 DOI: http://dx.doi.org/10.1590/S1980-6574202000030063

Systematic review

Effects of different methods of strength training on indicators of muscle fatigue during and after strength training: a systematic review

Guillermo D. Barahona-Fuentes[1], Álvaro Huerta Ojeda[1,3], Daniel Jerez-Mayorga[2]

[1]*Universidad de Las Américas, Grupo de Investigación en Salud, Actividad Física y Deporte, Escuela de Educación Física, Viña del Mar, Chile;* [2]*Universidad Andres Bello, Facultad de Ciencias de la Rehabilitación, Santiago, Chile;* [3]*Centro de Capacitación e Investigación Deportiva Alpha Sports, Valparaíso, Chile.*

Abstract - Introduction: The development of strength has shown to be beneficial to sports performance and health. However, during strength training, they also produce alterations in muscle fatigue indicators, leading to a decrease in the ability to generate strength. Despite this, there is still not enough knowledge about the levels of muscle fatigue generated by different methods of strength training and how this information can be integrated into sports planning. Review and analyze the studies existing between January 2009 and January 2019 that have used indicators of muscle fatigue established in the search terms during and after strength training as measurement variables. **Evidence acquisition**: The study corresponds to a systematic review of previously published studies, following the PRISMA model. Articles published between 2009 and 2019 that measured muscle fatigue indicators during and after strength training were evaluated. The electronic search was conducted through Web of Science, Scopus, Sport Discus, PubMed, and Medline. We included all articles that used a strength protocol and also measured indicators of muscle fatigue and its possible effect on physical performance. **Evidence synthesis:** A total of 39 articles were found, which were stratified according to the protocol used: (i) plyometric training, (ii) Bodypump® training, (iii) occlusion training, (iv) variable resistance training, (v) conventional strength training, (vi) eccentric strength training, (vii) rest times in strength training and (viii) concurrent training. **Conclusion:** At the end of the systematic review, it was shown that the different training methodologies for strength development generate increases in muscle fatigue indicators, and the increase generated in the different muscle fatigue indicators depends both on the methodology used and on the type of population, sex, level of training and type of sport. The most-reported indicators are [La], HR and RPE, DOM, MR variation, and ammonium.

Keywords: strength training; muscle fatigue indicators; sports performance.

Introduction

Today, sports training is based on the development of the various manifestations of force[1]. Thus, several investigations have recognized muscle strength as the main capacity to produce a high level of muscle power[1,2] and neuronal adaptations[3], which favor the development of muscular hypertrophy[4]. In this sense, optimal muscle development has been associated with sports performance and a better quality of life[5]. On the contrary, a decrease in muscle strength and neuromuscular control change the functional behavior of an athlete, limiting performance and possibly triggering an injury[6].

In order to achieve optimal development of strength, power and muscular hypertrophy, traditional[7-13] and non-traditional training methods have been used, including plyometric exercises on land[14–18], plyometrics in the aquatic environment[19], occlusion training[20–23], training with elastic bands[24], electrostimulation training[11], eccentric exercises[25], and Bodypump® programs[26,27]. These methods have demonstrated, in several cases, increases in sports performance[4,25,27]. However, it has also been documented that strength training produces alterations in muscle fatigue indicators[28–30]. In this sense, fatigue has been defined as a reduction in the ability of the neuromuscular system to generate strength or to carry out work resulting from physical exercise[31,32]. Thus, a decrease in the production of strength, in its different manifestations during and after strength training, has been associated with increases in blood uric acid[33], ammonium[32], lactate concentrations ([La])[34], elevated heart rate (HR)[16], increased perception of effort (RPE)[35], increased muscle pain (DOMS)[36], and decreased range of motion (ROM)[17]. These metabolic and physiological responses produced by strength exercise[37] have been identified as synonymous with fatigue[17,32,33].

However, it is not yet fully established if these fatigue indicators always produce a decrease in performance[26]. That is why there is a need to establish whether indicators of muscle fatigue are constantly associated with a decrease in performance. As a result of the above, the objective of this systematic review was to review and analyze the studies existing between January 2009 and January 2019 that have used indicators of muscle fatigue established in the search terms during and after strength training as measurement variables. As a secondary objective, the programs were described, establishing the biochemical and physiological responses reported in each of the studies consulted.

Method

Procedure

The search identified articles published in the following databases: Web of Science (WOS), Scopus, Sport Discus, PubMed, and Medline. The search limits were: articles published in the last ten years (January 2009 to January 2019) that were written in English, Portuguese, French, German, or Spanish.

Bibliographic search

The literature search was performed in accordance with the guidelines for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)[38]. The title, abstract, and keyword search fields were searched in each of the databases. The following keywords combined with Boolean operators (AND/OR) were used: ([“Ammonium” OR “Ammonium lactate” OR “Lactic acid” OR “Lactate” OR “Acid-base equilibrium” OR “Acid-base balance” OR “Heart rate” OR “Muscular fatigue” OR “Muscle fatigue” OR “Ratings of perceived exertion” OR “RPE scale”] AND [“Sports performance” OR “Athletic performance”] AND [“Strength training” OR “Resistance training” OR “Force training” OR “Concurrent training” OR “Isometric training” OR “Isokinetic training” OR “Concentric training” OR “Eccentric training” OR “Velocity based training” OR “Complex training” OR “Contrast training”]). Each of the keywords related to the methods of fatigue and force had the purpose of broadening the search. Two authors searched and reviewed the studies, both of whom decided whether the inclusion of studies was appropriate. In case of disagreement, a third author was consulted. The search strategy and study selection are presented in Figure 1.

Inclusion criteria

The importance of each study was evaluated according to the following inclusion criteria: a) experimental study design; b) healthy subjects of both genders; c) studies with strength training protocols; d) studies reporting indicators of muscle fatigue through ammonia, lactate, pH, HR, muscle fatigue and perception of effort; e) those with increased or decreased performance post-intervention, and f) studies published in English, Spanish, French, Portuguese or German. Studies that did not meet the inclusion criteria were excluded. Discrepancies found were resolved by consensus of the investigators.

Evaluation of methodological quality

The Physiotherapy Evidence Database (PEDro) scale[39,40] was used to assess study quality. The classification was based on three criteria: selection (maximum three stars), comparability (maximum three stars), and results (maximum four stars). Articles scoring eight to ten were considered to be of high methodological quality, four to seven moderate, and less than four low. Thus, the score obtained by the articles according to the PEDro scale indicated that 13 studies obtained a high score and 26 articles obtained a moderate score (Table 1).

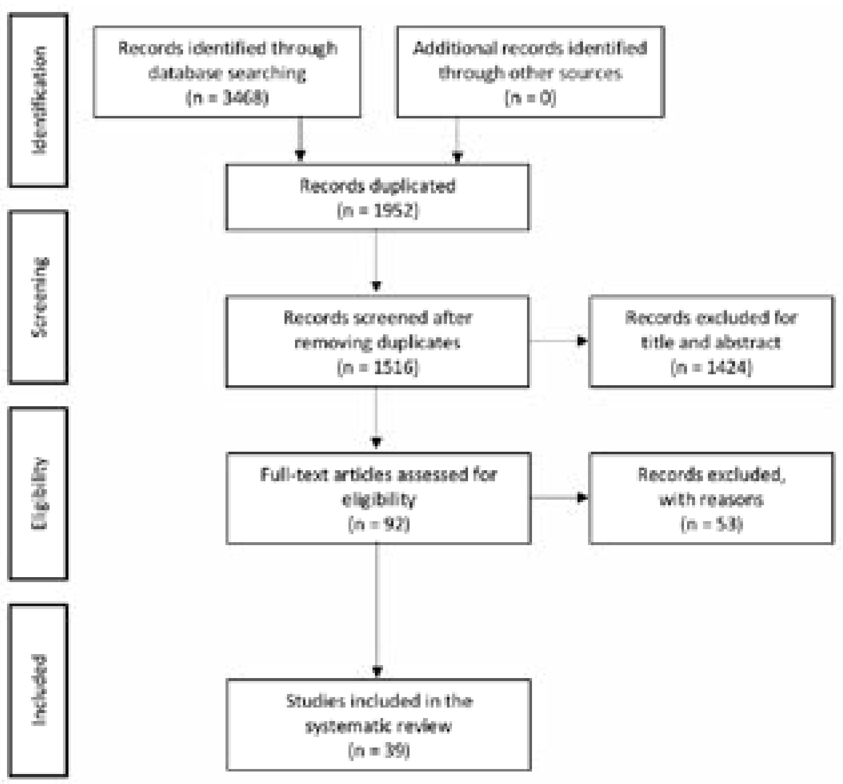

Figure 1 - Flow chart of search strategy and selection of articles.

Table 1 - List of included articles scored according to the PEDro scale.

	Selection (1-2-3-4)	Comparability (5-6-7)	Results (8-9-10-11)	Total
Oliveira et al. [26]	#-*-*-*	0-0-0	*-*-*-*	7
Wernbom et al. [20]	#-*-*-*	0-0-*	*-*-*-*	8
Brown et al. [16]	#-0-0-*	0-0-0	*-*-*-*	5
Chatzinikolaou et al. [17]	#-*-*-*	0-0-0	*-*-*-*	7
Smilios et al. [44]	#-0-0-*	0-0-0	*-*-*-*	5
Walker et al. [34]	#-0-0-*	0-0-0	*-*-*-*	5
Greco et al. [27]	#-*-*-*	0-0-0	*-*-*-*	7
Izquierdo et al. [33]	#-0-0-*	0-0-0	*-*-*-*	5
Sánchez-Medina et al. [32]	#-0-0-*	0-0-0	*-*-*-*	5
Buitrago et al. [37]	#-*-*-*	*-0-0	*-*-*-*	8
Hardee et al. [35]	#-*-*-*	*-0-0	*-*-*-*	8
Paulo et al. [45]	#-*-*-*	*-0-0	*-*-*-*	8
Walker et al. [12]	#-*-*-*	*-0-0	*-*-*-*	8
Couto et al. [11]	#-*-*-*	*-0-0	*-*-*-*	8
Fernandez-Gonzalo et al. [25]	#-0-0-*	0-0-0	*-*-*-*	5
Okuno et al. [21]	#-*-*-*	*-0-0	*-*-*-*	8
Pareja-Blanco et al. [2]	#-*-*-*	*-0-0	*-*-*-*	8
Rogatzki et al. [46]	#-*-*-*	0-0-0	*-*-*-*	7
Silva et al. [47]	#-0-0-*	0-0-0	*-*-*-*	5
Ammar et al. [48]	#-*-*-*	0-0-0	*-*-*-*	7
Gadruni et al. [24]	#-0-0-*	0-0-0	*-*-*-*	5
González-Badillo et al. [49]	#-*-*-*	0-0-0	*-*-*-*	7
Nicholson et al. [13]	#-*-*-*	*-0-0	*-*-*-*	8
Ojeda et al. [1]	#-0-0-*	0-0-0	*-*-*-*	5
Poton et al. [22]	#-*-*-*	*-0-0	*-*-*-*	8
Raeder et al. [39]	#-0-0-*	0-0-0	*-*-*-*	5
Sabido et al. [5]	#-*-*-*	0-0-0	*-*-*-*	7
Bartolomei et al. [50]	#-*-*-*	0-0-0	*-*-*-*	7
de Almeida et al. [23]	#-*-*-*	0-0-0	*-*-*-*	7
Johnston et al. [51]	#-*-*-*	*-0-0	*-*-*-*	8
Andreatta et al. [52]	#-0-0-*	0-0-0	*-*-*-*	5
Curty et al. [53]	#-*-*-*	0-0-0	*-*-*-*	7
dos Santos et al. [54]	#-0-0-*	0-0-0	*-*-*-*	5
Ojeda et al. [29]	#-0-0-*	0-0-0	*-*-*-*	5
Miranda et al. [55]	#-*-*-*	0-0-0	*-*-*-*	7
Párraga-Montilla et al. [56]	#-0-0-*	0-0-0	*-*-*-*	5
Sieljacks et al. [57]	#-*-*-*	*-0-0	*-*-*-*	8
Wertheimer et al. [19]	#-*-*-*	0-0-0	*-*-*-*	7
Tufano et al. [58]	#-*-*-*	*-0-0	*-*-*-*	8

Elements in the PEDro scale: 1 (eligibility criteria were specified); 2 (subjects were randomly assigned to groups); 3 (assignment was concealed); 4 (groups were similar at baseline relative to the most important prognostic indicators); 5 (all subjects were blinded); 6 (all therapists who administered therapy were blinded); 7 (all evaluators who measured at least one key outcome were blinded); 8 (measures of at least one of the key outcomes were obtained from more than 85% of the subjects initially assigned to the groups); 9 (results were presented for all subjects who received treatment or were assigned to the control group, or where not possible, data for at least one key outcome were analyzed by “intention to treat”); 10 (results from statistical comparisons between groups were reported for at least one key outcome); and 11 (study provides point and variability measures for at least one key outcome). # (has specified choice criteria; however, it is not counted as a score).

Results

Selected studies

The electronic search identified 3468 articles, of which 1952 were duplicated. The remaining 1516 articles were filtered by titles and abstracts, leaving 92 articles for full reading and analysis. After reviewing the 92 articles, 53 were removed, all for not meeting the inclusion criteria. By not including articles after a citation-oriented search, a total of 39 articles were obtained for a systematic review. These articles were stratified according to the protocol used: (i) plyometric training, (ii) Bodypump® training, (iii) occlusion training, (iv) variable resistance training, (v) conventional strength training, (vi) eccentric strength training, (vii) rest times in strength training and (viii) concurrent training.

At the end of the review, there was evidence from studies showing that strength training induces muscle fatigue as a result of physiological and biochemical responses related to strength training. Only those studies that related strength training to indicators of muscle fatigue are presented below (Table 2 and 3).

Table 2 - Characteristics of the participants in each study.

Author	Number (M/F)	Age	Sample type
Oliveira et al. [26]	0/15	21.7± 2.1	Not physically trained
Wernbom et al. [20]	8/3	20-39	Velocity and trained footballers
Brown et al. [16]	10/10	22.1±1.3	Recreative trained
Chatzinikolaou et al. [17]	24/0	25.5±1.9	Physically healthy subjects
Smilios et al. [44]	16/0	20.7±1.1	Young people with recreational experience in strength
Walker et al. [34]	10/0	23.6±2.5	Recreative trained in strength
Greco et al. [27]	0/19	21.4±2.0	Sedentary
Izquierdo et al. [33]	12/0	33.0±4.4	Physically active subjects
Sánchez-Medina et al. [32]	18/0	25.6±3.4	Trained subjects
Buitrago et al. [37]	10/0	27.3±3.2	Students physical education with experience in strength
Hardee et al. [35]	10/0	23.6±0.37	Subjects trained in strength
Paulo et al. [45]	19/0	25.7±4.4	Physically healthy young people
Walker et al. [12]	13/0	28.4 ± 3.7	Physically active subjects with no experience in strength
Couto et al. [11]	32/0	26.0±3.46	Subjects with experience in strength
Fernandez-Gonzalo et al. [25]	16/16	23±1	Healthy and physically active subjects
Okuno et al. [21]	9/0	24.0±2.9	Healthy subjects with experience in strength
Pareja-Blanco et al. [2]	29/0	23.3±3.2	Students of sports sciences with experience in strength
Rogatzki et al. [46]	6/0	18-24	Teenagers
Silva et al. [47]	11/0	32±6	Trained cyclists
Ammar et al. [48]	9/0	21±0.5	Experienced weightlifters
Gadruni et al. [24]	14/0	22.64±1.49	Taekwondo athletes and sedentary subjects
González-Badillo et al. [49]	9/0	23.3±3.9	Students of sports sciences with experience in strength
Nicholson et al. [13]	34/0	21.76±2.60	Trained subjects
Ojeda et al. [1]	19/0	24.8±5.3	Military pentathletes
Poton et al. [22]	12/0	23.4±3.8	Healthy and trained subjects
Raeder et al. [39]	14/9	24.1±2.0	Athletes
Sabido et al. [5]	17/0	23.2±3.6	Subjects with experience in strength
Bartolomei et al. [50]	12/0	24.5±4.2	Subjects with experience in strength
de Almeida et al. [23]	10/0	22.50±2.84	Subjects with experience in strength
Johnston et al. [51]	15/0	21±1	Rugby players
Andreatta et al. [52]	10/10	24±6	Healthy subjects with experience in strength
Curty et al. [53]	9/0	26±1	Healthy subjects with experience in strength
dos Santos et al. [54]	7/6	29.5±6	Physically active subjects
Ojeda et al. [29]	10/0	28.5±4.8	Military athletes
Miranda et al. 55	0/15	25.7±4.7	Recreative trained
Párraga-Montilla et al. 56	11/0	22.5±3.1	Subjects trained in strength
Sieljacks et al. 57	14/0	23-27	Untrained youth
Wertheimer et al. 19	20/0	22±1.80	Physically active subjects
Tufano et al. 58	8/0	25.2±4.1	Subjects trained in strength

M (male); F (female)

Table 3 - Characteristics of strength training programs with muscle fatigue indicators.

Author	Year	Objective	Variable	Treatment	Results from muscular damage	Force results	Performance
Oliveira et al. [26]	2009	Compare and analyze metabolic ([La]), cardiovascular (HR), and neuromuscular (EMG) parameters during a Bodypump® session.	Exercises proposed by Bodypump®	60 minutes of Bodypump®. These exercises were performed using 1 kg weights, except for the division squatting position, which used weights corresponding to 10% of 1RM (~ 5 kg) to standardize individual responses during sessions. A straight metal bar (1 kg) and 1, 2, and 5 kg disc weights were added to the bar.	↑ ($p < 0.05$) [La] and HR during the session. There was no significant correlation between EMG, lactate, and HR variables.	1RM and CMJ were ns	=
Wernbom et al. [20]	2009	Investigate whether there was any difference in muscle activity and endurance during low-intensity exercise in dynamic knee extension performed up to fatigue with and without occlusion.	Dynamic knee extension training with and without occlusion	Isotonic resistance in knee extenders, 4 sets of three repetitions at 85% of 1RM with 4 min rest intervals between sets.	RPE and acute pain were ns between leg with and without occlusion. DOMS increased ($p < 0.05$) in leg without occlusion after 48 hours.	Electrical activity between leg with occlusion and without occlusion was ns.	=
Brown et al. [16]	2010	Investigate acute changes in O2, HR, and blood [La] in a deep plyometric session in men and women.	Deep PD acute session	Resistance to 30% of 1RM. Occlusion was used at a pressure of 100 mm Hg just before the cuff exercise, and this pressure was maintained in the occluded leg during exercise, including rest periods between series. Subjects performed as many repetitions as possible for a total of 3 series for each leg. The rest between each series was 45 seconds for both the nonoccluded and occluded leg.	↑ ($p < 0.05$) in [La], HR and O2 during the session.	SJ was ns; however, women presented ↓ ($p < 0.05$) in jumping height compared to post-test men.	= in men, ↓ in women

Chatzinikolaou et al. [17]	2010	Investigate the temporal course of inflammatory, hormonal, and performance marker changes involved in the inflammatory response during a 5-day recovery period following an acute series of plyometric exercise	Acute PD session	8 sets of 10 jumps in-depth with both feet of a box 0.8 m high. When the subjects reached the ground with both feet, they immediately jumped as high as possible and touched a vertical jump measurement device; the subjects turned and mounted the jump box using 3 incremental steps that were 0.2 m higher than the previous one. Subjects performed 8 series of 10 repetitions with 3 minutes of passive recovery between series.	Range of motion ↓ ($p < 0.05$) up to 48 hrs post- exercise. DOMS, CK and lactate dehydrogenase ↑ ($p < 0.05$) until 72 hours. PCR ↑ ($p < 0.05$) until 24 hours. Uric acid and cortisol ↑ ($p < 0.05$) until 96 hours. [La] ↑ ($p < 0.001$).	CMJ and SJ ↓ ($p < 0.05$) 24 hours after PD and ↓ was maintained up to 72 hours.	↓
Smilios et al. [44]	2010	Examine (a) the mechanical power and activity of EMG during a moderately loaded muscular endurance session and (b) the maximum mechanics output power and EMG activity using a light load and then a heavy load	Medium, light and heavy load endurance exercise	50 jumps over 50 cm obstacles (5 sets of 10 repetitions) and 50 jumps with plyometric box drop 50 cm (5 sets of 10 repetitions). There were 2 and 5 minutes of rest between sets and exercises, respectively.	[La] ↑ ($p < 0.05$).	Loads used in third and fourth series ↓ ($p < 0.05$) versus first and second series. Production of force ↓ ($p < 0.05$) during last 2 series. Average speed of each series was ns.	↓
Walker et al. [34]	2010	Evaluate acute and endocrine neuromuscular responses during a contrast loading protocol	Contrast training	The lifting protocol was 10 x 5-speed squats at 70% of the mass of the system (1RM) with rest intervals of 2 minutes between sets.	[La] =	↑ ($p < 0.05$) on SJ jump and maximum isometric force.	↑
Greco et al. [27]	2011	To assess the effects of 12 weeks of the Bodypump® training program on neuromuscular aspects and metabolic variables, such as HR and lactate.	Body-pump®	Exercises for the upper extremities were performed using 1 kg weights. Squatting and ramming exercises were performed using weights corresponding to 10% of 1RM for the occupants (~ 5 kg). A straight metal bar (1 kg) and 1, 2, and 5 kg weights were attached to the bar and used during lower extremity exercises.	[La] and HR were ns.	↑ ($p < 0.05$) max. force	↑
Izquierdo et al. [33]	2011	Effects of heavy-duty training and its relationship between power loss and EMG rates and blood metabolite concentrations on exercise-induced dynamic fatigue	Strength training	Five series, with the load corresponding to 10 RM on the leg press with 120 s of rest between the series. After training, each subject performed an acute load resistance protocol with the same relative load (10 RM) as in the pre-workout test protocols.	[La], ammonia, and uric acid ↑ ($p < 0.05$)	Maximum power loss ($p<0.05$)	↓
Sánchez-Medina et al. [32]	2011	Analyze the acute mechanical and metabolic responses to resistance exercise protocols that differ in the number of repetitions performed in each series from the expected maximum number.	Bench press and/or squat exercises	Subjects performed 50 jumps at the maximum continuous intensity at approximately a 90-degree angle at the knees, and after 60 minutes of rest, performed the second series.	[La] and ammonia ↑ ($p < 0.05$)	↓ ($p < 0.05$) average speed of bar and CMJ movement	↓
Buitrago et al. [37]	2012	Examine acute physiological and metabolic responses to a comprehensive bench press exercise of 4 exercise modes with different speeds and different external loads.	Press banking	4 sets of 20 repetitions with an initial load of 50% of 1RM and 2 minutes rest in the squat exercise. In addition, subjects performed 4 repetitions with loads of 40% and 80% of 1RM before, immediately after, and 30 minutes after the end of the session.	[La] ↑ ($p < 0.01$) at high, medium and low loads	↓ ($p < 0.01$) number of repetitions	↓
Hardee et al. [35]	2012	Examine the effects of rest between repetitions on RPE ratings in the power clean exercise.	Power clean	4 sets of squats (3% to 80% of 1RM) interspersed with 4 sets of SJ (three repetitions). A 3-minute break was allowed between sets.	RPE ↑ ($p < 0.05$)	↓ ($p < 0.05$) on the output power	↓
Paulo et al. [45]	2012	Evaluate the influence of different rest intervals and the number of repetitions per set on the production of muscle power in the squat exercise between exercises and the rest ratio.	Squatting force work	MVC force and then the performance of a resistance exercise protocol composes of three series of bicep curls at 40% MVC with 1 minute or 3 minutes time interval between series.	[La] ↑ ($p < 0.05$) in (SSSI and LSLI). SSLI ↓ ($p < 0.05$) in [La] when compared to LSLI	Average power ↑ ($p < 0.05$) in SSLI	An ↑ in the intensity and volume of training produces ↓ performance

Walker et al. [12]	2012	To compare acute neuromuscular fatigue during maximum dynamic force and hypertrophic loads.	Exercise of force. 15 series of 1 maximum repetition (MAX) and 5 series of 10 maximum repetitions (HYP).	Bodypump®, the initial workload (kg) used for squats and onslaughts was 10% of 1RM squats. Upper limb and trunk exercises were performed at a workload of 2 kg for weights or 1 kg for free weights. Workload increases for squats and onslaughts were 5% every 2 weeks (4 sessions).	[La] ↑ ($p < 0.01$) in hypertrophy group	Concentric load during maximum force ↓ ($p < 0.05$), Concentric force and maximum isometric ↓ ($p < 0.001$) in both groups.	Hypertrophy work produces ↓ performance
Couto et al. [11]	2013	To verify the acute effects of the application of local vibration in the upper extremities during resistance training on the number of maximum repetitions and metabolic and hormonal responses.	Vibration strength training session and non-vibration strength training	5 sets of 10 repetitions in the leg press, with 2 minutes rest between sets.	[La], testosterone and cortisol ↑ ($p < 0.05$) after both interventions. However [La] and testosterone ↑ ($p < 0.05$) compared to the non-vibration group. CK and urea were ns in both groups.	Number of repetitions ↓ ($p < 0.05$) in both groups	↓
Fernandez-Gonzalo et al. [25]	2014	To evaluate markers of muscle damage and training adaptations to eccentric overload endurance exercise in men and women.	Supine squatting training position	Repetitions carried out in each series with respect to the maximum number foreseen.	The [La], was greater after the first training session ($p < 0.05$). CK ↑ ($P < 0.001$) in men after the first session. In both sexes, CK and [La] remained at baseline in both groups after the last session.	1RM ↑ ($p < 0.001$) in men and women. SJ and potency yield at 50%, 60%, 70% and 80% of 1RM ↑ in both sexes ($P < 0.05$). The improvement in potency at 80% of 1RM was greater ($P < 0.02$) in men than in women. Muscle mass ↑ ($P < 0.05$).	↑
Okuno et al. [21]	2014	To investigate the variability of HR after resistance training with and without occlusion.	Leg presses with and without occlusion	3 experimental sessions on different days, separated by at least 72 hours and a maximum of 120 hours: (a) 5 series of leg press exercises in 80% of 1RM without vascular occlusion (HI), (b) 5 series of leg press exercises at 40% of 1RM with vascular occlusion (IOL), and (c) 5 series of leg press exercises at 40% of 1RM without vascular occlusion (LI) of each leg.	HI, HR and [La] ↑ ($p < 0.05$), after exercise by over LI and IOL	Reduced recovery in HI	↓ in HI
Pareja-Blanco et al. [2]	2014	To compare the effect of 2 different isometric resistance training interventions on strength gains and selected neuromuscular performance measures using movement speed as an independent variable.	Strength training	Lifting loads 55% (low), 70% (MED) or 85% (high) 1 RM-in one of the four modes given, 4-1-4-1 (4-s concentric, 1-s isometric, 4-s eccentric and 1-s successive isometric actions), 2-1-2-1 (2-s concentric, 1-s isometric, 2-s eccentric and 1-s isometric successive actions), 1-1-1- 1 (1-s concentric, 1-s isometric, 1-s eccentric and 1-s successive isometric actions) or MAX (concentric maximum velocity, 1-s isometric, 1-s eccentric and 1-s successive isometric actions).	[La] and ammonia ↑ ($p < 0.05$) in MaxV as compared to HalfV	CMJ and maximum concentric speed ↑ ($p < 0.001$) in MaxV as compared to HalfV	↑
Rogatzki et al. [46]	2014	Study II aimed to describe acute and mechanical metabolic responses to the type of resistance exercise protocols used in Study I.	Squat with overload	Lifting of three loads 55 % (low), 70 % (med) and 85 % (high) of 1RM in one of the four modes given: 4-1-4-1 (4-s concentric, 1-s isometric, 4-s eccentric and 1-s successive isometric actions); 2-1-2-1 (2-s concentric, 1-s isometric), 2-s eccentric and 1-s isometric successive actions); 1-1-1-1 (1-s concentric, 1-s isometric, 1-s eccentric and 1-s successive isometric actions); or MAX (concentric maximum velocity, 1-s isometric, 1-s eccentric and 1-s successive isometric actions).	[La] ↑ ($p < 0.005$) in muscle endurance. ↑ ($p < 0.05$) plasma ammonium by over hypertrophy and strength group.	↓ ($p < 0.05$) in time to complete the 20 km counter-clockwise exercise. ↑ ($p < 0.01$) cycling economy.	↓ in muscle endurance group
Silva et al. [47]	2014	To determine the metabolic response of resistance exercise in overloaded squats with different training protocols.	Leg press	Muscle resistance performed in 2 series of 20 repetitions at 53% of 1RM with 45 s of rest between the series. Hypertrophy training consisting of 3 series of 10 repetitions at 70% of 1RM with 120 s of rest between the series. For strength, the trainings were 5 series of 5 repetitions at 85% of 1RM with 180s of rest between the series.	[The] and RPE were ns	Total load volume ↑ ($P < 0.001$) in the afternoon as compared with the morning and evening.	↑

Ammar et al. [48]	2015	Check whether a pre-test 5RM strength exercise would improve cycling performance during a 20 km (TT20 km) cycling event.	Olympic weightlifting at different times of day (morning, afternoon, or evening)	Program that involved a rapid gradual increase in the number of jumps, drop height, and depth of squat and weight addition.	RPE ↑ ($P < 0.01$) in the morning and evening. Lactate dehydrogenase ↑ ($P < 0.01$) in the morning and evening. CK ↑ ($P < 0.05$) at three hours of the day. Alanine aminotransferase, gamma-glutamyl, and alkaline phosphate ↑ ($P < 0.001$) in the morning.	Not measured	↑ in the afternoon and ↓ in the morning and evening
Gadruni et al. [24]	2015	Investigate the performance of an Olympic weightlifting training session three times a day on performance related to biochemical responses.	Elastic exercises with progressive resistance	Subjects performed 36 repetitions at 60% of 1RM with different rest times per group. Short interval condition of short duration (SSSI; 12 series of 3 repetitions with an interval of 27.3 seconds between series); long interval condition of short set (SSLI; 12 series of 3 repetitions with an interval of 60 seconds between series); and long interval (LSLI; 6 series of 6 repetitions with a rest interval of 60 seconds between series).	DOMS and RPE ↑ ($P < 0.05$). ↑ ($P < 0.05$) CK, LDH, IL-6 and PCR in sedentary and athletes.	Group to failure, ↓ ($p < 0.05$) CRGA speed and CMJ	↓
González-Badillo et al. [49]	2016	Investigate the effect of acute cycles of progressive rubber band exercises on muscle damage and inflammatory responses in Taekwondo athletes.	Bench press and squat with overload	Two leg press loads, separated by one week, consisting of 15 sets of 1 maximum repetition (MAX) and 5 sets of 10 maximum repetitions.	[La] ↑ ($p < 0.05$) In both groups. CK and cortisol ↑ ($p < 0.05$) in the group with maximum repetitions until failure	1RM ↑ ($P < 0.001$) in each group	Higher volume versions ↓ performance
Nicholson et al. [13]	2016	Analyze time course of recovery after 2 protocols of resistance exercises that differ in the level of effort: maximum (until failure) versus half the maximum number of repetitions per series.	Squat with overload in maximum strength mode, hypertrophy, or group with more rest, or another group with less volume and total rest.	Conventional resistance training session and a resistance training session with local vibration. In both interventions, the volunteers performed 4 series with the greatest possible number of repetitions of the exercise that could be deployed at 55% of the maximum voluntary contraction. During the vibration resistance training intervention, the vibration was applied locally (20 Hz and 12 mm). During conventional resistance training, volunteers performed the same procedures without vibration.	Maximum strength and hypertrophy training [La] ↑ ($p < 0.001$); RPE ↑ ($p < 0.05$) in hypertrophy protocol	The Vmax, Vpro, and Pmax were ns. La Ppro ↓ ($p = 0.002$).	↑
Ojeda et al. [1]	2016	Determine the acute effect of Complex Training on bench press on grenade throwing velocity on military pentathletes.	Protocol of complex training in bench press	4 sets of 5 repetitions at 30% one Repetition Maximum (1RM) + 4 repetitions at 60% 1RM + 3 grenade throws with a 15-second rest.	[La] ↑ ($p = 0.001$)	Not measured	↓
Poton et al. [22]	2016	To determine the acute effect of a protocol of complex training in press banking on the speed of the launch of the grenade in military pentathletes.	Exercise of force in extension of the knee with or without restriction of blood flow.	(a) 5 series of leg press exercises at 80% of 1RM without vascular occlusion (HI), (b) 5 series of leg press exercises at 40% of 1RM with vascular occlusion (IOL), and (c) 5 series of leg press exercises at 40% of 1RM without vascular occlusion (LI).	HI, HR and diastolic blood pressure↑ ($P < 0.05$). [La] ↑ ($p < 0.05$) in LI-BFR and HI. RPE ↑ ($p < 0.05$) in LI-BFR	1RM ↓ ($p < 0.05$)	↓
Raeder et al. [39]	2016	To compare the hemodynamic response during resistance exercise to HI, LI, and LI-BFR in healthy subjects.	6-day intensive strength training	Subjects trained twice a day, in the morning (~9 AM) and the afternoon (~3 PM), on 6 consecutive days. They performed multiple resistance combined with maximum eccentric strength exercises, focusing mainly on the training of the lower extremities.	DOMS, perceived recovery and stress ↑ ($p < 0.05$). CK ↑ ($p < 0.05$).	All protocols caused ↓ ($p < 0.05$) at peak speed	↓
Sabido et al. [5]	2016	Analyze neuromuscular, physiological, and perceptual marker changes for routine evaluation of fatigue and recovery in high endurance strength training.	Strength training with traditional methodology, pyramid, super-sets of agonists and super series of agonist pairs	Individualized muscle endurance consisted of 2 sets of 20 repetitions (2 × 20) at 53% of 1RM with a 45-second rest period between sets. The hypertrophy training consisted of 3 × 10 at 70% of 1RM with a 120-second rest period between series. For strength, the workouts were 5 × 5 at 85% of 1RM with a 180-second rest period between sets.	Paired agonist super series caused ↑ ($p < 0.05$) in [La] and RPE.	CMJ and isometric MVC ↓ ($p < 0.001$ and $p < 0.008$, respectively)	↓

Bartolomei et al. [50]	2017	To compare the acute effects of four different resistance training methodologies aimed at hypertrophy.	High intensity overloaded squat and/or high volume overloaded squat	Squat with overload 4 series force of 5RM (potentiation condition)	LDH, CK and Mb ↑ ($p < 0.05$) in HV and HI. Cortisol and IL-6 ↑ ($p < 0.001$ and $p < 0.05$, respectively) in HV.	Maximum torque ↓ ($p < 0.05$) in occlusion training	HV ↓
de Almeida et al. [23]	2017	To compare the variables related to asymmetry, peak torque, and fatigue index in the traditional strength training method and the occlusion training method.	Traditional strength training and occlusion training	Resistance stroke followed immediately by a force load or force session followed by resistance stroke.	Training with occlusion ↑ ($p < 0.05$) lactate dehydrogenase levels, [La], fatigue index and CK	CMJ, times 50 meters, was ns	↓
Johnston et al. [51]	2017	To examine the acute effect of the sequence of strength and speed training on neuromuscular, endocrine, and physiological responses for 24 hours.	Strength training followed by speed training and vice versa	5 sets of exercise (i.e., two sets at 85% of 1RM with three repetitions per series and three sets at 90% of 1RM with two repetitions per series).	[La] ↑ ($p < 0.05$) immediately after speed training. CK, cortisol, testosterone, and DOMS were ns in both protocols.	SJ and CMJ ↓ ($p < 0.05$) in HI group	=
Andreatta et al. [52]	2018	Assess whether cell-free DNA (cfDNA) levels increased immediately after light and heavy endurance exercise and whether cfDNA levels are associated with functional muscle capacity up to 48 hours after an exercise session.	Leg press HI and LI	3 series of hip flexion, hip extension, and hip abduction exercises by an elastic band.	[La] ↑ ($p < 0.05$) in both groups. CK and cfDNA concentration ↑ ($p < 0.05$) in the HI group	ROM ↓ ($p < 0.05$) in both groups; however, HI eccentric exercise combined with occlusion was recovered at 24 hours, while no occlusion recovered at 48 hours.	↓ in HI force protocols
Curty et al. [53]	2018	To assess acute effects of eccentric HI exercise combined with occlusion on markers of muscle damage and perceptual and cardiovascular responses.	Eccentric exercise in elbow flexion with occlusion and without occlusion	3 sets of 8 repetitions until failure, while the second protocol was separated by 14 days and consisted of 3 sets by 4 repetitions both protocols at 80% of 1RM	DOMS ↑ ($p < 0.05$) in eccentric HI exercise combined with occlusion. HR ↑ ($p < 0.05$) in both groups	Maximum absolute and relative muscle power ↓ ($P < 0.0001$)	↓ in both protocols, but non-occlusive training presents more durable↓
dos Santos et al. [54]	2018	To investigate cardiovascular, neuromuscular, and metabolic responses of physically active subjects during a session of sled drag with resistance (RST).	Sled drag with resistance	Strength (4 × 6 repetitions, 85% of 1RM, 900 s of total rest), hypertrophy (5 × 10 repetitions, 70% of 1RM, 360 s total rest), group 1: 4 × 6 simple repetitions, 85% of 1RM, 1400 s of total rest and group 2: 4 × 6 simple repetitions, 90% of 1RM, 1400 s total rest	HR ↑ ($P < 0.05$) and [La] ↑ ($P < 0.0001$)	Distance in grenade launch ↑ ($p < 0.05$)	↓
Ojeda et al. [29]	2018	Determine the behaviour of blood cortisol, metabolic CK, total CK and [La] after application of a VR protocol (5 × 30% of 1RM + 4 × 60% of 1RM in bench press + 3 pomegranate throws with 15-second pause) at 24 hours after the expenditure of effort.	Variable resistance protocol	Four sets of 5 repetitions at 30% of 1RM + 4 repetitions at 60% of 1RM + 3 pomegranate throws separated by 15 seconds.	[La], cortisol and metabolic CK were ns	Total load volume ↓ ($p < 0.05$) in 24-hour rest protocol	↑
Miranda et al. [55]	2018	Examine the effect of different recovery periods (24, 48, and 72 hours) between repeated resistance training (RT) sessions for upper body muscles on repetitive performance and blood lactate responses in trained men.	Press banking with 24, 48 or 72 hours rest	Three sets of unilateral knee extension exercises in LI-BFR and LI (15 repetitions; 20% of 1RM) and HI (8 repetitions; 80% of 1RM).	[La] ↑ ($p < 0.05$) in 24-hour rest protocol	Number of repetitions performed ↓ ($p < 0.05$) in series 2 and 3. Average propulsion speed of repetitions and CMJ ↓ ($p < 0.05$) after 24 and 48 hrs.	↓ in 24-hour rest protocol
Párraga-Montilla et al. [56]	2018	Explore the acute and delayed effects (24 and 48 hours after exercise) of a resistance training session leading to muscle failure.	Squat with overload until muscle failure	Twice daily training, morning (9 AM) and afternoon (3 PM), on 6 consecutive days, resulting in a total of 11 training sessions (training program consisted of multiple resistance and basic multijump combined with maximum eccentric strength exercises, focusing primarily on parallel squat training).	RPE and [La] ↑ ($p < 0.05$).	Both protocols produced ↑ ($p < 0.05$) muscle size and muscle function.	↓
Sieljacks et al. [57]	2018	To compare training with occlusion performed to failure versus occlusion without failure with regard to changes in muscle size, function, and perceptual responses.	Training with occlusion	Traditional, 6 series for 10 repetitions at 70% of 1RM; Super series of agonist pairs, 6 series for 10 repetitions at 70% of 1RM; Super series of agonists, 3 series for 10 repetitions at 60% of 1RM; Pyramid, 6 series for 6, 8, 10, and 12 repetitions at 80%, 75%, 70%, and 70% of 1RM, respectively.	RPE and DOMS ↓ ($p < 0.05$) in occlusion without failure as compared to occlusion until failure.	Not measured	↓ in occlusion up to judgment by over a protocol of occlusion without judgment

Wertheimer et al. [19]	2018	To compare the muscle stress of serum urea and indicators of lactate dehydrogenase and CK muscle damage after eight weeks of plyometric training. Training program conducted in water and on land.	Plyometric training in water and/or on soil	HI protocol was composed of eight sets of three at 90% of 1-RM repeats. The recovery time between the series was 3 min. During the protocol, HV was composed of eight series of ten repetitions at 70% of 1RM. The recovery time between series was 1.25 min.	Lactate dehydrogenase was ns for both protocols. Serum urea ↑ ($p < 0.05$) for the ground group. Ground plyometry ↑ ($p < 0.05$) in CK activity as compared with water.	↓ ($p = 0.026$) on the average speed loss in protocol of short rest duration	It is stated that the plyometric group in water presents fewer indicators of muscle damage.
Tufano et al. [58]	2019	Compare kinematic, metabolic, endocrine, and perceptual responses of three backward squat protocols with equal loads, number of repetitions, and the total duration of rest.	Squat with an overload of different resting protocols	Traditional strength training protocol consisted of four series of 8 to 12 1RM with the execution speed of one second in the concentric phase and for 2 seconds in the eccentric phase with an interval of 90 seconds between the series. Whereas, the protocol with occlusion consisted of 4 series of 8 to 12 MRIs with blood flow restriction.	All rest protocols led to ↑ ($p < 0.05$) RPE and [La], which remained elevated up to 30 minutes after exercise.	1RM and CMJ were ns	↓ when the protocol had a short rest period

[La] (lactate concentrations); HR (heart rate); EMG (electromyography); 1RM (1 maximum repetition); CMJ (counter movement jump); SJ (squat jump); ns (non-significant); = (maintained); RPE (effort perception); DOMS (increased muscle pain); O2 (oxygen consumption); EP (plyometric exercises); CK (creatine kinase); CRP (C-reactive protein); MVC (maximum voluntary contractions); ↑ (increases); ↓ (decreases); SSLI (short set long interval condition, 12 series of 3 repetitions with an interval of 60 seconds between series); SSSI (short duration short interval condition, 12 series of 3 repetitions with an interval of 27.3 seconds between series); LSLI (long interval condition, 6 series of 6 repetitions with a rest interval of 60 seconds between series); HI (high intensity); IOL (low intensity with vascular occlusion); LI (low intensity); MaxV (predicted maximum concentric velocity); HalfV (average maximum velocity); IL-6 (interleukin-6); Vmax (maximum velocity); Vpro (average velocity); Pmax (maximum power); Ppro (average power); LI-BFR (low intensity with restriction of blood flow); and VH (high volume).

Discussion

At the end of the systematic review and based on the main objective that sought to find evidence of alterations in muscle fatigue indicators during and after strength training, 39 studies were found between January 2009 and January 2019. Of which only In 4 there was evidence of increased performance despite having indicators of altered muscle fatigue. This may be due to the normal physiological response of the subjects. This evidence allowed us to visualize that there were protocols for the development of strength that generate alterations in muscle fatigue markers, such as [La], HR, RPE, DOMS, the variation of MR and ammonium. This shows that there are force protocols that, according to their characteristics, impact, and difficulty, should only be performed in some types of populations. Therefore, and for a better understanding, the different protocols for the development of strength and the changes they generate in muscle fatigue markers will be stratified separately.

1. Plyometric training and muscle fatigue

Drinkwater et al.[14], following an acute plyometric exercise intervention in recreational rugby players, observed significant decreases in maximum voluntary contractions (MVC) ($p < 0.05$) and torque development rate ($p < 0.01$), triggering peripheral fatigue and resulting in decreased performance. Skurvydas et al.[18], using plyometrics in physically active male students, recorded that the strength of MVC decreased significantly after two continuous series of high-intensity jumps ($p < 0.05$), while the DOMS increased significantly ($p < 0.05$). Similarly, Brown et al.16 also showed increases in HR and [La] after an acute plyometric session in recreationally trained men and women ($p < 0.05$), and these components have been considered on several occasions as precursor variables of fatigue[17].

Kamandulis et al.[30], after nine sessions of plyometric intervention in physically active athletes, reported that increases in jumping training load lead to an increase in muscle fatigue markers, thus suppressing acute mechanical function after exercise; however, after three weeks of training and adequate recovery, an increase in overall muscle performance was observed. In this sense, it has been observed that between plyometric exercise sessions, and for adequate recovery, there must be a 72-hour rest period. In this way, alterations in muscle fatigue indicators[17,41] can be reduced, leading to performance[14].

Chatzinikolaou et al.[17] showed that an acute session of plyometrics in healthy men, with a pause of 2 minutes between series (5 series of 10 repetitions) and 5 minutes of rest between jumping of obstacles and jumps with a fall from a plyometric box, can induce a substantial decrease in jump performance resulting from increases in [La] ($p < 0.001$), as well as substantial alterations in blood biomarkers of muscle damage (BSDM) such as CK, cortisol, uric acid, and C-reactive protein ($p < 0.05$). These variables were directly related to muscle damage up to 72 hours after the intervention. These findings are similar to those found by Thomas et al.[41], who state that plyometric exercises require 72 hours to decrease exercise-induced levels of muscle fatigue.

2. Bodypump® Training and Muscle Fatigue

The Bodypump® is a methodology that consists of training with bars, occupying loads ranging from 45–60 minutes with a standardized sequence of music[26]. This program has shown to be effective in improving maximum strength and muscular endurance of the lower extremities in untrained women[27]. In this sense, in research carried out by Greco et al.[27], there was no evidence of increases in [La] or HR after 12 weeks of training in sedentary women ($p > 0.05$). On the other hand, Oliveira et al.[26], after an acute Bodypump® intervention, showed significant increases in [La] and HR ($p < 0.05$); variables considered as precursors of muscle fatigue[17]. However, Oliveira et al.[26] stated that there was no significant correlation between the electromyographic activity of the muscle and the [La] and HR. Although Bodypump® training produces acute fatigue[26], this would be sufficient to increase the maximum strength and muscular endurance of the lower extremities in untrained subjects[26,27].

3. Training with occlusion and muscle fatigue

In recent times, low load training with occlusion has attracted the attention of trainers as both a possible alternative to high endurance exercises in the context of rehabilitation[20] and a training method to increase muscle strength and hypertrophy[21]. In this sense, Okuno et al.[21] indicated that training with occlusion appears to be more favorable than traditional force training without occlusion[12,25]. Similarly, Curty et al.[42] concluded that training with occlusion in trained men had preventive effects on indicators of muscle fatigue and indirect responses induced by eccentric exercise. Therefore, training with occlusion would produce less metabolic stress[21,42]. Even training with occlusion would be recommended as a training method in those subjects who present with cardiovascular problems and who cannot perform strength exercises over 80% of 1RM[21]. Sieljacks et al.[43] mentioned that training with occlusion without reaching muscle failure in repetitions in untrained subjects allows for increases in muscle size and muscle function, while it also implies lower RPE, discomfort, and less appearance of DOMS. However, unlike the findings reported by Okuno et al.[21], Curty et al.[42], and Sieljacks et al.[43], Poton, Polito[22] established that healthy, trained subjects who undergo occlusion training may have muscle fatigue due to the increase in [La], as well as an increase in RPE ($p < 0.05$).

In addition to what was previously reported by Poton, Polito[22], there is a study conducted by Almeida et al.[23]. These researchers obtained a higher level of fatigue after the application of a force with the occlusion method; this fatigue was associated with increases in [La] and with increases in BSDM indicators, such as CK and lactate dehydrogenase ($p < 0.05$), as well as higher values in the fatigue index when compared to a traditional force method in subjects with experience in strength training. Therefore, these BSDMs would have a direct relationship with the increase in muscle fatigue indicators[17,23]. However, more studies are needed that can clarify the use of occlusive methods on indicators of muscle fatigue and sports performance. Each of the occlusive protocols analyzed in this review used a 1-minute pause between series.

4. Variable resistance and muscle fatigue training

Variable resistance (RV) corresponds to the change of intensity during the application of force training load, within the various variable resistances are intra-variable resistance, intra-repetition variable resistance, and intra-series variable resistance[44]. Some types of VR have reported increases in the indicators of muscle fatigue and inflammation in both athletes and sedentary people, evidencing increases in the DOMS and [La][24]. On the other hand, VR protocols cause general and local fatigue in military athletes that is related to the increase in [La] ($p < 0.001$) and decreases in average power ($p < 0.002$)[1]. However, unlike the muscle fatigue reported by Ojeda et al.[1], these same authors in other research did not report increases in muscle fatigue indicators after a VR protocol. This would allow inferring that the athletes were in an anabolic process and without the presence of muscle fatigue, reflecting an increase in explosive strength using a grenade throw[29].

5. Conventional strength and muscle fatigue training

This type of training has been used over the years occupying high volume load protocols (muscular endurance)[45,46], high-intensity exercises (maximum strength)[47,48], or muscular hypertrophy programmes[12,13]. In this sense, it has been reported that high volume muscle endurance training performed at a low-intensity of 1RM increases DOMS levels in healthy sedentary subjects ($p < 0.05$), regardless of whether it is performed with short intervals (1 minute) or long intervals (3 minutes) of rest between series[36]. Similarly, Hardee et al.[35], showed that high-volume power clean exercises, performed at low intensity on trained subjects, increase the RPE independent of rest time between series ($p < 0.05$), which is directly related to a decrease in output power ($p < 0.05$). Likewise, Date et al.[15] showed a significant increase in [La] in physically active males ($p < 0.05$) after power clean training that considered a high load volume. Similarly, Rogatzki et al.[45] showed that a protocol of muscular resistance, when compared with a protocol of hypertrophy and maximum strength, significantly increased the blood levels of ammonium and lactate in adolescents ($p < 0.05$). These findings are consistent with other research that reported muscle fatigue following the use of high volume, low-intensity loads[15,35,36]. In another study developed by Silva et al.[47], it was concluded that acute interventions with high-intensity strength exercises (5RM) produce neither alterations in [La] nor increases in RPE. Therefore, an acute session of 4 series of 5RM could enhance performance in cyclists[47].

On the other hand, Nicholson et al.[13] showed increases in [La] in maximum strength and hypertrophy programs in trained subjects ($p < 0.001$), while Walker et al.[12] and Izquierdo et al.[33] showed increases in [La] during hypertrophy sessions ($p < 0.05$) and increases in ammonia and uric acid concentrations in maximum strength sessions, respectively; both studies were in physically active subjects ($p < 0.05$). However, Bartolomei et al.[49], after comparing two strength protocols (high load volume versus high intensity) in subjects with strength experience, concluded that high volume training induces greater muscle fatigue due to the increase in [La]. Thus, endurance training up to muscle failure significantly reduces metabolic recovery and hormonal homeostasis 24–48 hours after exercise[50]. Likewise, Andreatta et al.[48] showed increases in [La] after the application of a high-intensity force protocol (80% of 1RM) in healthy subjects with strength experience. On the other hand, Silva et al.[47] showed no increase in [La] after a high-intensity protocol. Bartolomei et al.[49] also showed that the high-volume protocol generates greater muscle fatigue than a high-intensity protocol. This may be associated with the number of repetitions since Bartolomei et al.[49] evaluated only 3 repetitions versus 10 repetitions performed in the Andreatta et al.[48] protocol. The latter protocol could be considered a high-volume protocol[15]. Therefore, strength training up to muscle failure produces significant increases in metabolic stress, with greater muscle fatigue in the subjects who practice it[46]. This is why the large decreases in mechanical performance together with the high metabolic stress suggest a lower use of force protocols with high volume[46,51].

In conventional strength protocols, BSDMs also have a close relationship to increased indicators of muscle fatigue. In this sense, Bartolomei et al.[49], along with evidence of an increase in muscle fatigue indicators ([La]), also observed alterations in CK, cortisol, and IL-6 ($p < 0.001$) in high-volume training, which is possibly associated with post-exercise muscle damage. Other research also reported alterations in both fatigue indicators[28,34] and BSDM after high volume training[34]. Therefore, a direct association between indicators of muscle fatigue and muscle damage, along with decreased performance, would discourage high-volume strength protocols.

6. Eccentric strength and muscle fatigue training

Both high-intensity and low-intensity eccentric exercises have been shown to produce muscle fatigue, resulting in decreased strength and therefore decreased performance[52]. In this sense, Fernandez-Gonzalo et al.[25], after a first eccentric training session, showed significant increases in the [La] in the group of healthy and physically active males; however, these same variables after 15 sessions did not present alterations, so a muscular adaptation to the eccentric training was inferred. Gauche et al.[52] reported that the maximum voluntary contraction was significantly reduced after eccentric exercise in the biceps ($p < 0.01$), by 20% after high-intensity exercise and by 25% after low-intensity exercise in healthy untrained subjects. These voluntary maximum contraction values remained reduced after 48 hours for both high-intensity and low-intensity exercise ($p < 0.001$). These results are similar to conventional strength training in which low-intensity strength sessions have found to induce an increase in muscle fatigue[49] and a decrease in performance[48]. Finally, alterations in the BSDM continue to be directly related to markers of muscle fatigue; thus, Fernandez-Gonzalo et al.[25], along with evidence of increases in the [La], also presented alterations in blood CK.

7. Different times of rest in the training of strength and muscular fatigue

It has been established that strength training for 6 consecutive days induces significant alterations in DOMS, stress, and perceived recovery, which is directly related to a decrease in 1RM, thus inducing muscle fatigue in both men and women[53]. Also, DOMS levels have been reported to increase significantly ($p < 0.05$) with either short 1-minute rest intervals or long 3-minute rest intervals between series[36]. Paulo et al.[54] indicated that a 1-minute break between series results in greater production of average power in exercise sessions aimed at developing muscle power in healthy young people. However, Miranda et al.[55], in the context of neural activation, stated that a 3-minute rest interval between series may represent a neuromuscular window between a state of fatigue and a state of the total recovery in trained women. These same researchers examined the effect of the different recovery periods (24, 48, and 72 hours) between sessions of strength training using press banking in trained subjects. At the end, they concluded that a recovery period of only 24 hours induces an increase in [La] and RPE ($p < 0.05$)[56], variables that are considered as indicators of muscular fatigue[35] and that are directly related to the decrease in performance[48]. When comparing the kinematic, metabolic, endocrine, and perceptual responses of three overloaded squatting protocols in trained subjects, Tufano et al.[57] concluded that muscle fatigue occurs by increasing [La] and RPE, regardless of the organization of rest time used. Thus, Ammar et al.[58] showed increases in [La] and RPE ($p < 0.01$) in weightlifters. These findings were independent of training schedules during the day (morning, afternoon, or night), and BSDM continued to be elevated after 48 hours of recovery ($p < 0.05$). Thus, [La] and RPE have also been altered in other studies[12,17,36,59] and declared as precursors of muscle fatigue[17].

In general terms, and based on the systematic review, it is suggested that strength sessions be separated by 72 hours to reduce exercise-induced muscle fatigue levels[41]. Finally, Ammar et al.[58] and Tufano et al.[57] also showed an increase in BSDM simultaneously with increases in muscle fatigue indicators, so this history continues to demonstrate a close relationship between muscle fatigue indicators and BSDM.

8. Concurrent training and muscle fatigue

In this type of training, Taipale et al.[59] showed significant increases ($p < 0.05$) in [La] after a resistance run intervention followed by a strength protocol or vice versa in both trained men and women, but also showed increases in CK concentrations. This last variable can play a determining role in the decrease of strength production capacities during recovery[12,17,36,59]. On the other hand, not all research[60] has shown an increase in variables that induce fatigue and muscle damage after a concurrent protocol. Johnston et al.[60] only reported an increase in [La] and not BSDM after each speed protocol followed by strength training, but not when strength was trained and then speed. Due to the lack of evidence, more studies are needed to address the variables involved, and thus clarify the order of exercises at the time of concurrent training and mitigate possible decreases in performance in athletes.

Conclusions

At the end of the systematic review, it was shown that the different training methodologies for strength development generate increases in muscle fatigue indicators, and the increase generated in the different muscle fatigue indicators depends both on the methodology used and on the type of population, sex, level of training and type of sport.

At the same time, it became evident that there are different ways of quantifying fatigue in strength training. Among the most commonly used fatigue indicators are [La], HR, RPE, DOMS, MR variation, and ammonium. The most-reported indicators are [La], HR, and RPE. Finally, considering that more studies are still needed to determine the real effect of these training methods on fatigue indicators, and in light of the facts, there are indications that plyometric training, training with variable resistance and conventional strength training with high volume loads are the ones that could incur the greatest increase in muscle fatigue.

Limitations

One limitation of the study is to a lack of homogeneity associated with the study outcomes, study design, and time points of follow-up across the studies, they do not allow to perform a meta-analysis.

Practical Applications

Based on the results of the systematic review, and to minimize muscle fatigue levels, increasing load volumes, and enhancing athlete performance, some considerations for stratified methods are presented:

1. Plyometric training: As it has a great impact, it should be applied to athletes capable of lifting twice their body weight in a squat. It is also suggested that the pause between series should be greater than 2 minutes and there should be a minimum of 72 hours between sessions. Although an indicator of fatigue for this method is the impossibility of reaching the training heights established for athletes, [La] was used as an indicator of fatigue in most of the research consulted.
2. Bodypump® training: This methodology can be applied to non-physically trained subjects, while the most reported fatigue indicators are HR and [La].
3. Training with occlusion: This type of protocol can be used in both trained and untrained subjects. In most of the investigations consulted, they used a 1-minute pause between series. This pause triggered increases in muscle fatigue indicators in some studies. As a result, new research is suggested to clarify the optimal pause time between series, while the suggested fatigue indicators are perceived DOMS, RPE, and [La].
4. Variable endurance training: This type of protocol should be aimed at athletes, being discouraged in physically inactive subjects. Although it is important, in order to establish the pause, to consider the variation of the intensity within the series, pauses of 15 seconds are suggested. The fatigue indicators with the greatest evidence are perceived DOMS and [La].
5. Conventional strength training: This type of protocol can be used in inactive subjects as well as athletes. However, and with the purpose of mitigating muscular fatigue alterations, it is suggested to avoid high volume loads, privileging high-intensity sessions. It is recommended that the pause time between series be greater than 3 minutes and the rest between each session should be around 72 hours, while the suggested fatigue indicators are RPE, DOMS perceived, and [La].
6. Eccentric training: This type of protocol should be used in physically active subjects. Evidence showed that high-intensity executions have less alteration in muscle fatigue indicators, but more studies are needed to determine the effect of these protocols on fatigue indicators. However, the suggested rest time between each session should be around 72 hours, while the suggested fatigue indicators are [La].
7. Different rest times in strength training: This section suggests starting with strength protocols that include a minimum break of 3 minutes between sets, and then generating individualized guidelines for each strength protocol. However, the 72 hours of rest between each session are independent of the type of strength training, while the fatigue indicators are [La] and RPE.
8. Concurrent training: this type of protocol should be occupied by trained subjects. After the review, it is suggested to first train strength exercises and then speed exercises, but more evidence is needed to clarify the order of execution of concurrent training. Finally, the fatigue indicators used for these protocols are [La].

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Corresponding author

Guillermo D. Barahona-Fuentes
Camino del Sol 2.300, Condominio Paso Hondo IV, Casa H1, Quilpué, Chile.
Mobile phone: +56963989823
E-mail: danielbarahonaf@gmail.com

Editor: Angelina Zanesco, UNESP/Rio Claro, SP, Brazil

Manuscript received on April 15, 2020

Manuscript accepted on May 2, 2020