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SYSTEMATIC REVIEW

Deconstructing the Ergogenic Effects of Photobiomodulation: A Systematic Review and Meta-analysis of its Efficacy in Improving Mode-Specific Exercise Performance in Humans

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Abstract

Background Photobiomodulation therapy (PBMT) is defined as non-thermal electromagnetic irradiation through laser or light-emitting diode sources. In recent decades, PBMT has attracted attention as a potential preconditioning method. The current meta-analysis was conducted to assess the effectiveness of PBMT in improving mode-specific exercise performance in healthy young adults.

Methods A computerized literature search was conducted, ending on 15 May 2022. The databases searched were PubMed, Cochrane Central Register of Controlled Trials, Embase, SPORTDiscus, and the Physiotherapy Evidence Database. Inclusion/exclusion criteria limited articles to crossover, double-blind, placebo-controlled studies investigating the PBMT effects as a preconditioning method. The included trials were synthesized according to exercise mode (single-joint, cycling, running, and swimming). All results were combined using the standardized mean differences (SMDs) method and the 95% confidence intervals (CIs) were described.

Results A total of 37 individual studies, employing 78 exercise performance measurements in 586 participants, were included in the analyses. In single-joint exercises, PBMT improved muscle endurance performance (SMD 0.27, 95% CI 0.12–0.41; $p<0.01$) but not muscle strength performance ($p=0.92$). In cycling, PBMT improved time to exhaustion performance (SMD 0.35, 95% CI 0.10–0.59; $p<0.01$) but had no effect on all-out sprint performance ($p=0.96$). Similarly, PBMT had no effect on time to exhaustion ($p=0.10$), time-trial ($p=0.61$), or repeated-sprint ($p=0.37$) performance in running and no effect on time-trial performance in swimming ($p=0.81$).

Conclusion PBMT improves muscle endurance performance in single-joint exercises and time to exhaustion performance in cycling but is not effective for muscle strength performance in single-joint exercises, running, or swimming performance metrics.

1 Introduction

Photobiomodulation therapy (PBMT) is defined as non-thermal electromagnetic irradiation through laser or light-emitting diode sources [1] and since the 1960s has been used

Key Points

Photobiomodulation therapy improves muscle endurance performance in single-joint exercises and time to exhaustion performance in cycling.

Photobiomodulation therapy is not able to improve muscle strength performance in single-joint exercises, running, or swimming performance metrics.

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as a therapeutic intervention to promote healing and reduce tissue inflammation [2, 3]. Likewise, PBMT was reported to delay the reduction in force during evoked tetanic contractions in rats [4]. After this pioneering finding, PBMT has attracted attention as a potential preconditioning method, which led to an expansion in the commercialization of the method as well as an increase in the number of studies investigating its acute ergogenic effects [5–16].

The mechanisms of PBMT rely on its interaction with light-responsive molecules called chromophores [17]. In mammalian cells, the most notable chromophore is the cytochrome C oxidase (CCO) enzyme, which is located in the inner mitochondrial membrane [17]. After absorption of photons, CCO increases the transfer of electrons through the mitochondrial membrane [18], which drives adenosine triphosphate (ATP) synthase and enhances the rate of ATP resynthesis by the oxidative pathway [19]. PBMT can also photodissociate nitric oxide from copper proteins in CCO, as well as from other chromophores (e.g., heme proteins in haemoglobin and myoglobin) [20]. The increased bioavailability of nitric oxide triggers signalling pathways to events such as vasodilation, which may improve tissue microcirculation and tissue oxygenation [21, 22].

Some research suggests that the biological effects of PBMT on CCO activity and ATP resynthesis may last for at least 24 h after treatment [18, 19]. Therefore, it is argued that acutely exposing the prime-mover muscles to PBMT before starting exercise would reduce the muscle metabolic perturbation and be conducive to muscle fatigue resistance [23]. Theoretically, PBMT-induced improvements in tissue microcirculation, tissue oxygenation, and rate of ATP resynthesis by the oxidative pathway may enhance muscle blood flow and muscle oxidative capacity [23]. In turn, these improvements would be expected to blunt the increase in ATP resynthesis by the non-oxidative systems during fatiguing exercises, decelerating the accumulation of the fatigue-inducing metabolites such as hydrogen ions (H^+), inorganic phosphate (Pi), and adenosine diphosphate (ADP) [24]. The net result is enhanced metabolic stability during exercise, which may in turn reduce the rate of fatigue development [4, 19, 25].

Over the past few decades, a variety of studies have been conducted on the topic of 'PBMT effects on exercise'; however consensus regarding the ergogenic effects of PBMT is yet to be established [23, 26, 27]. A potential reason for this is the variance in the testing protocols used to assess PBMT ergogenic effects [7, 23]. For example, PBMT ergogenic effects have been investigated when used in conjunction with various and distinct exercise modes, such as low- or upper-limb single-joint efforts, running, and cycling exercises [23]. Such exercise modes differ in the degree of muscle fibre recruitment and, consequently, substrate utilization [28], cardiovascular control [29], cardiorespiratory responses [30], and neuromuscular demands [31]. As such, it is possible that PBMT may elicit differing ergogenic effects (or lack thereof) between different exercise modes. On balance, existing literature suggests that PBMT may provide ergogenic aid when used in conjunction with single-joint exercises [6, 14, 32–34], but evidence to support its ergogenic effect in running [12, 35–37], cycling [5, 7, 11, 38], and swimming [39] performance is limited.

Furthermore, PBMT ergogenic effects have been investigated in several performance metrics (e.g., time to exhaustion, time trial, all-out sprint, repeated sprint) [23]. Considering PBMT mechanisms (i.e., improved muscle blood flow and muscle oxidative capacity), it could be hypothesized that endurance-related performance metrics (e.g., time to exhaustion) would be more benefit than those that were anaerobic or strength-related (e.g., all-out sprint). Thus, to better understand the effects of PBMT as a preconditioning method, the current study aimed to perform a systematic review and meta-analysis of its ergogenic efficacy. Specifically, this systematic review with meta-analysis will investigate the effectiveness of PBMT in improving mode-specific exercise performance in healthy young adults compared with placebo. The effects of PBMT on performance will be investigated according to exercise mode (e.g., single-joint, running and cycling exercises), performance metric (e.g., muscle strength and muscle endurance) and test protocol (e.g., time to exhaustion and time-trial).

2 Methods

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [40]. Two independent authors performed the selection and data extraction processes (YMD and ASE), methodological quality analysis, and risk of bias analysis (YMD and ESM). Disagreements were resolved by a third author (AMZ).

2.1 Search Strategy

An electronic search of the literature was conducted in the following databases: MEDLINE/PubMed, Cochrane Central Resister of Controlled Trials (CENTRAL), Embase, SPORTDiscus, and the Physiotherapy Evidence Database (PEDro). The literature search ended on 15 May 2022. Databases were searched for a combination of the following keywords (titles and abstracts only): (1) photobiomodulation OR phototherapy OR low-level laser OR low level laser OR light-emitting diode OR light emitting diode OR led-irradiation OR led irradiation OR light-irradiation OR light irradiation; AND (2) ergogenic OR performance OR exercise performance OR exercise tolerance OR time to exhaustion

OR time-to-exhaustion OR fatigue. The search syntax for each database is available in the electronic supplementary material (ESM). Articles not published in the English language were excluded and no year restriction was placed on the search. After this process, the reference lists of all the eligible studies and previous relevant reviews [23, 26] were manually searched for articles to be included in the review.

2.2 Selection of Study

Any accessible full-text article was retrieved for assessment if it was judged to be eligible by at least one reviewer. The study selection process was then performed by two independent authors in two stages: (1) the title and abstract of the selected studies were checked for relevance; and (2) the full-text article was retrieved and considered for inclusion. The criteria for inclusion of studies were (1) being a clinical trial or original investigation conducted in a crossover, placebo-controlled design; (2) being conducted with healthy young human adults (i.e., < 35 years of age and absence of illness or disease); (3) having performed PBMT treatment no more than 6 h before exercise measures (i.e., time window selected to characterize an acute use of PBMT according to the available literature); and (4) having performed the physical tests in a rested state. Book sections, theses, dissertations, opinion articles, observational studies, conference papers, and reviews that passed through the initial filter were subsequently excluded.

2.3 Data Extraction and Variable Categorization

The data extraction process was performed using a standardized form that included details such as characteristics of participants, exercise protocol used, outcomes measured, and PBMT treatment characteristics. Initially, data were categorized according to exercise mode, which enables data on single-joint, running, cycling, and swimming exercises to be separated. For single-joint exercises, data were separated into muscle strength and muscle endurance performance tests. For cycling, data could be separated into time to exhaustion and all-out sprint performance tests. For running, it was feasible to split data into time to exhaustion, time-trial, and repeated-sprint performance tests. For swimming, the included data only came from freestyle time-trial performance tests.

In the present review, the main outcome under investigation was physical performance after PBMT (compared with a placebo treatment). Physiological measures were not included in the present study. Data extracted for meta-analysis were the mean and standard deviation of peak torque and peak force for muscle strength performance in single-joint exercise tests; time to maintain force production at a given percentage of maximum (i.e., time to exhaustion), maximal number of lifts at a given percentage of maximum, mean force and work for muscle endurance performance in single-joint exercise tests; test duration (i.e., time to exhaustion) for time to exhaustion performance tests in running and cycling; test duration for time-trial performance tests in running and swimming; peak power and mean power for all-out sprint performance in cycling; and best time and mean time for repeated-sprint performance in running. The data extracted from the included studies to perform the meta-analysis are summarized in Table 1.

A custom-written MATLAB (The MathWorks Inc., Natick, MA, USA) routine was used for data that were reported as figures [41]. Data that were not displayed in the manuscript were requested directly from the corresponding author by e-mail and/or ResearchGate.

Table 1 Data extracted from the included studies for the analysis of PBMT effect on exercise performance

Exercise mode	Exercise measures	Data extracted
Single-joint exercises	Muscle strength performance	Peak force in kilogram-force (kgf) and Peak torque in newtons (N)
	Muscle endurance performance	Time in seconds maintaining force production at a given percentage of maximum (i.e., time to exhaustion in seconds), maximal number of lifts until exhaustion, mean force in kilogram (kg) and work in joule or kilojoule (J or kJ, respectively)
Cycling, running, and swimming exercises	Time to exhaustion performance in cycling and running	Time in seconds (s) maintaining exercise in a predefined intensity until volitional exhaustion
	Time-trial performance in running and swimming	Time in seconds (s) to complete the tests
	Repeated-sprint performance in running	Best time and mean time in seconds (s)
	All-out sprint performance in cycling	Peak power and mean power in Watts (W) during Wingate tests

2.4 Data Analysis

Review Manager version 5.3 software (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) was used for the statistical analyses and to generate forest plot figures, while the I^2 statistic was used to explore heterogeneity. I^2 values of < 50%, 50–75%, and > 75% were considered to represent low, moderate, and high levels of heterogeneity, respectively. Data were pooled in meta-analyses using (a) exercise measures mean and standard deviation of the PBMT and placebo conditions; and (b) study sample size. Eight main meta-analyses were performed for the effect of PBMT on (1) muscle strength performance in single-joint exercises; (2) muscle endurance performance in single-joint exercises; (3) time to exhaustion performance in running; (4) time-trial performance in running; (5) repeated-sprint performance in running; (6) time to exhaustion performance in cycling; (7) all-out sprint performance in cycling; and (8) time-trial performance in freestyle swimming. Subgroup meta-analyses were also performed for all-out sprint performance in cycling evaluating the effects of PBMT on peak power and mean power, and for repeated-sprint performance in running assessing PBMT effects on best time and mean time.

All results were combined using the standardized mean differences (SMDs) method and the 95% confidence intervals (CIs) were described. Fixed effects were calculated due to the low heterogeneity of the studies ($I^2 < 50\%$). The pooled effects sizes were categorized as small (SMD 0.20), medium (SMD 0.5), or large (SMD 0.8) [42]. The statistical significance threshold was set at $p < 0.05$. In addition, the mean ± standard deviation and 95% CI of the percentage changes in exercise measures due to PBMT were calculated.

2.5 Quality and Risk of Bias Assessments

For the quality analysis, the PEDro scale, considering 10 criteria (random allocation, concealed allocation, baseline comparability, blinding participants, therapists and assessors, adequate follow-up, intention-to-treat, between-group comparison, point estimates, and variability), was used [43, 44]. Based on the summary scores, the studies were classified as being of 'excellent quality' (9 or 10 points), 'good quality' (6–8 points), 'fair quality' (4 or 5 points) or 'poor' methodological quality (≤ 3 points) [43, 44]. The quality assessment was not used as an inclusion criterion.

The risk of bias analysis was calculated according to the Cochrane Collaboration guidelines using the Review Manager version 5.3 software. The bias risk was judged as high, low, or unclear, considering five methodological domains (selection, performance, attrition, reporting, and other) [45]. In addition, the likelihood of publication bias was assessed by funnel plot according to standard recommendations [46].

3 Results

3.1 Search Results

The primary search matched/found 4827 articles: 3670 articles from MEDLINE, 612 articles from CENTRAL, 278 articles from Embase, 171 articles from PEDro, and 96 articles from SPORTDiscus. After duplicates were excluded, titles and abstracts from a total of 4023 articles were analysed, which resulted in the selection of 51 studies for full-text analysis. Of these studies, 37 met the criteria for data extraction. The reasons for the exclusion of studies deemed ineligible are listed in the ESM. No studies were added after the reference review process. The schematic process of study selection is shown in Fig. 1.

3.2 Study Characteristics

The characteristics and results of the studies that investigated PBMT ergogenic effects are described in Tables 2, 3, 4, 5, 6, 7 and 8. The methodological quality of the studies reached a mean score of 7.2 ± 1.2 arbitrary units, indicating good quality. The total number of participants across these studies was 586 (489 men and 97 women). Most of the studies included only men, although some studies included only women [47–51], or a combination of men and women volunteers [8, 11, 52]. The median number of participants per study was 13, ranging between 8 [5] and 34 [14]. Studies included volleyball players [5, 6, 33, 34], soccer players [16], volleyball and soccer players [53], rugby players [13], futsal players [50], resistance-trained individuals [8, 14], recreationally trained cyclists [7, 38], well-trained cyclists [54], recreationally trained runners [15, 35, 55], well-trained runners and triathletes [37], swimmers [39], untrained individuals [10, 11, 32, 51, 52, 56, 57], and participants classified as physically active [12, 25, 36, 47–49, 58–63]. Among the included studies, 17 conducted single-joint exercise tests [6, 8, 14, 15, 25, 32–34, 47–49, 51, 52, 57, 59–61], 8 conducted time to exhaustion performance tests in running [10, 12, 16, 36, 55, 56, 58, 63], 4 conducted time to exhaustion performance tests in cycling [7, 11, 38, 54], 3 conducted all-out sprint performance tests in cycling [5, 53, 62], 2 conducted time-trial performance tests in running (i.e., 1500 m running [35], 3000 m running [37]), 2 conducted repeated-sprint performance tests in running [13, 50], and 1 conducted a time-trial performance test in swimming (100, 200, and 400 m freestyle test [39]).

The target muscles of treatment across studies were the first interosseous [52], biceps brachii [6, 25, 32–34, 48, 51, 57], rectus femoris [47], quadriceps femoris [5, 7, 10–16, 35–39, 50, 53–56, 58–63], hamstrings [7, 10, 12, 13, 15, 16, 37–39, 50, 55, 56, 58, 59, 63], gluteus maximus [7, 37],

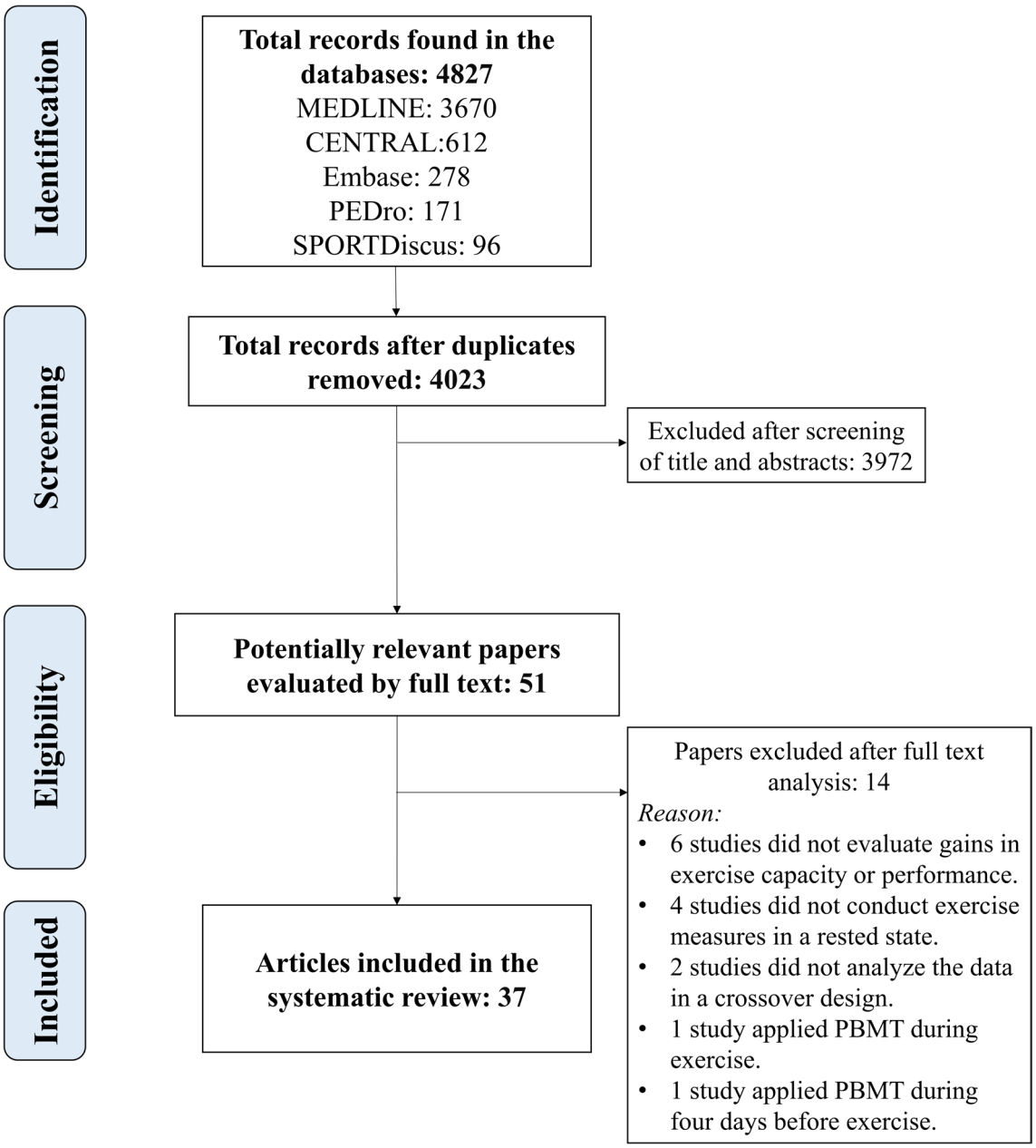

Fig. 1 Selection of studies. *MEDLINE* Medical Literature Analysis and Retrieval System Online, *CENTRAL* Cochrane Central Register of Controlled Trials, *PEDro* Physiotherapy Evidence Database, *PBMT* photobiomodulation therapy

plantar flexors [8, 10–13, 15, 16, 35, 37–39, 50, 55, 56, 58, 63], tibialis anterior [49], pectoralis major, middle deltoid, and triceps brachii [39]. The median number of treatment areas on the quadriceps femoris and biceps brachii was four, three on the rectus femoris, two on the hamstrings, two on the plantar flexors, and one on the gluteus maximus. The first interosseous was treated through a continuous scanning motion covering the muscle, the tibialis anterior was treated in 29 areas, and the pectoralis major, middle deltoid, and triceps brachii were treated in one site each. The median power of irradiation per diode was 0.025 W (ranging from 0.0003 W [56] to 4 W [52]). The median energy delivered to the target muscles in each treatment area was 30 J (ranging from 0.81 J [49] to 300 J [37]). The characteristics and results of the included studies are described in Tables 2, 3, 4, 5, 6, 7 and 8.

Table 2 Characteristics and results of the included studies that investigated PBMT effects on single-joint exercise performance

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Azuma et al. [51]; GIF	Untrained females ($n=13$)	Single-diode laser (808 nm, 0.028 cm^2, 0.1 W)	Biceps brachii: 4 treatment sites. Energy delivered on each site: 7 J	Single-joint exercise. Six sets of maximal elbow-flexion repetitions until exhaustion with a load of 60% of 1 repetition maximum, with 60-s rest intervals	Number of repetitions to failure over six sets PBMT = 93 ± 22 PLA = 90 ± 19	Extracted from the text	8
Baroni et al. [60]; GIF	Physically active males ($n=17$)	Cluster with 69 LED diodes: 34 red diodes (660 nm, 0.2 cm^2, 0.01 W) and 35 infrared diodes (850 nm, 0.2 cm^2, 0.03 W)	Quadriceps femoris: 3 treatment sites. Energy delivered on each site: 41.7 J	Single-joint exercise. Thirty maximal isokinetic repetitions of concentric knee extension-flexion at speed of 180°·s^{-1}. The dominant lower limb was assessed	Knee-extension peak torque (N·m) PBMT = 153.6 ± 27.1 PLA = 156.0 ± 27.0 Total work (kJ) PBMT = 4113.2 ± 677.3 PLA = 4205.2 ± 746.1	Extracted from the text	7
De Almeida et al. [32]; GIF	Untrained males ($n=10$)	Single-diode laser (0.0028 cm^2, 0.05 W) with two wavelengths: red mode (660 nm) and infrared mode (830 nm)	Biceps brachii: 4 treatment sites (for both modes). Energy delivered on each site: 5 J (for both modes)	Single-joint exercise. One maximal isometric elbow-flexion for 60 s (elbow flexed at 90°). The nondominant upper limb was assessed	Mean peak force (kgf) PBMT (infrared) = 24.3 ± 4.9* PBMT (red) = 23.8 ± 4.5* PLA = 21.2 ± 4.9 Mean average force (kgf) PBMT (infrared) = 15.5 ± 2.9* PBMT (red) = 15.46 ± 1.9* PLA = 13.7 ± 2.0	Extracted from the text	7
Dellagrana et al. [15]; GIF	Recreationally trained male runners ($n=18$)	Cluster with 5 laser and 28 LED diodes: 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W) and 8 infrared LED diodes (950 nm, 1.28cm^2, 0.015 W)	Quadriceps femoris: 8 treatment sites; Hamstrings: 4 treatment sites; and Plantar flexors = 2 treatment sites. Energy delivered on each site: 15 or 30 or 60 J	Single-joint exercise. One maximal isometric knee-extension, knee-flexion and ankle plantar-flexion for 5 s (knee flexed at 70°, ankle at neutral position). The right lower limb was assessed	Peak torque (N·m) Knee-extension PBMT (15 J) = 218.2 ± 38.8 PBMT (30 J) = 216.0 ± 41.1 PBMT (60 J) = 224.0 ± 44.8 PLA = 226.2 ± 45.7 Knee-flexion PBMT (15 J) = 102.0 ± 28.4 PBMT (30 J) = 106.7 ± 33.3 PBMT (60 J) = 103.2 ± 19.1 PLA = 104.7 ± 24.7 Plantar-flexion PBMT (15 J) = 209.7 ± 50.0 PBMT (30 J) = 212.0 ± 54.3 PBMT (60 J) = 215.9 ± 46.0 PLA = 201.9 ± 49.6	Extracted from the text	8

Table 2 (continued)

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Dos Santos Maciel et al. [49]; GIF	Physically active females ($n=12$)	Single-diode laser: red (780 nm, 0.2 cm^2, 0.03 W)	Tibialis anterior: 29 treatment sites. Energy delivered on each site: 0.81 J	Single-joint exercise. Five maximal isokinetic repetitions of concentric ankle-dorsiflexion at a speed of $60°{\cdot}s^{-1}$ with the dominant lower limb	Peak torque (N·m) PBMT = 12.6 ± 0.6 PLA = 13.3 ± 0.7	Extracted from a figure using a MatLab algorithm	6
Hemmings et al. [14]; NR	Resistance-trained males ($n=34$)	Cluster with 69 LED diodes: 34 red diodes (660 nm, 0.01 W) and 35 infrared diodes (850 nm, 0.03 W). Cluster diode area: 28.2 cm^2 (each diode area was not reported by the authors)	Quadriceps femoris: 6 treatment sites. Energy delivered on each site: 41.7 or 83.4 or 166.8 J	Single-joint exercise. Maximal number of isokinetic repetitions of eccentric knee-extension until exhaustion with a load of 120% of maximal isometric knee-extension and at speed of $60°{\cdot}s^{-1}$. The dominant lower limb was tested	Number of repetitions PBMT (30 s) = 51.0 ± 35.2 PBMT (60 s) = 61.9 ± 34.7* PBMT (120 s) = 61.8 ± 38.7* PLA = 48.6 ± 32.0	Extracted from the text	4
Higashi et al. [48]; NR	Recreationally trained females ($n=20$)	Single-diode laser: infrared (810 nm, 0.0028 cm^2, 0.1 W)	Biceps brachii: 8 treatment sites. Energy delivered on each site: 7 J	Single-joint exercise. Maximal number of isotonic repetitions of concentric elbow flexion for 60 s with a load of 75% of 1 repetition maximum. The dominant upper limb was tested	Number of repetitions PBMT = 25.1 ± 9.9 PLA = 22.6 ± 7.6	Extracted from the text	7
Larkin-Kaiser et al. [52]; GIF	Untrained males ($n=4$) and females ($n=5$)	Single-diode laser (1.72 cm^2) with mixed wavelength: 20% infrared (810 nm, 2 W) and 80%, infrared (980 nm, 4 W)	First dorsal interosseous: number of treatment sites not described. Quote: "covering the first dorsal interosseous muscle". Energy delivered: 240 or 480 J	Single-joint exercise. Isometric index finger abduction until exhaustion with a load of 30% of 1 repetition maximum. The nondominant upper limb was assessed	Test duration (s) PBMT (240 J) = 332.6 ± 108.4* PBMT (480 J) = 310.6 ± 102.9 PLA = 245.1 ± 85.2	Extracted from the text	7

Table 2 (continued)

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Leal-Junior et al. [6]; NR	Male volleyball players ($n=10$)	Single-diode laser: infrared (830 nm, 0.0028 cm^2, 0.1 W)	Biceps brachii: 4 treatment sites. Energy delivered on each site: 5 J	Single-joint exercise. Maximal number of isotonic repetitions of concentric elbow flexion with a load of 75% of 1 repetition maximum. The dominant upper limb was assessed	Number of repetitions PBMT = 30.1 ± 8.1* PLA = 25.6 ± 6.1	Extracted from the text	8
Leal-Junior et al. [34]; GIF	Male volleyball players ($n=10$)	Cluster with 69 LED diodes: 34 red diodes (660 nm, 0.2 cm^2, 0.01 W) and 35 infrared diodes (850 nm, 0.2 cm^2, 0.03 W)	Biceps brachii: 1 treatment site. Energy delivered: 41.7 J	Single-joint exercise. Maximal number of isotonic repetitions of concentric elbow flexion with a load of 75% of 1 repetition maximum. The dominant upper limb was assessed	Number of repetitions PBMT = 38.6 ± 9.0* PLA = 34.2 ± 8.7	Extracted from the text	7
Leal-Junior et al. [33]; GIF	Male volleyball players ($n=9$)	Cluster with 5 infrared laser diodes (810 nm, 0.0364 cm^2, 0.2 W)	Biceps brachii: 2 treatment sites. Energy delivered on each site: 30 J	Single-joint exercise. Maximal number of isotonic repetitions of concentric elbow flexion with a load of 75% of 1 repetition maximum. The dominant upper limb was assessed	Number of repetitions PBMT = 39.6 ± 4.3* PLA = 34.6 ± 5.6	Extracted from the text	8

Table 2 (continued)

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Orssatto et al. [8]; GIF	Resistance-trained males ($n=7$) and females ($n=7$)	Cluster with 5 laser and 28 LED diodes: 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W), and 8 infrared LED diodes (950 nm, 1.28 cm^2, 0.015 W)	Plantar flexors: 6 treatment sites. Energy delivered on each site: 60 J	Single-joint exercise. Maximal number of isotonic repetitions of concentric ankle plantar-flexion with a load of 12 maximum repetitions. The test was conducted with 6 sets of repetitions until concentric failure and 2 min rest between sets. Both limbs were individually tested in different days, randomly treated with PBMT or placebo	Total number of repetitions (sum of the 6 sets) PBMT = 55.4 ± 10.9 PLA = 54.8 ± 13.0	Extracted from the text	8
Rossato et al. [25]; GIF	Physically active males ($n=10$)	Cluster with 5 laser and 4 LED diodes (small cluster): 5 red LED diodes (670 nm, 0.64 cm^2, 0.01 W), and 4 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W) Cluster with 5 laser and 28 LED diodes (large cluster): 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W), and 8 infrared LED diodes (950 nm, 1.28 cm^2, 0.015 W)	Biceps brachii: 2 treatment sites (for both devices). Energy delivered on each site: 30 J (for both devices)	Single-joint exercise. One isometric elbow-flexion until exhaustion with a load of 60% of maximal isometric elbow-flexion. The right limb was tested	Time to exhaustion (s) PBMT (large cluster) = 48.7 ± 9.2* PBMT (small cluster) = 49.8 ± 14.2* PLA (large cluster) = 43.4 ± 13 PLA (small cluster) = 44.1 ± 13.4	Extracted from a figure using a MatLab algorithm	8

Table 2 (continued)

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Rossato et al. [61]; GIF	Physically active males ($n=16$)	Cluster with 5 laser and 28 LED diodes (large cluster): 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W) and 8 infrared LED diodes (950 nm, 1.28 cm^2, 0.015 W)	Quadriceps femoris: 9 treatment sites. Energy delivered on each site: 30 J	Single-joint exercise. Forty-five maximal isokinetic repetitions of concentric knee extension-flexion at speed of $180°·s^{-1}$. The dominant lower limb was assessed	Knee-extension peak torque in the initial 15 repetitions (N·m) PBMT (immediately before) = 164.0 ± 31.0 PBMT (6 h before) = 166.0 ± 21.0 PBMT (6 h + immediately before) = 165.0 ± 24.0 PLA = 165.0 ± 29.0 Knee-extension work in the initial 15 repetitions (J) PBMT (immediately before) = 809.0 ± 158.0 PBMT (6 h before) = 811.0 ± 177.0 PBMT (6 h + immediately before) = 808.0 ± 156.0 PLA = 800.0 ± 179.0	Extracted from the text	8
Rossato et al. [59]; GIF	Physically active males ($n=18$)	Cluster with 5 laser and 28 LED diodes (large cluster): 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W) and 8 infrared LED diodes (950 nm, 1.28 cm^2, 0.015 W)	Quadriceps femoris: 9 treatment sites. Energy delivered on each site: 15 or 30 or 60 J	Single-joint exercise. Five sets of 10 maximum isokinetic repetitions of concentric knee extension-flexion at speed of $60°·s^{-1}$ with intervals of 60 s between sets. The right lower limb was assessed	Knee-extension work (J) PBMT (135 J) = 9365.0 ± 2190.0 PBMT (270 J) = 9405.0 ± 2270.0 PBMT (540 J) = 9166.0 ± 2262.0 PLA = 8907.0 ± 2228.0	Extracted from the text	7
Stamborowski et al. [57]; NR	Untrained males ($n=14$)	Single-diode laser: infrared (808 nm, spot size not reported, 0.1 W)	Biceps brachii: 9 treatment sites. Energy delivered on each site: 3 J	Single-joint exercise. Three maximal isometric elbows-flexion for 50 s with intervals of 50 s between test (elbows flexed at 45°)	Mean force [test 1] (N) PBMT = 0.78 ± 0.13 PLA = 0.79 ± 0.17	Extracted from the text	5

Table 2 (continued)

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Toma et al. [47]; GIF	Physically active females ($n = 18$)	Cluster with 12 infrared laser diodes (904 nm, 0.5 cm^2, 0.06 W)	Rectus femoris: 3 treatment sites. Energy delivered on each site: 43.2 J	Single-joint exercise. Sixty maximal isokinetic repetitions of concentric knee extension-flexion at a speed of 180°·s^{-1}. The dominant limb was tested	Knee-extension peak torque (N·m) PBMT = 92.6 ± 20.8* PLA = 89.6 ± 21.5 Knee-extension work (J) PBMT = 2760.0 ± 578.7* PLA = 2647.0 ± 664.7	Extracted from the text	7

GIF government and/or institutional funding, *LED* light-emitting diode, *NA* not reported, *PBMT* photobiomodulation therapy, *PLA* placebo

*Indicates significant difference from placebo ($p < 0.05$)

3.3 Methodological Quality

In general, all studies included in the meta-analysis presented a low risk of bias. Of the 37 studies included, 24 (65%) presented explicit information about the methods used in the randomization (e.g., drawing lots, website, randomization table at a central office), 29 (78%) about allocation concealment (e.g., opaque and sealed envelopes), 33 (89%) about blinding of participants (e.g., use of opaque goggles during PBMT and placebo treatment) and personnel (e.g., PBMT and placebo treatment performed by a technician/assistant researcher not involved in exercise testing and data analysis), and 33 (89%) about outcome assessments (e.g., exercise testing and analysis performed by a researcher blinded to subjects' allocation to treatment). Explicit information about sample loss was provided by 19 studies (51%), although 18 (49%) provided insufficient information to permit the judgement about missing data (e.g., sample size was not reported in the outcomes). All studies presented appropriate outcome reporting (i.e., without selective reporting) and did not present other limitations, except two studies (0.05%) that did not perform standard null hypothesis testing [15, 59]. In addition, the funnel plot demonstrated that there were no clear indications of publication bias (ESM Fig. S1). The risk of bias summary for all included studies and the support for our judgement is available in the ESM (Fig. S2).

3.4 Effects of Photobiomodulation Therapy (PBMT) on Single-Joint Exercises

For the analysis of the effect of PBMT on muscle strength performance in single-joint exercises, six studies were used, of which two provided data related to peak force or peak torque in isometric contractions [15, 32] and four included data from isokinetic exercises [47, 49, 60, 61]. There was no significant effect of PBMT on muscle strength performance (overall SMD 0.01, 95% CI − 0.16 to 0.18; $p = 0.92$, $I^2 = 0\%$) [ESM Fig. S3]. For the analysis of the effect of PBMT on muscle endurance performance in single-joint exercise, 15 studies were used, of which four provided data related to work [47, 59–61] and one provided data related to mean force produced in isokinetic exercises [32], two provided data related to time to maintain force production at a given percentage of maximum (i.e., time to exhaustion) in isometric contractions [25, 52], one provided data related to mean force produced in isometric contractions [57], and seven included maximal number of lifts until exhaustion [6, 8, 14, 33, 34, 48, 51]. A significant increase in muscle endurance performance in single-joint exercises was verified when PBMT was performed prior to exercise, compared with a placebo (overall SMD 0.27, 95% CI 0.12–0.41; $p < 0.01$, $I^2 = 0\%$) (Fig. 2).

Table 3 Characteristics and results of the included studies that investigated PBMT effects on time to exhaustion performance in cycling

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Da Silva Alves et al. [11]; NR	Untrained males ($n=9$) and females ($n=9$)	Cluster with 7 infrared laser diodes (850 nm, 0.05 cm^2, 0.1 W)	Quadriceps femoris: 3 treatment sites; Plantar flexors: 1 treatment site Energy delivered on each site: 14 J	Cycling exercise. Graded-exercise test started at 25 W for women or 50 W for men with increments of 15 W for women or 20 W for men every minute until exhaustion	Test duration (s) PBMT = 648.0 ± 87.0 PLA = 648.0 ± 95.0	Extracted from the text	4
Dutra et al. [7]; GIF	Recreationally trained male cyclists ($n=13$)	Multi-diode array with 50 LED spots of 4 diodes: 25 red spots (660 nm, 3.14 cm^2, 0.05 W) and 25 infrared spots (850 nm, 3.14 cm^2, 0.08 W)	Quadriceps femoris: 1 treatment site; Hamstring: 1 treatment site; and Gluteus maximus: 1 treatment site Energy delivered on each site: 130 or 260 J	Cycling exercise. Constant-load test until exhaustion at Δ60% intensity (Δ60% intensity = 60% of difference between maximal aerobic power and power output and respiratory compensation point)	Test duration (s) PBMT (130 J) = 544.0 ± 172.0 PBMT (260 J) = 537.0 ± 185.0 PLA = 519.0 ± 150.0	Author's own work	8
Dutra et al. [38]; GIF	Recreationally trained male cyclists ($n=13$)	Multi-diode array with 264 LED diodes: 120 red diodes (630 nm, 0.2 cm^2, 0.0012 W) and 144 infrared diodes (850 nm, 0.2 cm^2, 0.015 W)	Quadriceps femoris: 2 treatment sites; Hamstring: 2 treatment sites; and Gluteus maximus: 1 treatment site Energy delivered on each site: 152 J	Cycling exercise. Constant-load test until exhaustion at Δ60% intensity (Δ60% intensity = 60% of difference between maximal aerobic power and power output and respiratory compensation point)	Test duration (s) PBMT (30 min before) = 469.0 ± 92.0 PBMT (6 h before) = 497.0 ± 104.0 PLA (30 min before) = 458.0 ± 100.0 Placebo (6 h before) = 481.0 ± 90.0	Author's own work	7
Lanferdini et al. [54]; NR	Well-trained male cyclists ($n=20$)	Cluster with 5 infrared laser diodes (810 nm, 0.029 cm^2, 0.2 W)	Quadriceps femoris: 9 treatment sites Energy delivered on each site: 15 or 30 or 45 J	Cycling exercise. Constant-load test until exhaustion at maximal aerobic power	Test duration (s) PBMT (135 J) = 172.0 ± 29.0* PBMT (270 J) = 162.0 ± 29.0* PBMT (405 J) = 163.0 ± 21.0* PLA = 149.0 ± 23.0	Extracted from the text	8

GIF government and/or institutional funding, *LED* light-emitting diode, *NR* not reported, *PBMT* photobiomodulation therapy, *PLA* placebo

*Indicates significant difference from placebo ($p < 0.05$)

Table 4 Characteristics and results of the included studies that investigated PBMT effects on time to exhaustion performance in running

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Dellagrana et al. [55]; GIF	Recreationally trained male runners ($n=15$)	Cluster with 5 laser and 28 LED diodes (large cluster): 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W) and 8 infrared LED diodes (950 nm, 1.28 cm^2, 0.015 W)	Quadriceps femoris: 8 treatment sites; Hamstrings: 4 treatment sites; and Plantar flexors: 2 treatment sites Energy delivered on each site: 15 or 30 or 60 J	Running exercise. Graded-exercise test started at 10 $km{\cdot}h^{-1}$ with increments of 1 $km{\cdot}h^{-1}$ every 3 min until exhaustion	Test duration (s) PBMT (15 J) = 1240.0 ± 272.0* PBMT (30 J) = 1245.0 ± 244.0* PBMT (60 J) = 1224.0 ± 237.0 PLA = 1202.0 ± 273.0	Extracted from the text	8
De Marchi et al. [10]; GIF	Untrained males ($n=22$)	Cluster with 5 infrared laser diodes (810 nm, 0.0364 cm^2, 0.2 W)	Quadriceps femoris:6 treatments sites; Hamstrings: 4 treatments sites; and Plantar flexors: 2 treatments sites Energy delivered on each site: 30 J	Running exercise. Graded-exercise test started at 3 $km{\cdot}h^{-1}$ with increments of 1 $km{\cdot}h^{-1}$ every minute until exhaustion	Test duration (s) PBMT = 711.4 ± 87.5* PLA = 697.3 ± 83.6	Extracted from the text	6
Ferreira-Junior et al. [36]; GIF	Physically active females ($n=12$)	Cluster with 69 LED diodes: 34 red diodes (660 nm, 0.2 cm^2, 0.01 W) and 35 infrared diodes (850 nm, 0.2 cm^2, 0.03 W)	Quadriceps femoris: 2 treatment sites Energy delivered on each site: 41.7 J	Running exercise. Constant-load test until exhaustion at maximal aerobic speed	Test duration (s) PBMT = 571 ± 78 PLA = 544 ± 69	Extracted from a figure using a MatLab algorithm	6
Malta et al. [12]; GIF	Physically active males ($n=15$)	Cluster with 104 LED diodes: 56 red diodes (660 nm, 0.2 cm^2, 0.01 W) and 48 infrared diodes (850 nm, 0.2 cm^2, 0.03 W)	Quadriceps femoris: 2 treatment sites; Hamstring: 2 treatment sites; and Gastrocnemius: 1 treatment site Energy delivered on each site: 60 J	Running exercise. Constant-load test until exhaustion at 115% of maximum oxygen uptake intensity	Test duration (s) PBMT = 154.6 ± 4 PLA = 155.5 ± 4	Extracted from the text	7
Mezzaroba et al. [58]; GIF	Physically active males ($n=26$)	Cluster with 104 infrared LED diodes (850 nm, 0.2 cm^2, 0.03 W)	Quadriceps femoris: 2 treatment sites; Hamstring: 2 treatment sites; and Gastrocnemius: 1 treatment site Energy delivered on each site: 93.6 J	Running exercise. Graded-exercise test started at 8 $km{\cdot}h^{-1}$ with increments of 1 $km{\cdot}h^{-1}$ every 3 min until exhaustion	Test duration (s) PBMT = 1362.7 ± 209.1* PLA = 1338.4 ± 213.3	Extracted from the text	8

Table 4 (continued)

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Miranda et al. [56]; GIF and EF	Untrained males ($n=20$)	Cluster with 4 laser and 8 LED diodes:4 red LED diodes (640 nm, 0.9 cm^2,0.015 W), 4 infrared LED diodes (875 nm, 0.9 cm^2, 0.0175 W) and 4 infrared laser diodes (905 nm, 0.44 cm^2, 0.0003125 W)	Quadriceps femoris: 9 treatment sites; Hamstring: 6 treatment sites; and Gastrocnemius: 2 treatment sites Energy delivered on each site: 30 J	Running exercise. Graded-exercise test started at 3 $km{\cdot}h^{-1}$ with increments of 1 $km{\cdot}h^{-1}$ every 1 min until 16 $km{\cdot}h^{-1}$ was reached	Test duration (s) PBMT = 780.2 ± 91.0* PLA = 742.1 ± 94.0	Extracted from the text	8
Peserico et al. [63]; GIF	Physically active males ($n=15$)	Cluster with 104 LED diodes: 56 red diodes (660 nm, 0.2 cm^2, 0.01 W) and 48 infrared diodes (850 nm, 0.2 cm^2, 0.03 W)	Quadriceps femoris: 2 treatment sites; Hamstring: 2 treatment sites; and Plantar flexors: 1 treatment site Energy delivered on each site: 30 or 120 or 180 J	Running exercise. Graded-exercise test started at 8 $km{\cdot}h^{-1}$ with increments of 1 $km{\cdot}h^{-1}$ every 3 min until exhaustion	Test duration (min) PBMT (30 J) = 22.5 ± 5 PBMT (120 J) = 22.4 ± 4.8 PBMT (180 J) = 22.3 ± 5.2 PLA = 22.2 ± 4.9	Extracted from the text	6
Tomazoni et al. [16]; GIF	Male soccer players ($n=22$)	Cluster with 5 infrared laser diodes (810 nm, 0.0364 cm^2, 0.1 W)	Quadriceps femoris: 9 treatment sites; Hamstring: 6 treatment sites; and Plantar flexors: 2 treatment sites Energy delivered on each site: 50 J	Running exercise. Graded-exercise test started at 3 $km{\cdot}h^{-1}$ with increments of 1 $km{\cdot}h^{-1}$ every 1 min until 16 $km{\cdot}h^{-1}$ was reached	Test duration (s) PBMT = 563.3 ± 159.5* PLA = 504.6 ± 160.4	Extracted from the text	10

EF external funding, *GIF* government and/or institutional funding, *LED* light-emitting diode, *PBMT* photobiomodulation therapy, *PLA* placebo

*Indicates significant difference from placebo ($p < 0.05$)

Table 5 Characteristics and results of the included studies that investigated PBMT effects on all-out sprint performance in cycling

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Leal-Junior et al. [5]; NR	Male volleyball players ($n=8$)	Single-diode laser: infrared (830 nm, 0.0364 cm^2, 0.2 W) Cluster with 69 LED diodes: 34 red diodes (660 nm, 0.2cm^2, 0.03 W) and 35 infrared diodes (850 nm, 0.2cm^2, 0.03 W)	Quadriceps femoris: 2 treatment sites (for both devices) Energy delivered on each site: 6 J (laser) and 41.7 J (cluster)	Cycling exercise. Wingate test	Peak power (W/kg) PBMT (cluster) = 12.3 ± 0.8 PBMT (single-probe) = 12.20 ± 0.5 PLA = 12.7 ± 0.6 Mean power (W/kg) PBMT (cluster) = 9.6 ± 0.6 PBMT (single-probe) = 9.5 ± 0.3 PLA = 9.6 ± 0.4	Extracted from the text	7
Leal-Junior et al. [53]; NR	Male volleyball ($n=9$) and soccer ($n=11$) players	Single-diode laser: infrared (830 nm, 0.0028 cm^2, 0.1 W)	Quadriceps femoris: 5 treatment sites (for both groups) Energy delivered on each site: 4 J (volleyball players) and 3 J (soccer players)	Cycling exercise. Wingate test	Total work (kJ) PBMT (soccer players) = 16.2 ± 1.6 PBMT (volleyball players) = 21.9 ± 2.1 PLA (soccer players) = 16.3 ± 1.7 PLA (volleyball players) = 22.4 ± 2.8	Extracted from the text	8
Molina-Correa et al. [62]; GIF	Physically active males ($n=16$)	Single-diode LED: red (630 nm, 1.32 cm^2, 0.3 W)	Quadriceps femoris: 8 treatment sites; Hamstring: 4 treatment sites; and Gastrocnemius: 4 treatment sites Energy delivered on each site: 6 J	Cycling exercise. Wingate test	Peak power (W) PBMT = 949.2 ± 133.4* PLA = 916.2 ± 129.8 Mean power (W) PBMT = 707.3 ± 102.3 PLA = 700.4 ± 103.5 Total displacement (m) PBMT = 313.3 ± 26.4* PLA = 291.4 ± 24.3	Extracted from the text	8

GIF government and/or institutional funding, *LED* light-emitting diode, *NR* not reported, *PBMT* photobiomodulation therapy, *PLA* placebo

*Indicates significant difference from placebo ($p < 0.05$)

Table 6 Characteristics and results of the included studies that investigated PBMT effects on time-trial performance in running

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Dellagrana et al. [35]; GIF	Recreationally trained male runners ($n=19$)	Cluster with 5 laser and 28 LED diodes (large cluster): 12 red LED diodes (670 nm, 1.92 cm^2, 0.01 W), 5 infrared laser diodes (850 nm, 0.06 cm^2, 0.1 W), 8 infrared LED diodes (880 nm, 1.28 cm^2, 0.025 W) and 8 infrared LED diodes (950 nm, 1.28 cm^2, 0.015 W)	Quadriceps femoris: 8 treatment sites; Hamstrings: 4 treatment sites; and Plantar flexors: 2 treatment sites Energy delivered on each site: 30 J	Running exercise. Time-trial performance test in 1500 m	Test duration (s) PBMT = 336.0 ± 30.9 PLA = 338.7 ± 26.5	Provided by the author	8
Lanferdini et al. [37]; NF	Male endurance runners and triathletes ($n=20$)	Cluster with 152 infrared LED diodes (880 nm, 0.1357 cm^2, 0.033 W)	Quadriceps femoris: 2 treatment sites; Hamstring: 1 treatment site; Plantar flexors: 1 treatment site; and Gluteus maximus: 1 treatment site Energy delivered on each site: 150 J	Running exercise. Time-trial performance test in 3000 m	Test duration (s) PBMT = 639.6 ± 46.8* PLA = 646.8 ± 51.1	Provided by the author	7

GIF government and/or institutional funding, *LED* light-emitting diode, *NF* no external funding, *PBMT* photobiomodulation therapy, *PLA* placebo

*Indicates significant difference from placebo ($p < 0.05$)

Table 7 Characteristics and results of the included studies that investigated PBMT effects on repeated-sprint performance in running

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Pinto et al. [13]; GIF	Male rugby players ($n=12$)	Cluster with 4 laser and 8 LED diodes:4 red LED diodes (640 nm, 0.9 cm^2, 0.015 W), 4 infrared LED diodes (875 nm, 0.9 cm^2, 0.0175 W) and 4 infrared laser diodes (905 nm, 0.44 cm^2, 0.0003125 W)	Quadriceps femoris: 9 treatment sites; Hamstring: 6 treatment sites; and Plantar flexors: 2 treatment sites Energy delivered on each site: 30 J	Running exercise. Bangsbo sprint test	Average time (s) PBMT = 6.5 ± 0.2* PLA = 6.7 ± 0.2	Extracted from the text	8
Santos et al. [50]; GIF	Female futsal players ($n=13$)	Cluster with 69 LED diodes: 34 red diodes (660 nm, 0.234 cm^2) and 35 infrared diodes (850 nm, 0.234 cm^2). Power of the device was not reported by the authors	Quadriceps femoris: 2 treatment sites; Hamstring: 2 treatment sites; and Plantar flexors: 1 treatment site Energy delivered on each site: 200 J	Running exercise. Illinois agility run test	Average time in Illinois agility run test (s) PBMT = 19.6 ± 1 PLA = 19.6 ± 0.7	Extracted from the text	6

GIF government and/or institutional funding, *LED* light-emitting diode, *PBMT* photobiomodulation therapy, *PLA* placebo

*Indicates significant difference from placebo ($p<0.05$)

3.5 Effects of PBMT on Cycling

Four studies provided data related to cycling exercises [7, 11, 38, 54]. A significant increase in time to exhaustion was verified when PBMT was used prior to cycling exercise compared with placebo (overall SMD 0.35, 95% CI 0.10–0.59; $p<0.01$, $I^2=0\%$) (Fig. 3). Three studies were used to analyse PBMT effects on all-out sprint performance in cycling, and no changes in all-out sprint performance in cycling were verified (overall SMD 0.01, 95% CI − 0.30 to 0.31; $p=0.96$, $I^2=0\%$) (ESM Fig. S4).

3.6 Effects of PBMT on Running

Eight studies provided data related to time to exhaustion performance tests in running [10–12, 16, 55, 56, 58, 63], and no changes in time to exhaustion performance were verified in running (SMD 0.17, 95% CI − 0.03 to 0.37; $p=0.10$, $I^2=0\%$) (Fig. 4). For the analysis of PBMT effects on time-trial performance in running, two studies were used (i.e., 1500 m [35] and 3000 m [37]), with no changes observed in time-trial performance in running (SMD − 0.12, 95% CI − 0.56 to 0.33; $p=0.61$, $I^2=0\%$) (ESM Fig. S5). Two studies were also used to analyse PBMT effects on repeated-sprint performance in running [13, 50], and again, there was no significant effect of PBMT on repeated-sprint performance in running (overall SMD − 0.18, 95% CI − 0.58 to 0.21; $p=0.37$, $I^2=0\%$) (ESM Fig. S6).

3.7 Effects of PBMT in Swimming

One study was used to analyse PBMT effects on time-trial performance in swimming [39]. This study provided data related to 100, 200, and 400 m swimming freestyle time-trial tests, with no change observed in time-trial performance in swimming (overall SMD 0.05, 95% CI − 0.36 to 0.46; $p=0.81$, $I^2=0\%$) (ESM Fig. S7).

Table 8 Characteristics and results of the included studies that investigated PBMT effects on time-trial performance in swimming

Study; funding	Participants	PBMT light source	Muscle groups treated in each limb	Exercise description	Outcomes selected for meta-analysis	Data source	PEDro score
Teixeira et al. [39]; NR	Swim-trained males ($n = 15$)	Cluster with 104 LED diodes: 56 red diodes (660 nm, 0.2 cm^2, 0.01 W) and 48 infrared diodes (850 nm, 0.2 cm^2, 0.03 W)	Pectoral muscle: 1 treatment site; Dorsal muscle: 1 treatment site; Middle deltoid: 1 treatment site; Triceps brachii: 1 treatment site; Quadriceps femoris: 1 treatment site; Biceps femoris: 1 treatment site; and Plantar flexor: 1 treatment site. Energy delivered on each site: 30 J	Swimming exercise. Freestyle swimming time-trial performance in 100, 200 and 400 m	Swimming time (s): 100 m PBMT = 65.5 ± 6.3 PLA = 65.2 ± 5.6 200 m PBMT = 148.5 ± 17.9 PLA = 149 ± 16.4 400 m PBMT = 327.7 ± 38.2 PLA = 321.6 ± 47.7	Extracted from the text	7

LED light-emitting diode, *NR* not reported, *PBMT* photobiomodulation therapy, *PLA* placebo

4 Discussion

The purpose of this systematic review with meta-analysis was to investigate the ergogenic efficacy of PBMT in different exercise modes and performance metrics. Specifically, data were obtained to assess the ergogenic effects of PBMT on single-joint, running, cycling, and swimming exercises. For single-joint exercises, PBMT improved (overall SMD 0.27, 95% CI 0.12–0.41) muscle endurance performance but did not affect muscle strength performance. For cycling, PBMT enhanced (overall SMD 0.35, 95% CI 0.10–0.59) time to exhaustion performance but had no impact on all-out sprint performance. For both swimming and running, no significant effects were observed for time-trial performance. In addition, no significant effects were observed for time to exhaustion or repeated-sprint performance in running. The results of the current study are consistent with previous data reporting that the ergogenic benefits associated with PBMT are exercise mode-specific [23].

4.1 PBMT Positive Effects on Exercise Performance

The positive effects of PBMT on muscle endurance performance in single-joint exercises and time to exhaustion performance in cycling may be explained by a decreased rate of muscle fatigue development [4, 18]. Muscle endurance and time to exhaustion performance are strictly related to the recruitment of slow-twitch motor units (i.e., type I muscle fibres) [64, 65]. In these muscle fibres, the oxidative pathway is the main ATP source for the processes involved in tissue contraction [66]. The primary mechanisms of PBMT rely on an increase in the activity of the CCO enzyme located in the inner mitochondrial membrane, and release of nitric oxide from copper proteins in the CCO and from heme proteins in haemoglobin and myoglobin [17]. As a result, PBMT enhances the rate of ATP resynthesis by the oxidative pathway [19] (i.e., CCO increases the transfer of electrons through the mitochondrial membrane that drives ATP synthase [18]) and improves tissue microcirculation and tissue oxygenation [21, 22] (i.e., increased nitric oxide bioavailability triggers vasodilation [20]). In vitro findings also suggest that PBMT effectiveness is impacted by tissue characteristics such as mitochondrial content, as evidenced by the observation that muscles with more mitochondria respond better to PBMT than muscle with fewer mitochondria [67]. Taken together, PBMT may favour the activity of slow-twitch motor units and attenuate the reliance on fast-twitch motor units (i.e., type II muscle fibres) to sustain fatiguing exercise [68–70]. Type II muscle fibres have a lower mitochondrial density than type I muscle fibres, and thus are more dependent on glycolysis and cytosolic ATP

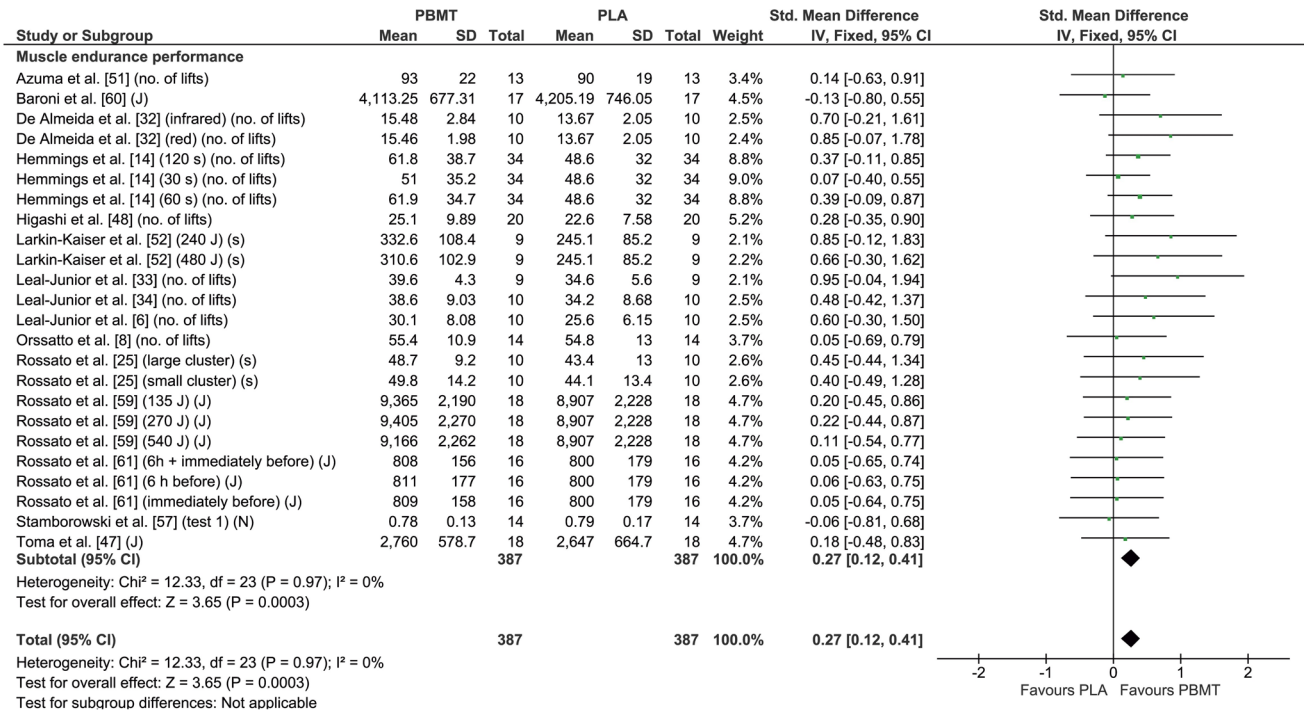

Fig. 2 Forest plot of the meta-analysis illustrating the comparison between PBMT and PLA condition for *muscle endurance* performance in single-joint exercise. Data extracted from the included studies for the analysis were time maintaining force production at a given percentage of maximum (i.e., *time to exhaustion*, s), *maximal number of lifts until exhaustion*, *mean force* (kgf) and *work* (J or kJ). *CI* confidence interval, *PBMT* photobiomodulation therapy, *PLA* placebo, *IV* inverse variance, *SD* standard deviation, *Std* standard, *df* degrees of freedom

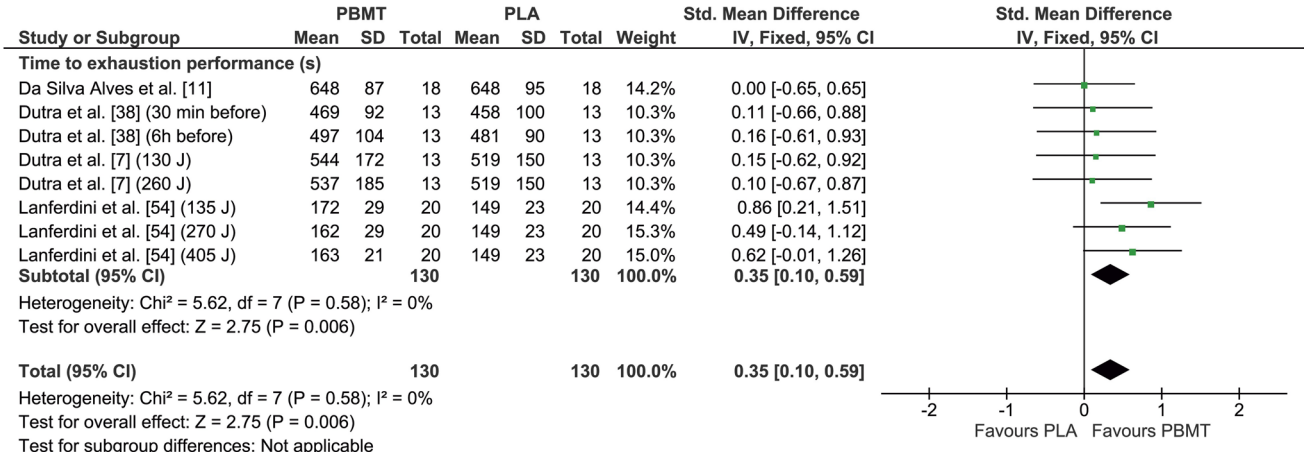

Fig. 3 Forest plot of the meta-analysis illustrating the comparison between PBMT and PLA condition for *time to exhaustion* performance in cycling. *CI* confidence interval, *PBMT* photobiomodulation therapy, *PLA* placebo, *IV* inverse variance, *SD* standard deviation, *Std* standard, *df* degrees of freedom

turnover [66]. The net result is an attenuated increase in ATP resynthesis by the non-oxidative systems and accumulation of fatigue-inducing metabolites (e.g., H^+, Pi, ADP), which in turn decreases fatigue development and enables exercise to be sustained for longer [24].

4.2 Absence of PBMT Positive Effects on Exercise Measures

PBMT does not improve muscle strength performance in single-joint exercises, all-out sprint performance in cycling, repeated-sprint, time to exhaustion or time-trial performance

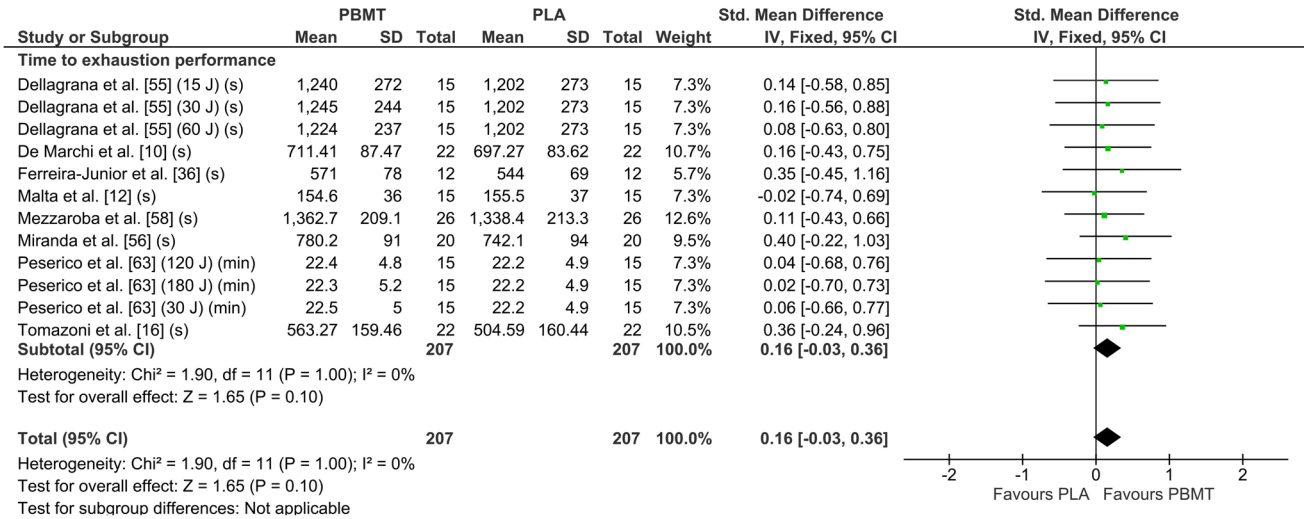

Fig. 4 Forest plot of the meta-analysis illustrating the comparison between PBMT and PLA condition for *time to exhaustion* performance in running. *CI* confidence interval, *PBMT* photobiomodulation therapy, *PLA* placebo, *IV* inverse variance, *SD* standard deviation, *Std* standard, *df* degrees of freedom

in running, or time-trial performance in swimming. The maximal voluntary force that a muscle may exert depends on the degree of fast-twitch motor units recruitment and/or the rate at which motor neurons discharge action potentials [71]. The recruitment of fast-twitch motor units is also a key determinant of all-out sprint cycling performance [72] and is responsible for the majority of force production during supra-maximal exercises (e.g., running sprints) [73]. Moreover, performance in these exercises is strictly related to the muscle's capacity to resynthesize ATP via non-oxidative systems [74, 75], and is therefore unlikely to be influenced by PBMT-induced improvements in muscle blood flow and muscle oxidative capacity [23]. To date, there is no evidence linking PBMT effects to increases in spinal-level excitability, motor-unit recruitment, or ATP resynthesis by non-oxidative systems. As such, it is reasonable to suggest that the ergogenic effects of PBMT on muscle strength, all-out sprint performance in cycling (peak power and mean power), or repeated-sprint performance in running (best time and mean time) are negligible.

Nevertheless, the capacity of PBMT to increase nitric oxide bioavailability has been suggested as a potential mechanism to explain previously reported improvements in all-out sprint cycling performance [62]. Indeed, increased bioavailability of nitric oxide may enhance contractile properties [76], decreasing the degradation of phosphocreatine in high-intensity exercises [77]. Given the essential role of phosphocreatine during all-out sprint cycling [78], its delayed depletion would help to maintain power production during exercise [79, 80]. However, there is no evidence that PBMT can induce increases in nitric oxide bioavailability in humans [38], and as such this proposed mechanism remains speculative. Thus, future studies investigating the capacity of PBMT to enhance nitric oxide bioavailability in humans, as well as the influence this has on performance during exercises requiring a large degree of fast-twitch recruitment (e.g., all-out sprint cycling), are warranted.

The present review included two studies investigating PBMT effects on repeated-sprint performance in running, with one reporting an improvement in mean time [13] and the other reporting no effect [50]. The former study was performed in professional male rugby athletes, whereas the lack of positive effects was reported in amateur female futsal players. It could be expected that due to training level, professional rugby players had a higher content of type I muscle fibre than amateur female futsal players [81, 82]. As earlier discussed, this higher content of type I muscle fibre and, consequently, higher mitochondrial content, may favour the effects of PBMT [67], which might contribute to the PBMT positive effects. The reported ergogenic effect may have been a result of enhanced phosphocreatine resynthesis and delayed fatigue due to greater muscle oxidative capacity [83] and muscle blood flow [84], respectively. Thus, careful interpretation of the current findings and future studies are needed to better understand the PBMT ergogenic effects on mean time during repeated sprints in running.

This review also reports that PBMT does not enhance time to exhaustion performance in running. A potential reason for this is the large heterogeneity in the methodological procedures of the included studies. For example, the exercise intervention utilized ranged from constant-load tests at supramaximal intensity (e.g., 115% of VO_{2peak}) [12], to graded exercise tests with long durations (~20 to 22 min)

[55, 58, 63]. Exercise maintenance in supramaximal intensities is associated with the recruitment of fast-twitch motor units and ATP resynthesis by non-oxidative systems [85–87]. On the other hand, exhaustion in prolonged graded-intensity tests (> 12 min) may be largely influenced by distinct factors beyond cardiorespiratory function, such as increased body temperature, greater dehydration, subject discomfort, or ventilatory muscle fatigue [88, 89]. Considering the PBMT mechanisms discussed earlier, it is expected that PBMT favours exercise performance in protocols that rely more heavily on the recruitment of the slow-twitch motor units and oxidative ATP synthesis. Taken together, it is possible that the small effects reported in these studies may have counterbalanced the large effects observed in the other included studies (i.e., constant-load test at maximal intensity [36] and graded-intensity test protocols with ~13 min duration [10, 16, 56]), contributing to the absence of an overall positive effect.

In addition, there were no positive effects of PBMT on time-trial performance in running or swimming. Although it can be argued that performance tests better represent 'real world' competitive sport [90], they may not necessarily elicit maximal exertion and require pacing strategies to be employed, which can mask any potential ergogenic benefits [91, 92]. However, it is noteworthy that the evidence about PBMT effects on running and swimming time-trial tests is sparse (i.e., two and one studies included in the meta-analysis, respectively). Thus, careful interpretation of the current findings and future studies are needed to better understand the PBMT ergogenic effects on time-trial tests.

4.3 Methodological Quality of the Included Studies

The studies included in the current systematic review were classified as high (30 studies), moderate (four studies) and low (two studies) quality. Moreover, most studies presented a low risk of bias, apart from three studies that presented an unclear risk. An important limitation in the included studies was that no study investigated the effectiveness of the blinding intervention. Considering PBMT does not elicit specific sensations in the skin (e.g., heat, flushing), it is expected that participants were adequately blinded to the treatment they received. However, without asking the participants to indicate which intervention they received (i.e., PBMT or placebo), it is unknown if the blinding was successful. Future studies may consider exploring the effectiveness of the participant´s blinding, taking into account that correct treatment identification may influence exercise performance and therefore bias the results [93].

4.4 Intricacies of PBMT Mechanisms and Usage Parameters in Humans

There are a number of limitations associated with PBMT. First, the mechanisms associated with PBMT's ergogenic benefits (e.g., increased CCO activity, ATP production, and nitric oxide bioavailability) have been validated in in vitro assays [18] and animal model studies [19] only. The first law of photobiology states that for PBMT to elicit effects on biological activities, the energy delivered must be absorbed by the chromophores in the target tissue [1]. Moreover, the dose–response effect inherent to PBMT states that if the energy absorbed is insufficient, no reaction or small changes will occur. Conversely, if an excessive amount of energy is absorbed, cell functions will be suppressed or inhibited [1]. In in vitro assays, light penetrates the cells directly, whereas in animal and human models, skin (~0.21 to 0.67 mm in mice [94], and ~2.3 to 4.7 mm in humans [95]) will absorb the incoming photons [96, 97], thereby reducing light penetration and delivery to skeletal muscle cells. Thus, it is possible that the level at which PBMT impacts biological activities may change between models of investigation. Although there is evidence of PBMT improving CCO activity [22], microcirculation [98], and blood/oxygen supply to muscle tissue [21, 22] in humans, there are contradictory data about its effects during exercise. For example, previous studies report no effect of PBMT on systemic physiological responses during exercise, including acid–base balance or cardiorespiratory control [7, 38]. To strengthen the literature regarding the ergogenic effects of PBMT, future studies may consider exploring PBMT effects on biological activities in vivo in humans.

In addition, the optimal treatment parameters for using PBMT are not fully elucidated. PBMT is composed of several treatment parameters, such as light wavelength (nm), power of the light (W), power density ($W \cdot cm^{-2}$, which is calculated as power divided by device spot area), time of irradiation (s), the number of sites of irradiation, and the total dose delivered over the target tissue (J; which is calculated as the time of irradiation in seconds multiplied by power of the light watts) [1]. The literature suggests that the use of inadequate parameters is likely to provide no effects of PBMT on biological activities [1]. To date, it is known that red/infrared light (wavelength of 780–950 nm) should be preferred to treat deeper tissues (e.g., skeletal muscle) due to higher penetration of light in these wavelengths through human tissues. Moreover, in these wavelengths, light emitted with a power density of 100 $mW \cdot cm^{-2}$ can penetrate up to 50 mm below the skin surface [99]. There is sparse evidence about the impact of the number of irradiation points on PBMT efficacy as a preconditioning method [25]. Nevertheless, previous reviews suggested to cover as much of the prime mover muscles area as possible avoiding excessive energy delivery [23, 68]. Delivering a total dose of between 120 and 300 J and 20 and 60 J has been the most effective at eliciting an ergogenic effect during exercises using large and small muscle groups, respectively [23]. However, it is unknown whether altering these PBMT parameters is capable of inducing meaningful differences in human biological activities, exercise-induced physiological responses, and

exercise performance. Future studies investigating the effects of different PBMT methodologies on exercise performance are warranted.

4.5 Strength and Limitations

A limitation of the current review is the heterogeneity in fitness between studies. Specifically, cohorts varied across team-sports athletes, recreational runners and cyclists, physically active, and untrained subjects. The effects of PBMT seem to be impacted by tissue characteristics such as mitochondrial content, as evidenced by the fact that muscles with greater mitochondrial content respond better to PBMT than those with lesser mitochondrial content [67]. Skeletal muscle mitochondrial content is heavily dependent on individual training status [90]. Therefore, the heterogeneity in fitness between the included studies could be a confounding factor for the findings of the present review. Future studies should explore the ergogenic effects of PBMT in populations with varying training status (e.g., untrained vs. endurance-trained and/or resistance-trained). Other limitations are related to the heterogeneity of PBMT treatment parameters, as the effectiveness of PBMT may be dependent on the configuration of the device [23]. Thus, further studies should consider the effects of PBMT treatment parameter settings on exercise performance. In contrast to previous reviews on the current topic, our study conducted a series of meta-analyses investigating the effects of PBMT on distinct exercise modes (i.e., single-joint, running, cycling, and swimming), with a particular focus on mode-specific exercise performance. Thus, our study provides practical recommendations for the exercise mode that is most likely to benefit from PBMT.

4.6 Practical Implications

Individuals interested in improving muscle endurance during single-joint exercises, and time to exhaustion performance in cycling, may consider using PBMT as an acute preconditioning method. For single-joint exercises, PBMT may lead to a small increase in the time to maintaining and the mean force produced during an isometric action, maximal number of lifts at a given load, or isokinetic total work. For cycling, PBMT may lead to a small increase in the time maintaining exercise at a predefined intensity until volitional exhaustion. PBMT does not seem to be ergogenic for muscle strength in single-joint exercises, running or swimming.

5 Conclusions

Our findings indicate that PBMT increases muscle endurance performance in single-joint exercises, and time to exhaustion performance in cycling. There were no significant effects on muscle strength performance in single-joint exercises, running, or swimming performance metrics. From a practical standpoint, these results allow individuals to make informed decisions as to the likelihood of an ergogenic benefit with PBMT based on their chosen exercise (e.g., single-joint and cycling exercises) and performance metric (e.g., muscle endurance rather than muscle strength performance in single-joint exercises; time to exhaustion rather than all-out sprint performance in cycling). Although the current data support the efficacy of PBMT during certain exercise scenarios, its precise influence on biological activities in humans, especially in skeletal muscle, remain to be fully elucidated. Moreover, the best treatment parameter settings for ergogenic benefits require further clarification. Future studies are warranted to determine the ideal PBMT treatment parameter settings and their effects on exercise-induced physiological responses and exercise performance. PBMT has also been used as a post-exercise recovery method. Therefore, oncoming research addressing PBMT effects on recovery biomarkers, delayed-onset muscle soreness and perceived recovery could be of interest to the scientific community and public at large.

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Declarations

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Conflict of interest/competing interest Yago Medeiros Dutra, Elvis de Souza Malta, Amanda Soler Elias, James R Broatch and Alessandro Moura Zagatto declare they have no conflicts of interest relevant to the contents of this review.

Author contributions YMD, ESM, ASE and AMZ contributed to the study conception, design, material preparation, data collection and analysis. YMD, ESM, JRB and AMZ contributed to data interpretation and manuscript writing. All authors read and approved the final manuscript.

Data availability All data generated and/or analysed during this study are included in this published article (and its electronic supplementary information files).

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