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SYSTEMATIC REVIEW

Effects of Rest Interval Duration in Resistance Training on Measures of Muscular Strength: A Systematic Review

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Abstract

Background Rest interval (RI) duration is an important resistance-training variable underlying gain in muscular strength. Recommendations for optimal RI duration for gains in muscular strength are largely inferred from studies examining the acute resistance training effects, and the generalizability of such findings to chronic adaptations is uncertain.

Objective The goals of this systematic literature review are: (i) to aggregate findings and interpret the studies that assessed chronic muscular strength adaptations to resistance training interventions involving different RI durations, and (ii) to provide evidence-based recommendations for exercise practitioners and athletes.

Methods The review was performed according to the PRISMA guidelines with a literature search encompassing five databases. Methodological quality of the studies was evaluated using a modified version of the Downs and Black checklist.

Results Twenty-three studies comprising a total of 491 participants (413 males and 78 females) were found to meet the inclusion criteria. All studies were classified as being of good to moderate methodological quality; none of the studies were of poor methodological quality.

Conclusion The current literature shows that robust gains in muscular strength can be achieved even with short RIs (< 60 s). However, it seems that longer duration RIs (> 2 min) are required to maximize strength gains in resistance-trained individuals. With regard to untrained individuals, it seems that short to moderate RIs (60–120 s) are sufficient for maximizing muscular strength gains.

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Key points

While improvements in muscular strength within a resistance training program may be achieved across different rest interval durations, the evidence suggests that rest intervals lasting more than 2 min are needed to maximize muscular strength gains in resistance-trained individuals.

For individuals without previous experience in resistance training, the majority of the current body of evidence indicates that short to moderate duration rest intervals are sufficient for gains in muscular strength.

It remains unclear whether combining rest intervals of different duration based on exercise selection and training load would further enhance gains in muscular strength.

1 Introduction

Muscular strength is the ability to exert a force on an external object or resistance, with mechanisms attributed to both neural and muscular components [1]. Increases in

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muscular strength coincide with improvements in jumping, sprinting, agility, and sport-specific performance [2], and, as such, muscular strength may be a fundamental component in various athletic endeavors. Furthermore, gains in muscular strength with resistance training may reduce the difficulty of performing activities of daily living, increase energy expenditure [3], reduce skeletal muscle wasting [4], and possibly enhance psychosocial status in overweight and obese children and adolescents [5].

Planning and designing a resistance training program for muscular strength-related goals involves manipulation of program variables that include exercise selection, training volume, training intensity, movement velocity, and rest intervals (RIs). RIs are defined as the time dedicated to recovery between sets and exercises [6]. RIs may affect metabolic responses [7], volume load [8], and hormonal levels [9]. The duration of a RI must be sufficient to allow for replenishment of adenosine triphosphate and phosphocreatine, and for the removal of accumulated lactic acid [10]. Insufficient RI length may increase reliance on glycolytic energy production and affect metabolic buildup [11]. Such events might compromise the ability to sustain repeated high-force muscular contractions and may be suboptimal when training for muscular strength [12]. While RI duration is a significant variable underlying gain in muscular strength, it has often been overlooked by both exercise practitioners and scientists.

The frequently used [13] classification of RIs is: (i) short (< 60 s); (ii) moderate (60–120 s); and (iii) long (> 120 s, usually 2–5 min). A commonly cited tenet by the American College of Sports Medicine is that extended RI duration should be utilized when the goal is to increase muscular strength [14]. However, the position stand is based on level 4 category of evidence or "expert level," not on level 1 evidence (systematic reviews provide level 1 evidence [15, 16]). De Salles et al. [17] carried out a narrative review on the topic of RI length and muscular strength outcomes. However, conclusions from this review were largely inferred from studies examining the acute effects of RI duration [10, 18], and generalizability of such findings to chronic adaptations is uncertain.

Considerable evidence is accumulating from longitudinal studies (> 4 weeks in duration) that investigated muscular strength adaptations to different RI duration [19–22]. However, the findings between studies seem to be equivocal. For instance, a study by Villanueva et al. [20] involving resistance training naïve participants found that a shorter duration RI (i.e., 1 min) may contribute to greater muscular strength gains as opposed to a longer RI duration (i.e., 4 min). Following 8 weeks of resistance training, the group that trained with short RIs achieved an 11 and a 10% greater increase in upper- and lower-body muscular strength than the group that trained with longer RIs, respectively. By contrast, De Salles et al. [22] reported that longer duration RIs (i.e., 3 and 5 min) are more beneficial for muscular strength improvements in comparison with short RIs (i.e., 1 min). To further confound matters, other studies reported no significant differences in muscular strength outcomes when comparing RIs of varying duration [23].

To achieve clarity on the topic, an objective scrutiny of the literature through a systematic review should be carried out. Accordingly, the intention of this review is twofold: (i) to aggregate findings and interpret the studies that assessed muscular strength adaptations to different RI durations, and (ii) to provide evidence-based recommendations for exercise practitioners and athletes. Such a treatise will be useful to coaches, athletes, and to a wider community participating in resistance-training activities with a goal of increasing muscular strength.

2 Methods

2.1 Literature Search

The review was performed following the PRISMA guidelines [24] with a literature search encompassing Scopus, PubMed/MEDLINE, Web of Science, Cochrane Library, and Open Access Theses and Dissertations databases. The following syntax with no year restriction was used for the search: "rest intervals" OR "rest periods" AND ("resistance training" OR "muscle strength" OR "strength training" OR "strength" OR "recovery" OR "training intensity" OR "training volume"). Forward citation tracking of the included studies was performed in Scopus and Google Scholar. Reference lists of the included studies were scanned for additional findings. The search was individually performed by two authors (JG and MS) and concluded on 1 May 2017. The reviewers were not blinded to any of the studies' details.

2.2 Inclusion Criteria

The studies were assessed for eligibility based on the following inclusion criteria: (i) published in English as a full-text manuscript or thesis; (ii) compared the use of different duration RIs in resistance training, with all other training variables remaining equal; (iii) at least one muscular strength test was utilized [all tests up to 10 repetitions maximum (RM) were considered including isometric and isokinetic muscular strength tests]; (iv) the resistance training protocol lasted for a minimum of 4 weeks, with a minimal resistance-training frequency of two times per week, and; (v) the included participants had no known medical condition or injury. Both doctoral dissertations and masters' theses were considered, given evidence that they provide equal methodological quality as peer-reviewed studies [25].

2.3 Study Coding and Data Extraction

Studies were read and independently coded by two investigators (JG and MS). The following data were extracted in an Excel template/spreadsheet: (i) author(s), title, and year of publication; (ii) descriptive information of participants by the group, including the number of participants in each group, sex, age, and experience in resistance training (for age and resistance training, the classification presented in Grgic et al. [26] was used); (iii) study characteristics (duration of the study, weekly training frequency, RI duration, and set and repetition scheme used); (iv) test(s) for assessing changes in muscular strength; (v) pre- and post-treatment mean ± standard deviation (SD) values for muscular strength tests. Where figures were used instead of numerical data, the data were extracted where possible. Coding files were cross-checked between the authors, with discussion and agreement over any observed differences.

2.4 Methodological Quality Assessment

Assessment of the methodological quality of the included studies was performed using the Downs and Black checklist [27] modified as in Davies et al. [28]. The list details may be found elsewhere [27]. Briefly, out of the maximal 29 points, studies scoring in the range of 20–29 were considered to be of good quality, studies scoring 11–20 points were considered to be of moderate quality, and studies scoring < 11 points were considered to be of poor methodological quality. The appraisal of the methodological quality was performed independently by two authors (JG and TD), with discussion and consensus used to resolve any observed differences.

3 Results

3.1 Description of Studies

The search yielded 2575 results, of which 51 full-text studies were inspected based on scrutiny of the abstracts. Twenty-three studies comprising a total of 491 participants (413 males and 78 females) were found to meet the inclusion criteria [19–23, 29–46]. Four studies were masters' theses [43–46] while the rest were peer-reviewed and published in journals. The majority of the studies (i.e., 20) involved young participants (i.e., aged 18–39 years), with two studies comprising older adults (i.e., aged > 65 years) as participants. Age was not reported in one study [42]. The search process is depicted in Fig. 1.

Training status varied across studies: ten studies involved a resistance-trained population while 12 studies involved resistance-training naïve participants. Training status of the participants was not reported in one study [42]. The details of training interventions from each study are presented in Table 1. The pre- and post-intervention mean ± SD muscular strength test data along with corresponding percent changes are listed in Table 2. Due to the heterogeneity of study designs, a meta-analysis was not performed [47].

Muscular strength was most commonly tested using the 1 RM test. Other forms of muscular strength testing included 3 RM, 5 RM, 10 RM, maximal voluntary isometric contraction, and isokinetic knee extension and/or flexion.

3.2 Methodological Quality

The mean ± SD values from the Downs and Black checklist were 18 ± 3 (range: 12–22 points). Five studies were classified as being of good quality and 18 as being of moderate methodological quality. Individual ratings are presented in Table 3.

4 Discussion

The goal of this systematic review was to investigate the effects of RI duration during resistance training on muscular strength development. The current body of literature indicates that increases in muscular strength may be achieved across a multitude of RI durations. Studies on the topic are methodologically sound, and, overall, the outcomes seem unaffected by the methodological design used. However, many nuances of individual studies need to be explored before extrapolating the findings to practical recommendations. The following sections are classified based on findings observed in trained and untrained participants. Such a classification was chosen as the optimal resistance-training design to elicit the desired effect seems to be different between trained and untrained individuals [11].

4.1 Findings on Trained Participants

In general, studies reported that young, resistance-trained individuals need a longer duration RI to maximize gains in muscular strength [21, 22]. Nonetheless, robust gains in muscular strength can be achieved with a short RI duration even in this population. Moreover, two 4-week interventions reported similar muscular strength gains when comparing 1-min RI to a 3-min RI [41, 44]. It seems that progressively decreasing the RI duration over time can result in similar muscular strength gains compared to

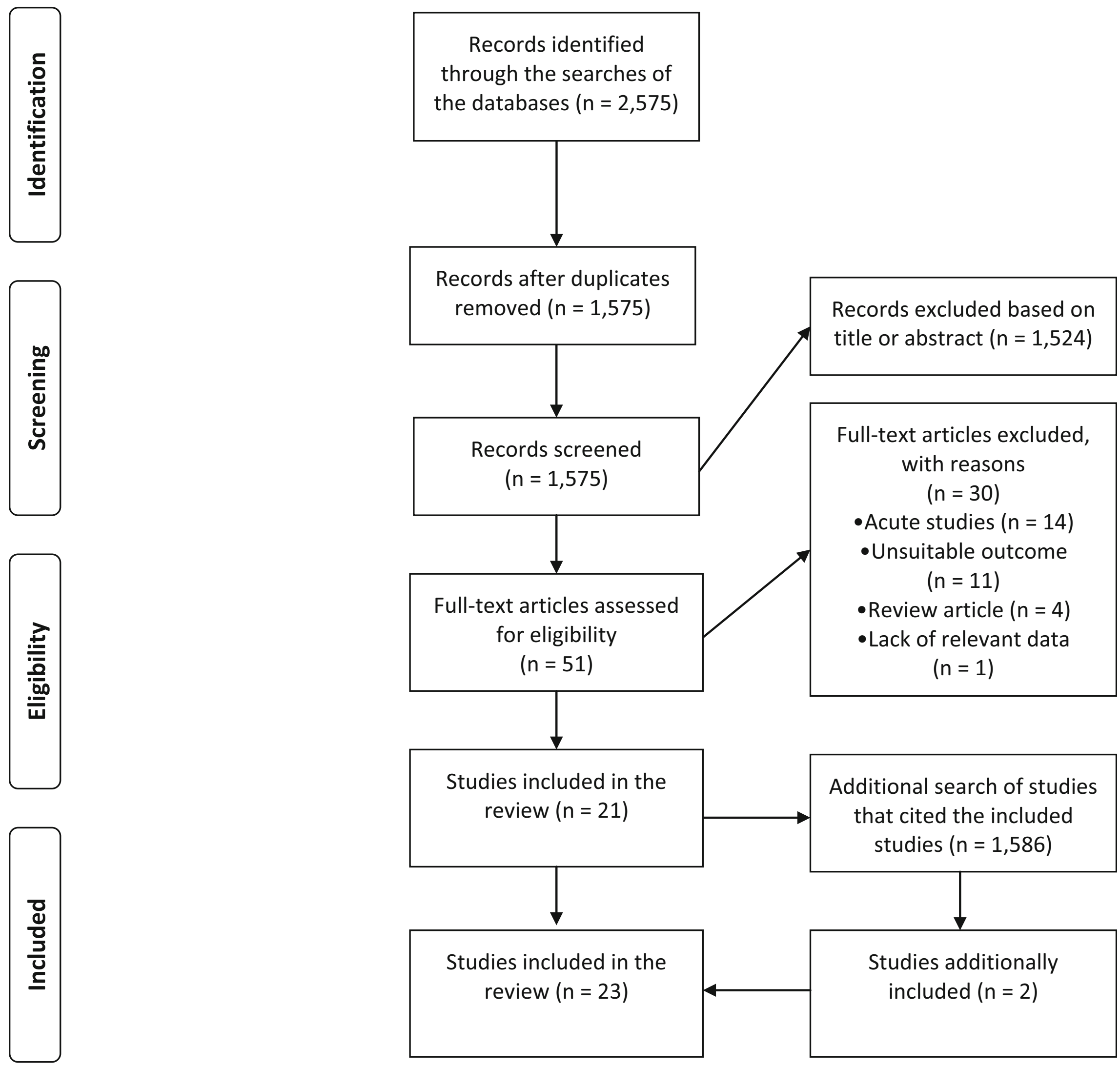

Fig. 1 Flow diagram of the search process

maintaining a long duration RI [34, 35]. The very limited data in resistance-trained older adults indicate that a short RI might be sufficient for reaping the muscular strength gains in this age group [36].

The seminal study by Robinson et al. [29] was the first to investigate the effects of different RI durations on muscular strength. Resistance-trained men ($n = 33$) were assigned to one of three groups: a short RI group (30 s), a moderate RI group (90 s), and a long RI group (180 s). At baseline, and following 5 weeks of resistance training with a weekly training frequency of 4 days, participants were tested using the 1 RM barbell back squat exercise. Pre- to post-intervention results revealed the greatest gains in muscular strength (+7%) in the group that employed 180-s RI. The gains in muscular strength mirrored the total training volume (i.e., the group that trained with the highest volume achieved the greatest increases in muscular strength). However, only a 1% greater increase in muscular strength was observed for the 180-s group in comparison with the 90-s group, at the expense of doubling the training session duration. The short RI duration group trained with the lowest overall volume and produced the smallest increases in muscular strength (+ 2%). It has been shown that training with shorter RI durations may impair performance and the total number of repetitions per set [8, 10]. Cumulatively, this would lead to a lower total training volume, as training volume is calculated as load × repetitions × sets. Due to the direct relationship between muscular adaptations and training volume in a dose–response fashion [48], it would seem that the use of a shorter duration RI is insufficient for maximizing gains in muscular strength.

In a longer-term intervention (i.e., 16 weeks), De Salles et al. [22] randomized 36 resistance-trained men into three

Table 1 Summary of the basic details from the included studies

Study	Participant characteristics	Exercise prescription (sets × repetitions)	Were repetitions performed to momentary muscular failure?	Duration of intervention; weekly training frequency	Rest intervals comparison (groups)	Strength test (s)
Ahtiainen et al. [32]	Young trained men ($n = 13$)	3–5 × 10	Yes	12 weeks; 4×	2 vs. 5 min	1RM LE MVIC
Buresh et al. [23]	Young untrained men ($n = 12$)	2–3 × 10	Yes	10 weeks; 2×	1 vs. 2.5 min	5RM BP 5RM SQ
Cassetty [43]	Young untrained women ($n = 16$)	3 × 10–12	Yes	12 weeks; 3×	30 vs. 60 s	1RM BP 1RM LP
De Salles et al. [22]	Young trained men ($n = 36$)	3 × 4–6 or 3 × 8–10	Yes	16 weeks; 4×	1 vs. 3 vs. 5 min	1RM BP 1RM LP
de Souza Jr et al. [34]	Young trained men ($n = 20$)	4 × 8–10	Yes	8 weeks; 6×	2 min–30 s (DI) vs. 2 min	1RM BP 1RM SQ PT KE PT KF
de Souza Jr et al. [35]	Young trained men ($n = 22$)	4 × 8–10	Yes	8 weeks; 6×	2 min–30 s (DI) vs. 2 min	1RM BP 1RM SQ PT KE PT KF
Fink et al. [33]	Young untrained men ($n = 21$)	4 × with a load of 40% 1RM	Yes	8 weeks; 2×	40 vs. 150 s	1RM BP 1RM SQ
Garcıa-Lopez et al. [39]	Young untrained men ($n = 14$)	3 × with a load of 60–75% MVIC	Yes	5 weeks; 2×	1 vs. 4 min	MVIC
Gentil et al. [19]	Young untrained men ($n = 34$)	2 × 8–12	Yes	12 weeks; 2×	1:3 work rest ratio vs. 1:6 work rest ratio	1RM BP 1RM LP
Hill-Haas et al. [30]	Young untrained women ($n = 18$)	2–5 × 15–20	Yes	5 weeks; 3×	20 vs. 80 s	3RM LP
Holmes [44]	Young trained men ($n = 12$)	3–6 × 10	Yes[a]	4 weeks; 4×	1 vs. 3 min	1RM BP 1RM SQ
Jambassi Filho et al. [36]	Trained older women ($n = 21$)	3 × 15	Yes[b]	8 weeks; 3×	1 vs. 3 min	MVIC
Mohamadimofrad et al. [42]	Men [$n = 40$ (age and training status were not presented)]	4 × 70% 1RM	Unclear	8 weeks; 2×	45 vs. 90 vs. 180 s vs. combined group	1RM BP 1RM SQ
Peers [45]	Young untrained men ($n = 21$)	3 × 70% 1RM	Unclear	5 weeks; 2×	1 vs. 3 min	10RM BP 10RM SQ
Piirainen et al. [40]	Young untrained men ($n = 21$)	3 × 10	Yes	7 weeks; 3×	55 s[c] vs. 2 min	10RM KE 10RM KF PT KE

Table 1 continued

Study	Participant characteristics	Exercise prescription (sets × repetitions)	Were repetitions performed to momentary muscular failure?	Duration of intervention; weekly training frequency	Rest intervals comparison (groups)	Strength test (s)
Pincivero et al. [37]	Young untrained men ($n = 15$)	4–8 × 10	Unclear	4 weeks; 3×	40 vs. 160 s	PT KE 60°/s
						PT KE 180°/s
						PT KF 60°/s
						PT KF 180°/s
Pincivero et al. [38]	Young untrained men ($n = 15$)	4–7 × 20	Unclear	6 weeks; 2×	40 vs. 160 s	PT KE
Reed [46]	Young untrained men ($n = 18$) and women ($n = 23$)	3 × 10–12	Yes	10 weeks; 3×	30 vs. 90 s	1RM BP
						1RM LP
Robinson et al. [29]	Young trained men ($n = 33$)	1–5 × 10	Yes[b]	5 weeks; 4×	30 vs. 90 vs. 180 s	1RM SQ
Schoenfeld et al. [21]	Young trained men ($n = 18$)	3 × 8–12	Yes	8 weeks; 3×	1 vs. 3 min	1RM BP
						1RM SQ
Simao et al. [41]	Young trained men ($n = 26$)	4 × 8–12	Yes	4 weeks; 3×	1 vs. 3 min	10RM BP
						10RM BC
Villanueva et al. [20]	Untrained older men ($n = 22$)	2–3 × 4–6	No	8 weeks; 3×	1 vs. 4 min	1RM CP
						1RM LP
Willardson et al. [31]	Young trained men ($n = 22$)	5–8 × 3–15	Yes[b]	12 weeks; 2×	2 vs. 4 min	1RM SQ

BC biceps curl, *BP* bench press, *CP* chest press, *DI* decreasing rest intervals, *KE* knee extensor, *KF* knee flexor, *LE* leg extension, *LP* leg press, *MVIC* maximum voluntary isometric contraction, *PT* peak torque, *RM* repetition maximum, *SQ* squat

[a] Repetitions were not performed to momentary muscular failure each training session

[b] Repetitions were performed to momentary muscular failure on the last set

[c] Heart rate based rest interval (55 s on average)

Table 2 The effects of rest interval length in resistance training programs on muscular strength

Study	Pre-intervention strength values (mean ± SD)	Post-intervention strength values (mean ± SD)	Change [%]
Ahtiainen et al. [32][a]	2 min MVIC (bilateral)		2
	2 min MVIC (unilateral)		8
	5 min MVIC (bilateral)		6
	5 min MVIC (unilateral)		8
Buresh et al. [23]	1 min BP = 85 ± 12 kg	1 min BP = 93 ± 12 kg	9
	1 min SQ = 119 ± 21 kg	1 min SQ = 141 ± 21 kg	18
	2.5 min BP = 70 ± 15 kg	2.5 min BP = 79 ± 14 kg	13
	2.5 min SQ = 98 ± 17 kg	2.5 min SQ = 125 ± 31 kg	28
Cassetty [43]	30 s BP = 40 ± 12 kg	30 s BP = 46 ± 11 kg	15
	30 s LP = 89 ± 23 kg	30 s LP = 97 ± 26 kg	9
	60 s BP = 40 ± 6 kg	60 s BP = 44 ± 6 kg	10
	60 s LP = 84 ± 25 kg	60 s LP = 97 ± 25 kg	16
De Salles et al. [22]	1 min BP = 87 ± 4 kg	1 min BP = 93 ± 4 kg	7
	1 min LP = 226 ± 19 kg	1 min LP = 276 ± 10 kg	22
	3 min BP = 85 ± 5 kg	3 min BP = 96 ± 5 kg	13
	3 min LP = 227 ± 19 kg	3 min LP = 305 ± 25 kg	34
	5 min BP = 88 ± 3 kg	5 min BP = 98 ± 4 kg	11
	5 min LP = 226 ± 14 kg	5 min LP = 321 ± 19 kg	42
de Souza Jr et al. [34]	DI BP = 96 ± 14 kg	DI BP = 132 ± 15 kg	38
	DI SQ = 121 ± 12 kg	DI SQ = 162 ± 23 kg	34
	DI PT KE (right leg) = 240 ± 22 N m	DI PT KE (right leg) = 258 ± 25 N m	8
	DI PT KE (left leg) = 232 ± 16 N m	DI PT KE (left leg) = 245 ± 24 N m	6
	DI PT KF (right leg) = 119 ± 19 N m	DI PT KF (right leg) = 127 ± 29 N m	7
	DI PT KF (left leg) = 119 ± 15 N m	DI PT KF (left leg) = 126 ± 27 N m	6
	2 min BP = 94 ± 12 kg	2 min BP = 120 ± 10 kg	28
	2 min SQ = 127 ± 10 kg	2 min SQ = 169 ± 14 kg	33
	2 min PT KE (right leg) = 267 ± 31 N m	2 min PT KE (right leg) = 272 ± 9 N m	2
	2 min PT KE (left leg) = 242 ± 32 N m	2 min PT KE (left leg) = 255 ± 12 N m	5
	2 min PT KF (right leg) = 131 ± 27 N m	2 min PT KF (right leg) = 140 ± 34 N m	7
	2 min PT KF (left leg) = 132 ± 25 N m	2 min PT KF (left leg) = 140 ± 38 N m	6
de Souza Jr et al. [35]	DI BP = 100 ± 12 kg	DI BP = 125 ± 12 kg	25
	DI SQ = 120 ± 22 kg	DI SQ = 160 ± 15 kg	33
	DI PT KE (right leg) = 244 ± 20 N m	DI PT KE (right leg) = 258 ± 25 N m	6
	DI PT KE (left leg) = 236 ± 14 N m	DI PT KE (left leg) = 246 ± 24 N m	4
	DI PT KF (right leg) = 129 ± 18 N m	DI PT KF (right leg) = 138 ± 19 N m	7
	DI PT KF (left leg) = 126 ± 22 N m	DI PT KF (left leg) = 138 ± 16 N m	10
	2 min BP = 102 ± 10 kg	2 min BP = 130 ± 10 kg	27
	2 min SQ = 115 ± 20 kg	2 min SQ = 155 ± 20 kg	35
	2 min PT KE (right leg) = 248 ± 22 N m	2 min PT KE (right leg) = 268 ± 10 N m	8
	2 min PT KE (left leg) = 246 ± 28 N m	2 min PT KE (left leg) = 257 ± 12 N m	4
	2 min PT KF (right leg) = 129 ± 22 N m	2 min PT KF (right leg) = 144 ± 30 N m	12
	2 min PT KF (left leg) = 131 ± 20 N m	2 min PT KF (left leg) = 145 ± 28 N m	11
Fink et al. [33]	40 s BP = 69 ± 12 kg	40 s BP = 76 ± 12 kg	10
	40 s SQ = 119 ± 19 kg	40 s SQ = 126 ± 17 kg	6
	150 s BP = 64 ± 11 kg	150 s BP = 70 ± 11 kg	9
	150 s SQ = 113 ± 17 kg	150 s SQ = 119 ± 17 kg	5
Garcıa-Lopez et al. [39]	1 min MVIC = 48 ± 15 kg	1 min MVIC = 54 ± 14 kg	13
	3 min MVIC = 48 ± 16 kg	3 min MVIC = 55 ± 12 kg	15

Table 2 continued

Study	Pre-intervention strength values (mean ± SD)	Post-intervention strength values (mean ± SD)	Change [%]
Gentil et al. [19]	1:3 work rest ratio BP = 62 ± 17 kg	1:3 work rest ratio BP = 72 ± 19 kg	16
	1:3 work rest ratio LP = 175 ± 55 kg	1:3 work rest ratio LP = 205 ± 55 kg	17
	1:6 work rest ratio BP = 65 ± 18 kg	1:6 work rest ratio BP = 72 ± 18 kg	11
	1:6 work rest ratio LP = 161 ± 30 kg	1:6 work rest ratio LP = 190 ± 62 kg	18
Hill-Haas et al. [30]	20 s LP = 93 ± 10 kg	20 s LP = 111 ± 10 kg	19
	80 s LP = 99 ± 11 kg	80 s LP = 144 ± 10 kg	45
Holmes [44]	1 min BP = 92 ± 22 kg	1 min BP = 99 ± 27 kg	8
	1 min SQ = 128 ± 38 kg	1 min SQ = 150 ± 46 kg	17
	3 min BP = 103 ± 27 kg	3 min BP = 108 ± 34 kg	5
	3 min SQ = 135 ± 34 kg	3 min SQ = 152 ± 41 kg	13
Jambassi Filho et al. [36]	1 min MVIC = 937 ± 156 N	1 min MVIC = 978 ± 233 N	4
	3 min MVIC = 811 ± 129 N	3 min MVIC = 852 ± 133 N	5
Mohamadimofrad et al. [42][a]	45 s BP		10
	45 s SQ		27
	90 s BP		11
	90 s SQ		27
	180 s BP		12
	180 s SQ		27
	Combined RI group BP		13
	Combined RI group SQ		27
Peers [45]	1 min BP = 60 ± 16 kg	1 min BP = 71 ± 20 kg	8
	1 min SQ = 74 ± 27 kg	1 min SQ = 82 ± 31 kg	11
	3 min BP = 58 ± 25 kg	3 min BP = 69 ± 30 kg	19
	3 min SQ = 95 ± 20 kg	3 min SQ = 107 ± 40 kg	13
Piirainen et al. [40]	55 s KE = 67 ± 20 kg	55 s KE = 108 ± 42 kg	61
	55 s KF = 47 ± 8 kg	55 s KF = 63 ± 16 kg	34
	55 s PT KE = 127 ± 33 N m	55 s PT KE = 171 ± 39 N m	35
	2 min KE = 87 ± 16 kg	2 min KE = 115 ± 26 kg	32
	2 min KF = 53 ± 11 kg	2 min KF = 65 ± 10 kg	23
	2 min PT KE = 150 ± 36 N m	2 min PT KE = 207 ± 36 N m	38
Pincivero et al. [37][a]	40 s PT KE 60°/s		1
	40 s PT KE 180°/s		1
	40 s PT KF 60°/s		−10
	40 s PT KF 180°/s		−8
	160 s PT KE 60°/s		6
	160 s PT KE 180°/s		8
	160 s PT KF 60°/s		−2
	160 s PT KF 180°/s		6
Pincivero et al. [38]	40 s PT KE = 161 ± 18 N m	40 s PT KE = 178 ± 14 N m	11
	160 s PT KE = 172 ± 13 N m	160 s PT KE = 198 ± 18 N m	15
Reed [46]	30 s BP (males) = 66 ± 12 kg	30 s BP (males) = 83 ± 12 kg	26
	30 s LP (males) = 88 ± 15 kg	30 s LP (males) = 105 ± 14 kg	19
	30 s BP (females) = 40 ± 12 kg	30 s BP (females) = 56 ± 10 kg	40
	30 s LP (females) = 60 ± 10 kg	30 s LP (females) = 78 ± 10 kg	30
	90 s BP (males) = 65 ± 12 kg	90 s BP (males) = 78 ± 10 kg	20
	90 s LP (males) = 87 ± 13 kg	90 s LP (males) = 100 ± 11 kg	15
	90 s BP (females) = 40 ± 10 kg	90 s BP (females) = 52 ± 12 kg	30
	90 s LP (females) = 59 ± 10 kg	90 s LP (females) = 71 ± 10 kg	20

Table 2 continued

Study	Pre-intervention strength values (mean ± SD)	Post-intervention strength values (mean ± SD)	Change [%]
Robinson et al. [29]	30 s SQ = 125 ± 24 kg	30 s SQ = 128 ± 24 kg	2
	90 s SQ = 120 ± 23 kg	90 s SQ = 127 ± 22 kg	6
	180 s SQ = 124 ± 27 kg	180 s SQ = 133 ± 29 kg	7
Schoenfeld et al. [21]	1 min BP = 94 ± 30 kg	1 min BP = 98 ± 29 kg	4
	1 min SQ = 119 ± 33 kg	1 min SQ = 129 ± 32 kg	8
	3 min BP = 93 ± 18 kg	3 min BP = 105 ± 19 kg	13
	3 min SQ = 118 ± 31 kg	3 min SQ = 136 ± 33 kg	15
Simao et al. [41]	1 min BP = 80 ± 8 kg	1 min BP = 85 ± 8 kg	6
	1 min BC = 34 ± 3 kg	1 min BC = 38 ± 3 kg	12
	3 min BP = 75 ± 4 kg	3 min BP = 79 ± 4 kg	5
	3 min BC = 31 ± 2 kg	3 min BC = 36 ± 2 kg	16
Villanueva et al. [20]	1 min CP = 75 ± 27 kg	1 min CP = 95 ± 30 kg	27
	1 min LP = 328 ± 102 kg	1 min LP = 430 ± 104 kg	31
	4 min CP = 68 ± 20 kg	4 min CP = 79 ± 26 kg	16
	4 min LP = 279 ± 90 kg	4 min LP = 338 ± 100 kg	21
Willardson et al. [31]	2 min SQ = 145 ± 24 kg	2 min SQ = 171 ± 25 kg	18
	4 min SQ = 150 ± 19 kg	4 min SQ = 182 ± 21 kg	21

BC biceps curl, *BP* bench press, *CP* chest press, *DI* decreasing rest intervals, *KE* knee extensor, *KF* knee flexor, *LP* leg press, *MVIC* maximum voluntary isometric contraction, *PT* peak torque, *SD* standard deviation, *SQ* squat, *RI* rest interval

[a] Raw data not available

groups varying in RI duration: 1, 3, or 5. Each group trained with loading schemes corresponding to 4–6 and 8–10 RM. Muscular strength was assessed using the bench press and leg press exercises. Greater increases in 1RM muscular strength were noted in the groups that trained with 3-min RIs and 5-min RIs in comparison with the group that trained with 1-min RIs. A significant difference was observed between the 5- and 1-min RI groups both for upper- and lower-body muscular strength. Congruent with previous research [29], gains in lower-body muscular strength showed a decline that paralleled the decrease in RI duration.

This superiority of longer duration RIs in resistance-trained individuals was corroborated in a recent study by Schoenfeld et al. [21], who observed greater increases in muscular strength in a group that trained with 3-min RIs versus a group that trained with 1-min RIs. Curiously, increases in upper-body muscular endurance were also greater in the 3-min group, a finding that runs contrary to general resistance training recommendations [49]. Willardson and Burkett [31] showed that using 4-min RIs may allow for greater training volumes and more meaningful muscular strength gains in comparison to 2-min RIs. Ahtiainen et al. [32] investigated the muscular strength-related effects of differing RI durations (2- vs. 5-min) in resistance training. In contrast to the findings of Schoenfeld et al. [21], the authors reported no significant differences in muscular strength changes between the two protocols. A caveat to the study was that training protocols were only partially supervised and mostly controlled by training diaries, which may have confounded the results. Nonetheless, it is also important to emphasize that the studies from Schoenfeld et al. [21] and Ahtiainen et al. [32] differed in their designs. Schoenfeld et al. [21] compared two independent groups while Ahtiainen et al. [32] employed a crossover design, in which the same participants performed resistance training with both 2-min RIs and 5-min RIs. A crossover design can minimize the possible interindividual differences in responses and is of great value in exercise intervention studies due to the wide ranges of muscular strength responses to regimented resistance training [50]. The exercise intervention in the Athiainen et al. [32] study also lasted 3 months for each condition, compared to the intervention in the study by Schoenfeld et al. [21], in which a 2-month long intervention was employed, which might also have influenced the results.

It has been suggested that progressively decreasing RI duration over time attenuates decreases in performance, and increases the ability for adaptation to shorter RI duration without excessive fatigue [7]. A study by de Souza et al. [34] tested this hypothesis. Twenty-two young men were allocated to either a constant RI or a decreasing RI group (from 2 min to 30 s). Muscular strength (1RM) in the squat and bench press exercises and isokinetic measures of peak torque in the knee flexors and extensors were

Table 3 Methodological quality evaluation using the modified Downs and Black methodological quality assessment

Study	Scale items																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Total
Ahtiainen et al. [32]	1	1	1	1	1	1	1	0	0	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	0	1	1	0	1	17
Buresh et al. [23]	1	1	1	1	1	1	1	0	0	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0	1	1	1	1	0	19
Cassetty [43]	1	1	1	1	1	1	1	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	1	0	0[a]	1	1	1	0	1	19
De Salles et al. [22]	1	1	1	1	1	1	1	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	21
de Souza Jr et al. [34]	1	1	1	1	0	1	1	0	1	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	0[a]	20
de Souza Jr et al. [35]	1	1	1	1	0	1	1	0	1	0	0[a]	0[a]	1	0	0	1	1	1	1	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	18
Fink et al. 2017 [33]	1	1	1	1	1	1	1	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	0[a]	0[a]	1	1	1	1	1	20
Garcıa-Lopez et al. [39]	1	0	1	1	0	1	1	0	1	0	0[a]	0[a]	0[a]	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	0[a]	15
Gentil et al. [19]	1	1	1	1	1	1	1	0	1	0	1	1	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	0	1	22
Hill-Haas et al. [30]	1	1	1	1	1	1	1	0	1	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	1	20
Holmes [44]	1	1	1	0	1	1	1	0	1	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	0	0	1	18
Jambassi Filho et al. [36]	1	1	1	1	1	1	1	1	1	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	0	1	1	1	1	22
Mohamadimofrad et al. [42]	0	1	1	1	1	1	0	0	1	0	0[a]	0[a]	0[a]	0[a]	0[a]	1	1	1	0[a]	1	0	0[a]	0	0	0	1	1	0	0	12
Peers [45]	1	1	1	1	1	1	1	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	0	0	1	1	1	0	0[a]	17
Piirainen et al. [40]	1	1	1	1	1	1	1	0	0	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0	1	1	0[a]	0	0	0	1	1	0	0[a]	15
Pincivero et al. [37]	1	1	1	1	0	1	1	0	1	1	0[a]	0[a]	0	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	0[a]	17
Pincivero et al. [38]	1	1	1	1	0	1	1	0	1	1	0[a]	0[a]	0	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	0[a]	17
Reed [46]	1	1	1	1	1	1	1	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	1	0	0	1	1	1	0	1	19
Robinson et al. [29]	1	1	1	1	0	1	1	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	0[a]	0	1	1	1	0	1	17
Schoenfeld et al. [21]	1	1	0	1	1	1	1	0	1	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	21
Simao et al. [41]	1	1	1	1	0	1	0	0	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	0[a]	0[a]	0	0	0	1	1	1	1	16
Villanueva et al. [20]	1	1	1	1	1	1	1	1	1	0	0[a]	0[a]	1	0[a]	0[a]	1	1	1	1	1	0[a]	0[a]	1	0[a]	1	1	1	1	1	21
Willardson et al. [31]	1	1	1	1	1	1	1	0	0	1	0[a]	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	0[a]	1	1	1	18

Items 1–10 are related to reporting, items 11–13 are related to external validity, items 14–26 are related to internal validity, item 27 is related to statistical power, item 28 to exercise adherence and item 29 to exercise supervision

1 criteria met, *0* criteria not met

[a] Item was unable to be determined, scored 0

assessed pre- and post-training. Training volume was significantly lower for the decreasing RI group compared to the constant group (bench press by 9.4%, squat by 13.9%). However, no significant differences between the groups were found for any of the muscular strength outcomes. In the follow-up work, de Souza et al. [35] employed the same protocol with the addition of creatine supplementation for both groups. While both groups achieved substantial gains in muscular strength, no significant between-group differences were noted for any of the outcomes. It should be pointed out that both studies [34, 35] were relatively short in duration (i.e., 8 weeks with 2 weeks of familiarization). These findings support the short-term data from Kraemer et al. [7], who noted that bodybuilders, when compared to powerlifters, better tolerate resistance exercise protocols based on short RIs. Bodybuilders often train with shorter duration RIs, compared to powerlifters who commonly employ longer duration RIs in their training routines. Based on these findings, it can be suggested that decreasing the RI duration with training experience might be a viable time-saving option. In the real-world setting of sport, this method might leave additional time for other conditioning priorities [31]. Still, future research with similar study designs is warranted.

Age of the individual is suggested to be an important variable when prescribing RI duration [51]. Acute studies have reported that older women recover faster than younger women between sets of a knee flexor exercise [51]. Theou et al. [51] suggested that a 1:1 exercise-to-rest ratio for knee flexor recovery might be needed for older adults, while in contrast, younger women require a 1:2 exercise-to-rest ratio for full recovery. The study by Jambassi Filho et al. [36] is the only longitudinal intervention that assessed gains in muscular strength in older adults with previous resistance training experience. The authors reported no differences in isometric muscular strength between 1-min RI and 3-min RI groups, suggesting that a 1-min RI might be sufficient recovery time for older female adults. That said, there is a paucity of longitudinal studies involving trained older adults, and further research is needed to draw firm conclusions on the topic. Future studies might also consider comparing chronic adaptations to different RIs between age groups, as, to date, there are no such studies.

4.2 Findings on Untrained Participants

Most of the studies that compared resistance training programs employing short-duration RIs to those employing long-duration RIs in individuals without previous resistance training experience reported no differences in gains in dynamic muscular strength [20, 23, 33, 39, 45]. Two studies reported greater gains in isokinetic strength when a longer duration RI was utilized [37, 38], albeit this remains equivocal [40]. Some studies showed a benefit for moderate duration RIs compared to short duration RIs [30]. Overall, for untrained individuals, it can be surmised that a short- to moderate-duration RI in resistance training is sufficient for inducing gains in muscular strength.

Buresh et al. [23] divided 12 males into either a 1-min RI group or a 2.5-min RI group. Following 10 weeks of the resistance training program, no statistically significant between-group differences were observed in the 5 RM tests. However, these findings should be interpreted with caution because the training intervention was unsupervised, calling into question whether participants adhered to the prescribed RI. Furthermore, the study used a 5 RM test as a proxy for assessing muscular strength rather than a 1 RM test, which is considered as the “gold standard” for practical settings [52]. Thus, while evidence from this study seems to suggest that RI duration does not influence muscular strength gains, the methodological limitations raise questions related to the practical usability of the findings.

Hill-Haas et al. [30] investigated muscular strength adaptations to different RI duration in females. Eighteen untrained women were randomly assigned to a 20-s RI or an 80-s RI group. Training sessions were carried out three times/week for 5 weeks using a combination of multi- and single-joint exercises. Results showed that the moderate RI (i.e., 80 s) was more conducive to increasing muscular strength (i.e., + 45% vs. + 19%) as assessed using the 3 RM leg press test. Nevertheless, the 20-s RI condition promoted substantial increases in muscular strength while training only 72 min per week (i.e., 24-min training duration per session). The ramifications of these findings may be significant from a public health standpoint. Novel recommendations for health-enhancing physical activity, in addition to accumulating 150 min of moderate to vigorous aerobic activity per week, also suggest resistance training $\geq$ 2 days per week [53]. However, population-based findings from Australia [54] and the USA [55] report very low participation rates (18.6 and 31.7%, respectively) in resistance training. Evidence derived from this study [30] may, therefore, encourage individuals to participate in resistance training, as robust muscular strength increases can be achieved with very limited training time.

The findings from Hill-Haas et al. [30] are somewhat in agreement with those of Pincivero et al. [37, 38], who reported greater isokinetic muscular strength gains when using 160-s RIs versus 40-s RIs. In contrast, Reed [46] observed greater muscular strength gains when using shorter RIs (i.e., 30 vs. 90 s) in a large sample of males and females. Studies examining acute effects of RI duration seem to indicate that shorter RIs may be more beneficial to females, as they appear to demonstrate better inter-set recovery compared to men [10]. In this regard, Celes et al. [56] reported that full quadriceps muscular strength recovery occurs with a 60-s RI in females. For men, a 120-s RI was needed for a full recovery, possibly because of different fatigability between sexes [57]. Some mechanisms that potentiate these differences may include muscle perfusion, skeletal muscle metabolism, and fiber-type properties [57]. A benefit of a shorter RI duration for females is supported by the findings of Cassetty [43], who reported that females achieved equal gains in upper-body muscular strength using 30-s RIs compared to 60-s RIs. Practitioners should acknowledge these differences in recovery rates between sexes and they should be taken into account when programming resistance training aimed at muscular strength development.

A recent study by Fink et al. [33] compared the effects of varying RI duration on 1RM muscular strength in a cohort of untrained men. The resistance-training program consisted of low loads (i.e., 40% of 1 RM)—lighter than commonly used when training for maximal muscular strength [58]. Twenty-one participants were allocated to either a 40-s RI group or a 150-s RI group. Both groups trained twice per week, performing the bench press and squat exercises to momentary muscular failure. Following 8 weeks of training, both groups significantly increased their bench press 1RM muscular strength (40-s group by 10%; 150-s group by 9%) and back squat 1RM muscular strength (40-s group by 6%; 150-s group by 5%) with no significant between-group differences. These findings suggest that shorter duration RIs may be sufficient for achieving increases in muscular strength when training with lighter loads, even when sets are performed to momentary muscular failure. Additional studies using low loads are needed to confirm this hypothesis. However, it would seem that training with lighter loads may be sub-optimal for the development of maximal dynamic muscular strength [59, 60].

Garcia-Lopez et al. [39] observed similar gains in isometric muscular strength when training with 1-min RIs versus 4 min RIs despite a 32% greater training volume in the 4-min RI group. It should be noted that the study involved only the arm curl exercise; it is not clear whether the inclusion of compound exercises would have impacted results. Rooney et al. [61] concluded that the associated fatigue from training without rest between sets might contribute to greater gains in muscular strength compared to resting for 30 s in untrained individuals. Additional support for short RIs comes from the findings by Villanueva et al. [20], who reported greater increases in muscular strength when resting 1 versus 4 min between sets. An important caveat to these findings is that sets were not performed to momentary muscular failure, and thus the short RI group ultimately trained closer to fatigue after the initial set [21]. Training near failure is thought to stimulate greater increases in muscular strength as it allows activation of more motor units [62], although evidence is equivocal on the matter [63]. Taking the above into account, caution should be used when extrapolating that short RIs are superior for maximizing muscular strength gains.

It has been suggested that the impact of RI length on muscular strength outcomes may be dependent on the exercise selection and the level of exertion [64]. When exercises are performed with maximal exertion, longer duration RIs may be necessary; in contrast, sub-maximal exertion may require only a short-duration RI to obtain full recovery. This hypothesis is supported by the findings from Villanueva et al. [20]. It has also been postulated that the duration of an RI may depend on the duration of work during the set. In this regard, Gentil et al. [19] randomized 34 untrained men to one of two groups: a group that followed a 1:3 work-to-rest ratio and a group that followed a 1:6 work-to-rest ratio. The participants were instructed to perform 8–12 repetitions per set at a tempo of 4 s per repetition (2 s for the concentric phase and 2 s for the eccentric phase). The work time ranged from 32 to 48 s, while the rest between sets ranged from 96 to 144 s and from 192 to 288 s for the 1:3 and 1:6 ratio groups, respectively. After 12 weeks of training, no differences in 1RM upper- (bench press) or lower-body (leg press) muscular strength were observed, indicating that a 1:3 work-to-rest ratio may be sufficient to elicit recovery between sets. In this case, the 1:3 work-to-rest ratio would correspond to moderate and long RI duration.

Several important implications need to be taken into account when prescribing RI duration within a structured resistance training program. Ultimately, the interaction between other resistance training variables such as exercise selection, load, and total training volume will determine RI duration. For instance, if a set is performed with higher repetitions, it might induce greater fatigue, which would result in a need for an RI of longer duration [10]. By contrast, sets conducted within lower repetition ranges will likely reduce the need for RI of longer duration due to the low energy depletion. Using shorter RIs might result in a higher discomfort, especially when performing multi-joint exercises such as squats and leg press, which also needs to be taken into account, especially when working with novice individuals [65]. With regard to clinical populations, longer duration RIs might be of benefit for individuals diagnosed with cardiovascular dysfunction, as Figueiredo et al. [66] noted that resting 1 min compared to resting 2 min is associated with greater cardiac stress in these individuals. For maintaining long-term adherence to resistance training in individuals with pre-existing conditions, this is an important variable to consider.

4.3 Methodological Quality

Assessing the methodological quality of the reviewed studies indicated that none of them fulfilled items 17 and 18, which were related to blinding of participants and investigators. Due to the nature of these studies, blinding is not feasible. The addition of checklist items 28 (exercises adherence) and 29 (training supervision) provided additional insights into the methodological quality of studies. When performing studies that involve finite variables such as RI duration, supervision of the resistance training program is paramount; however, several of the included studies [23, 31, 32, 42] performed the training intervention program in an unsupervised or partially supervised fashion [23, 31, 32, 42], and thus the findings should be interpreted with circumspection. Furthermore, studies should track adherence to the training regimes as variations in total training frequency between groups may ultimately determine the outcome.

5 Conclusion

The body of research indicates that long-duration RIs (i.e., > 2 min) are required to maximize gains in muscular strength in trained individuals. It is unclear if RIs longer than 5 min in duration would provide any additional benefits, as there is a paucity of studies that investigated such RIs. From a practical standpoint, it may be hypothesized that trained individuals could auto-regulate their RI duration based on their psychological and physiological readiness, rather than adhering to a predetermined RI duration. However, there are no studies comparing such principles over the long term, indicating a potentially interesting topic for future research.

With regard to untrained individuals, it would seem that short (< 60 s) to moderate (i.e., 60–120 s) RIs are sufficient for maximizing muscular strength gains. In certain cases, the use of longer duration RI may be of a greater benefit as opposed to a short to moderate RI duration; for instance, when a multi-joint exercise is performed and/or when a set results in a greater fatigue and is carried out for higher repetitions. It is well known that responses in resistance training may vary between individuals. Therefore, the resistance training program needs to be tailored in an individualized manner.

On a final note, shorter RIs are more time efficient than longer RIs, and thus may be appropriate for those who are time-pressed. The body of evidence shows that robust muscular strength gains can be achieved with short RIs. Whether additional increases in muscular strength from longer RIs are worth the tradeoff in time must be assessed on an individual basis based on one's needs and goals.

Compliance with Ethical Standards

Conflicts of Interest Jozo Grgic, Brad J. Schoenfeld, Mislav Skrepnik, Timothy B. Davies, and Pavle Mikulic declare that they have no conflicts of interest relevant to the content of this review.

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