack of VJ improvement in some EXP training studies is the forward movement in the explosive strength exercises performed (Pellegrino et al., 2016) (see table 3). Moreover, concurrent training protocols might have attenuated the VJ improvements, as seen in previous studies (Gäbler et al., 2018b; Pattison et al., 2020). VJ is a valuable indicator for monitoring neuromuscular interferences resulting from concurrent training (Pattison et al., 2020). Notably, the absence of significant VJ improvements can occur in both recreational (Taipale et al., 2010) and well-trained athletes (Pellegrino et al., 2016). Furthermore, the effect size of VJ improvements in the meta-analysis in MAX groups was small, and in EXP groups, very small. This reinforces the notion of potential attenuation of adaptations due to concurrent training protocols (García-Orea, 2016; Vikmoen et al., 2020). Additionally, evidence suggests that concurrent training is more likely to attenuate power adaptations than MAX adaptations (Wilson et al., 2012).

As for COMB training, although the five studies included in the meta-analysis reported significant improvements in VJ after performing COMB protocols (Beattie et al., 2017; Li et al., 2019; Sedano et al., 2013; Taipale et al., 2013; Taipale et al., 2014), the pooled effect in the meta-analysis showed no significant improvements. The reason for this discrepancy could be the small size of the improvements. It is plausible that COMB combined with endurance training might not be the most effective strategy to improve VJ since —while COMB can favor post-activation potentiation (Carter & Greenwood, 2014)— some studies also indicate that higher weekly concurrent training volume can lead to greater interference with VJ improvements (Eihara et al., 2022; Mikkola et al., 2011; Taipale et al., 2014).

According to the results, MAX training leads to greater improvements than COMB and EXP protocols in 1RM. These improvements are of great magnitude in both recreational and well-trained athletes. This large increase may be because middle- and long-distance runners do not habitually engage in strength training (Karp, 2007) because they were concerned about developing two opposing fitness components, which could lead to interference effects and potentially deteriorate their performance (Fyfe et al., 2014; Sedano et al., 2013). COMB protocols have also proven effective in enhancing 1RM, but the effect size is smaller compared to MAX training. This could be attributed to the potential attenuation in maximal strength adaptations when combining three different training modalities (MAX, EXP, and endurance). In the case of the EXP training protocols included in the present meta-analysis, no significant improvements in 1RM were observed when the study participants were highly trained subjects (Saunders et al., 2006). This outcome was expected and reflected that experienced athletes may require heavy loads and specific training to enhance their maximal strength.

One of the primary goals of endurance runners when incorporating strength training is to enhance RE, as it is considered a better indicator of endurance performance than VO_{2max} (Beattie et al., 2017). Nevertheless, based on the results, none of the three modalities (MAX, EXP, COMB) demonstrated clear superiority in improving RE. Accordingly, in one study conducted by Barnes et al. (2013), MAX was found to be more effective than COMB in improving RE, while in the research conducted by Berryman et al. (2010), EXP outperformed MAX. Also, the pooled effect was not statistically significant in the three cases (MAX, EXP, and COMB). There are a couple of potential reasons for this. Firstly, the magnitude of the improvements in RE was relatively small, and secondly, in some studies, significant improvements in RE were observed only at specific running speeds (Li et al., 2019). Researchers such as Lum et al. (2022) consider that the absence of significant RE enhancements after EXP training could be attributed to the training methodology due to the reduced percentage of work applied in each stride in trained athletes. Regarding MAX and COMB training, the reasons for the absence of significant improvements in RE observed in some of the 20 studies analyzed remain unclear. Mikkola et al. (2011) propose that this might be linked to differences in the atheltes′ training backgrounds and the limited improvements in explosive strength, which could hinder the efficient use of elastic energy in the stride.

As expected, the meta-analysis reflected the absence of significant improvements across groups. These results are consistent with the fact that in most of the 20 studies analyzed, no significant improvements were detected either after applying concurrent training protocols or with single-mode endurance training. Moreover, these results align with previous research that has shown limited enhancements in VO_{2max} with concurrent training in most cases (Flores-Zamora et al., 2017). Thus, although improvements in VO2max have been observed in the non-athlete population with concurrent training (Ilham et al., 2024), it may not confer a significant advantage in enhancing VO2max compared to single-mode endurance training in endurance athletes. Further, it is essential to consider that strength training can lead to undesired adaptations in middle- and long-distance runners, such as muscle hypertrophy and reductions in capillary diameter and number (Blagrove et al., 2020). Therefore, applying concurrent training to these athletes should avoid negatively impacting their $VO_{2max.}$ At this point, it is worth noting that despite VO_{2max} is a key performance variable in endurance runners, its trainability is conditioned by genetic factors (Williams et al., 2017). Additionally, specific endurance training methods, like interval training, are essential for improving VO_{2max} (Helgerud et al., 2007), and not all of the endurance protocols in the 20 studies included these methods consistently. Also, it is important to acknowledge that improvements in VO_{2max} are more likely to occur in individuals with lower aerobic fitness levels (Fyfe & Loenneke, 2018). However, this statement only partially agrees with the current study′s results; as, of the six studies carried out with recreational subjects, significant improvements in VO_{2max} were observed in three of them (Taipale et al., 2010; Taipale et al., 2013; Taipale et al., 2014).

Endurance runners aim to enhance their TT as a primary objective, and achieve partial goals like improving LT, VO_{2max}, and RE. According to the results of this study, COMB training may be more effective in improving TT than MAX and EXP training. The reason might be that combined MAX and EXP training favors the post-activation potentiation by improving the myosin regulatory light chains phosphorylation (Boullosa et al., 2018). Thus, it is possible that COMB training —which is a time-efficient training method (Li et al., 2019)— can be transferable more easily to running technique than EXP and MAX training. This aspect is relevant since transferring strength gains to the actual running performance is a significant challenge for endurance runners practicing concurrent training, and currently, there is no clear evidence of this transfer. Researchers like Trowell et al. (2020) suggest that improvements in TT following MAX and COMB training could be attributed to exercises like squats, which enhance MAX and peak power, leading to a reduction in the force applied by the runner in each stride. This implies that TT improvements are related to gains in strength rather than improvements in VO_{2max}, which is consistent with the fact that, in most of the 20 studies analyzed, TT improved without a corresponding increase in VO_{2max} (Berryman et al., 2010.; Li et al., 2019; Paavolainen et al., 1999; Spurrs et al., 2003). Finally, it is important to highlight that one of the studies included in the meta-analysis did not show a significant improvement in TT after MAX training. The reasons for this are unclear, but the absence of improvements in RE might be related to the lack of statistical significance in TT improvement (Vikmoen et al., 2016).

PV is a valuable performance indicator in endurance sports (Paavolainen et al., 1999). It enables middle- and long-distance runners to sustain a constant velocity or execute technical actions with reduced force application (Li et al., 2019). This variable relates RE and VO_{2max} in a single figure, offering insights into performance (Taipale et al., 2014). The results of this investigation demonstrate the utility of all three training protocols (MAX, EXP, COMB) in enhancing PV. However, the meta-analysis findings reveal only modest improvements, notably smaller than the substantial gains observed in 1RM. This outcome difference may be because concurrent training may interfere more with anaerobic power-related adaptations than MAX adaptations, as observed in a recent study involving recreationally active males (Shamim et al., 2018). Moreover, one of the 20 studies analyzed reported that MAX training was more effective than COMB in improving PV. This difference could be because MAX has a greater effect on improving muscle rigidity (Barnes et al., 2013).

Improving LT is one of the main objectives of endurance athletes due to its correlation with sports performance (Ghosh, 2004). However, based on the meta-analysis conducted, LT improvements were small in size in this research. The reason could be that neither MAX nor EXP significantly enhances anaerobic enzymes' functioning and muscle's buffering capacity (Edge et al., 2006; Theofilidis et al., 2018). Interestingly, MAX training showed improvements in all three studies where it was assessed, whereas EXP training resulted in improvements in only one out of three studies. Consequently, MAX may be more effective than EXP in enhancing LT. Concerning the impact of COMB training on LT, while COMB protocols were included in five of the 20 studies chosen for the meta-analysis, none of them specifically evaluated LT. Therefore, further research is needed to investigate the effect of COMB training on LT and compare it with the effects of MAX and EXP training.

Additionally, it is important to recognize that one of the primary reasons for implementing concurrent training programs in endurance runners is the role of striated skeletal muscles in managing and eliminating lactic acid (Juel & Halestrap, 1999). Therefore, based on the findings of this study, focusing on muscular endurance, as opposed to MAX and EXP training, might be a more suitable approach to achieve this physiological objective in middle- and long-distance runners due to its greater specificity regarding lactate concentrations, training exercises performed, and metabolic pathway used (Esteve-Lanao et al., 2008; Prieto-González & Sedlacek, 2022).

Concurrent training seems more effective than single-mode endurance training for enhancing endurance performance in middle- and long-distance runners. MAX training is more useful than EXP and COMB training in achieving specific objectives. These objectives include increasing maximum and explosive lower body strength, and improving LT and PV. These findings are consistent with prior research (Barnes et al., 2013; Eihara et al., 2022; Mikkola et al., 2011) and can be attributed to the benefits of MAX training. MAX training improves the recruitment and synchronization of motor units, increases firing frequency, enhances tendon stiffness, and enlarges the cross-sectional area of the Achilles tendon. This enlargement improves force distribution in the tendon, reducing both tendon stress and energy expenditure during submaximal speeds (Machado et al., 2022). Consequently, these adaptations may lead to a reduced percentage of force applied by athletes in each stride (Beattie et al., 2017; Mujika et al., 2016).

The meta-analysis findings also suggest that COMB training may be more effective in improving TT, a critical variable for endurance athletes, given its relevance in real performance scenarios. However, this circumstance is likely to occur only in more highly trained athletes (Balsalobre-Fernández et al., 2016; Li et al., 2019) as excessive strength training volume can potentially hinder adaptations in recreational athletes (Mikkola et al., 2011; Taipale et al., 2014). In trained athletes, due to the law of diminishing returns (Fyfe & Loenneke, 2018), that is, their lower margin to attain improvements, higher workloads are required to obtain adaptations (Petré, 2018).

The study results also reveal that, except for 1RM, the pooled effect of the improvements obtained for most performance variables is small. This finding aligns with the research conducted by Blagove et al. (2017). It underscores the importance of incorporating strength training into the regimen of middle- and long-distance runners, and carefully designing training periodization to prevent interferences between strength and endurance adaptations (Patoz et al., 2021). Furthermore, it is essential to create strength training protocols that are more specific to enhance the transfer of strength gains to running performance (Berryman et al., 2018a). The overall findings of this study only partially align with the conclusions drawn by Beattie et al. (2014). These authors concluded that middle- and long-distance runners with lower strength levels should engage in general strength training, while athletes with higher strength levels should focus on explosive strength training. However, the present study found that MAX is beneficial not only for recreational athletes, but also for trained athletes in improving VJ, 1RM, PV, and LT. The reason could be that experienced athletes may need to enhance their intramuscular coordination to reduce the relative force applied while running, which requires maximum strength training with higher loads. In contrast, explosive strength training often involves body-weight exercises or lower loads (see table 3), which may yield different strength adaptations.

The study findings indicate that COMB training might be more effective for enhancing TT, while MAX training shows superiority in improving 1RM, VJ, PV, and LT. However, considering the study's limitations, it is important to interpret these results cautiously. While the quality of 19 of the 20 included studies is good (and fair in the remaining one), this research has limitations. The screening was conducted in two languages, which can be seen as a strength. However, it also represents a limitation since articles published in languages other than Spanish or English were not considered. Some studies have small sample sizes. The training protocols designed to improve the same performance capacity vary slightly among studies. The duration of the interventions also differs between studies. Likewise, specific performance variables (i.e., LT, TT, PV) were not measured in several studies. Therefore, future randomized controlled studies are required to address these aspects. Thus, more accurate conclusions can be drawn.

Conclusions

Concurrent training is more effective than single-mode resistance training for enhancing selected performance parameters in adult endurance runners. Specifically, MAX is more effective than EXP and COMB in improving 1RM, VJ, PV, and LT. Conversely, COMB may outperform MAX and EXP in terms of improving TT. However, except for 1RM, the improvements obtained are generally modest. In addition, it remains unclear which type of strength is more effective in improving RE. As for VO_{2max}, including strength training in endurance runners' training regimens may not yield additional benefits. Consequentially, endurance athletes may opt for MAX training to target specific objectives, such as improving their maximal and explosive strength in the lower limb, LT, and PV. Subsequently, recreational and well-trained athletes could consider COMB to improve their TT (monitoring the training load in the case of recreational athletes). EXP training can also be a viable choice for improving certain performance variables. Furthermore, the validation of these findings necessitates additional randomized controlled trials.

Conflicts of Interest

The authors declare no conflict of interest.

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