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REVIEW

WILEY

Overview of muscle fatigue differences between maximal eccentric and concentric resistance exercise

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Abstract

Since the 1970s, researchers have studied a potential difference in muscle fatigue (acute strength loss) between maximal eccentric (ECC_{max}) and concentric (CON_{max}) resistance exercise. However, a clear answer to whether such a difference exists has not been established. Therefore, the aim of our paper was to overview methods and results of studies that compared acute changes in muscle strength after bouts of ECC_{max} and CON_{max} resistance exercise. We identified 30 relevant studies. Participants were typically healthy men aged 20–40 years. Exercise usually consisted of 40–100 isokinetic ECC_{max} and CON_{max} repetitions of the knee extensors or elbow flexors. Both ECC_{max} and CON_{max} exercise caused significant strength loss, which plateaued and rarely exceeded 60% of baseline, suggesting strength preservation. In upper-body muscles, strength loss at the end of ECC_{max} (31.4 ± 20.4%) and CON_{max} (33.6 ± 17.5%) exercise was similar, whereas in lower-body muscles, strength loss was less after ECC_{max} (13.3 ± 12.2%) than CON_{max} (39.7 ± 13.3%) exercise. Muscle architecture and daily use of lower-body muscles likely protects lower-body muscles from strength loss during ECC_{max} exercise. We also reviewed seven studies on muscle fatigue during *coupled* ECC_{max}-CON_{max} exercise and found similar strength loss in the ECC and CON phases. We also found evidence from three studies that more ECC than CON repetitions can be completed at equal *relative* loads. These results indicate that muscle fatigue may manifest differently between ECC_{max} and CON_{max} resistance exercise. An implication of the results is that prescriptions of ECC resistance exercise for lower-body muscles should account for greater fatigue resilience of these muscles compared to upper-body muscles.

KEYWORDS
elbow flexors, isokinetic, knee extensors, muscle strength, strength training

1 | INTRODUCTION

A resistance exercise repetition typically consists of both a volitional muscle shortening (i.e., concentric: CON) and lengthening (i.e., eccentric: ECC) phase or action. However, an exercise repetition can also consist of only *one* of these action types. Historically, the ability to complete sets of repeated ECC or CON exercise was limited to isokinetic dynamometers, which, although regularly used by researchers,[1] have not been widely adopted by strength and conditioning coaches,[2,3] and are rarely found in fitness centers. New exercise technologies[4–7] have potential to make completion of submaximal and maximal ECC or CON resistance exercise more feasible outside of the laboratory. Thus, increased participation in these modes of resistance exercise, particularly ECC, is anticipated in the future, and the acute physiological responses to such exercise should be understood to guide exercise prescriptions. One topic where there is still no consensus, and its potential implications still not fully realized, is whether muscle fatigability (i.e., acute strength loss)[8] manifests differently during bouts of *maximal* ECC (ECC_{max}) versus *maximal* CON (CON_{max}) resistance exercise. That no clear answer exists is perhaps surprising given that researchers first explored the topic in the 1970s.

In 1974, Komi and Rusko[9] reported, in a sample of five healthy men, that one set of 40 ECC_{max} repetitions of the elbow flexors reduced ECC muscle strength by 50% at the end of the exercise set, whereas one set of 40 CON_{max} repetitions reduced CON strength by 20%. In 1977, Komi and Viitasalo[10] reported similar results for knee extensors. In a sample of four healthy men, they found that one set of 40 ECC_{max} repetitions reduced ECC muscle strength by 35% at the end of the exercise set, whereas one set of 40 CON_{max} repetitions reduced CON strength by 13%. Nevertheless, subsequent studies,[11–14] many of which included larger and different samples, different muscle groups, and different volumes of exercise than in the original studies,[9,10] did not necessarily find the same results. Thus, after approximately 50 years of research on the question of whether muscles fatigue differently during ECC_{max} versus CON_{max} resistance exercise, an answer has remained elusive.

Therefore, the primary purpose of our paper was to overview studies that have reported acute changes in muscle strength during bouts of ECC_{max} versus CON_{max} resistance exercise. To supplement the primary aim, and provide additional perspective on muscle fatigue during ECC and CON resistance exercise, we also overviewed the existing literature on acute reductions in ECC and CON phase muscle strength during repeated *coupled* ECC_{max}-CON_{max} resistance exercise. Additionally, we overviewed the number of repetitions that can be completed during ECC and CON resistance exercise with equal *relative* loads.

2 | METHODS

To summarize methods and results of studies that examined acute strength loss during ECC_{max} versus CON_{max} resistance exercise, we overviewed the relevant research literature. An overview shares characteristics with narrative reviews and scoping reviews.[15,16] An overview is defined as a "summary of literature that attempts to survey the literature and describe its characteristics" and may or may not include comprehensive searching, assessments of study quality, or tabular syntheses of the literature.[15]

We identified relevant studies using a mixed approach similar to that described by Greenhalgh and Peacock.[17] This approach relied on the investigators' personal knowledge and checking of personal digital files associated with previous research,[5,6,18,19] keyword searches performed in PubMed and Google Scholar (e.g., "eccentric" AND "concentric" AND "fatigue"), and "snowballing" strategies (i.e., reference and citation tracking). Articles were eligible for inclusion in the review if they included human subjects and reported muscle strength data (e.g., torques, forces) before and at the end of acute bouts of ECC_{max}, CON_{max}, or coupled ECC_{max}-CON_{max} resistance exercise. Articles published up until March 1, 2023, were eligible. Our literature search was thorough, amounting to the largest repository of data on the topic, but the search was not necessarily exhaustive. We did not follow formal flow diagram procedures such as tracking numbers and reasons for exclusions. We also did not formally assess study quality. Thus, our interpretations of the results should be considered with some degree of caution, as the potential for investigator bias is thought to be more likely with overviews and narrative reviews compared to systematic reviews.[15]

Extracted data from eligible studies included sample size, sex, age, and resistance exercise history; resistance exercise protocol features (e.g., sets, repetitions, and movement velocity), and percent changes in muscle strength from the exercise protocol. For papers in which strength values were presented in figures, the values were estimated using an openly available graph digitzer (WebPlotDigitizer, https://apps.automeris.io/wpd/). The graph digitizer required the investigator to temporarily upload a copy of the figure to the website. The investigator then calibrated the image by clicking two reference points on the y-axis (usually 0 and top of the y-axis) and informing the software of the actual values represented by those two points. The investigator then clicked each symbol on the figure that represented a mean or standard deviation or standard error of interest. After all data points were identified in the figure, the software generated a spreadsheet of the values calibrated against the y-axis. Means for percent change in strength after exercise across studies were computed in Version 29 of the Statistical Software Package for the Social Sciences (SPSS, Armonk, United States) and weighted for study sample size.

3 | RESULTS AND DISCUSSION

3.1 | ECC_{max} versus CON_{max} resistance exercise

3.1.1 | Study characteristics

We identified 30 studies published between 1973 and March 2023 that compared acute strength loss from bouts of ECC_{max} and CON_{max} resistance exercise. The 30 studies included 33 distinct study groups with 40 ECC_{max} versus CON_{max} exercise comparisons across all study groups and muscle groups. The studies included 490 participants (337 men, 147 women), and the mean sample size was 16.3 participants per study. Characteristics of the samples and methods of the studies are presented in Table 1. Participants in the studies were typically healthy, adult men, who were 20–40 years of age. The elbow flexors and knee extensors were the two most frequently studied muscle groups, comprising 25 studies (83.3%). Isokinetic dynamometry was used in 90% of the studies to deliver the exercise. The velocities of isokinetic exercise ranged from 30 to 180°/s (89.4 ± 56.3°/s; mean ± SD). In one study, participants exercised with maximal effort on a connected adaptive resistance exercise machine, which involved maximal muscle actions performed within a range of velocities and with an external resistance that decreased (i.e., drop setting) in real-time to match the participant's force-generating capacity with fatigue.[5]

The ECC_{max} and CON_{max} exercise protocols typically involved a prescribed number of sets and repetitions. The protocols ranged from 1 to 10 sets (3.4 ± 2.5 sets) and from 6 to 100 muscle actions per set (29.3 ± 28.5 repetitions). The total number of repetitions generally ranged from 40 to 100, except for the ankle dorsiflexors, where 150 maximal muscle actions were completed (66.7 ± 35.9 repetitions). Other methods for inducing muscle fatigue consisted of one set of repeated maximal repetitions for a prescribed amount of time rather than a prescribed number of repetitions[20] and completing one set of repeated maximal repetitions until the participant felt they could no longer perform more repetitions.[21–23]

Regarding the measurement of acute strength loss after exercise, about one-third of studies included a separate strength test immediately after the last set of exercise, whereas the majority of studies measured final muscle strength as an average of strength across the final 2–5 repetitions of the last set (or we identified final strength in the

TABLE 1 Characteristics of samples and methods in studies that reported on acute strength loss from maximal eccentric (ECC_{max}) and concentric (CON_{max}) resistance exercise.

	n	%
Included studies	30	100
Sex (337 men, 147 women, 484 total)		
Only men	14	46.7
Only women	3	10.0
Mixed sex sample	13	43.3
Age		
Youth only (< 18 y)	1	3.3
Adults only (18–59 y)	26	86.7
Older adults only (≥60 y)	0	0
Adult and older adult sample	2	6.7
Not reported	1	3.3
Health status		
Healthy sample only	30	100
Patient sample only	0	0
Resistance exercise history		
Previous resistance exercise experience	7	23.3
No previous resistance exercise experience	5	16.7
Not reported	18	60.0
Muscle group		
Elbow flexors only	13	43.3
Shoulder internal and external rotators	1	3.3
Lumbar extensors only	1	3.3
Knee extensors only	11	36.7
Ankle plantarflexors only	1	3.3
Ankle dorsiflexors only	2	6.7
Elbow flexors, elbow extensors, knee extensors, knee flexors	1	3.3
Exercise equipment		
Isokinetic dynamometer	27	90.0
Other	3	10.0
Post-exercise strength test time		
Last repetitions	19	63.3
Immediate-post	10	33.3
Last repetitions and immediate-post	1	3.3
Strength test muscle action		
Same muscle action as during exercise	20	66.7
Same muscle action as during exercise and another muscle action	7	23.3
Isometric only	3	10.0

Abbreviations: CON, concentric; ECC, eccentric; ISO, isometric.

figures as the strength value representing the last repetition performed). Thus, in most studies, maximal muscle strength was measured via the muscle action type that was also performed during exercise. That is, strength loss from ECC_{max} exercise was typically measured via a maximal ECC muscle action, whereas strength loss from CON_{max} exercise was typically measured via a maximal CON muscle action. Some studies also incorporated tests of maximal voluntary *isometric* strength before and immediately after exercise.

3.1.2 | Acute strength loss

The *first finding* was that both ECC_{max} and CON_{max} exercise induced significant acute strength loss (Tables 2 and 3). Exceptions to this were studies in which there was not a significant acute loss in ECC strength after the ECC_{max} exercise.[13,20,24,25] The *second finding* was that when acute strength loss occurred from ECC_{max} or CON_{max} exercise, the magnitude of loss, irrespective of the volume of exercise completed, rarely exceeded 60% (Tables 2 and 3). Thus, during repeated maximal resistance exercise, a minimal level of muscle strength was preserved to allow for continued exercise repetitions. The *third finding* was that the acute strength loss was not exclusive to the muscle action type used during exercise (Tables 2 and 3). For example, both ECC_{max} and CON_{max} exercise often caused acute strength loss in ECC, CON, and isometric strength assessments.[22,26–29] In some studies, the acute strength loss was most pronounced in the muscle action type used during exercise (i.e., specificity of fatigue),[14,26] whereas in other studies, the acute strength loss was similar between strength assessments.[27,28] The *fourth finding* was that the muscle group undergoing the exercise impacted whether there was a difference in acute strength loss between ECC_{max} versus CON_{max} exercise. In the elbow flexors, the magnitude of acute strength loss from ECC_{max} and CON_{max} exercise was roughly the same (i.e., weighted mean of ~30%) (Tables 2 and 4). However, for the knee extensors and ankle dorsiflexors and plantarflexors, acute strength loss from ECC_{max} exercise was less than from CON_{max} exercise (i.e., weighted means of ~15% and ~40%, respectively) (Tables 3 and 4).

We speculate that more frequent use of lower-limb than upper-limb muscles for activities of daily living (e.g., descending stairs or hills), and/or greater pennation angles of the knee extensors than elbow flexors,[30–35] render the knee extensors less susceptible than the elbow flexors to strength loss from acute ECC_{max} resistance exercise. That use-dependence might mitigate the acute strength loss experienced during a bout of ECC_{max} resistance exercise is further supported by results showing that (a) individuals with a history of resistance exercise of the elbow flexors experience less isometric torque loss immediately, 30 min, and for 5 days after completing 10 sets of 6 ECC_{max} isokinetic muscle actions[36] and (b) 7 weeks of ECC resistance exercise of the elbow flexors lessens the amount of acute strength loss experienced during a fatiguing ECC protocol performed after the intervention.[37] Moreover, although loads experienced during activities of daily living are low, low loads protect against strength loss experienced immediately after, and in the days following, muscle-damaging ECC_{max} resistance exercise.[38] Also, larger pennation angles of vastus lateralis and medialis muscle fibers (10–17°)[30,33,35] compared to biceps brachii (~0°)[34] and brachialis muscle fibers (8–9°)[31,32] might mitigate the acute strength loss experienced during ECC_{max} resistance exercise of the knee extensors due to less muscle damage, as muscle fibers of pennate muscles undergo minimal lengthening during ECC muscle actions due to fascicle rotation (i.e., they operate in a higher gear ratio).[39] This reduced length change in muscle fibers of pennate muscles during ECC muscle actions might also help explain why the knee extensors are less susceptible to muscle damage from ECC exercise than the elbow flexors.[38,40–45]

Finally, although acute strength loss in the elbow flexors was roughly similar at the end of ECC_{max} and CON_{max} resistance exercise (Tables 2 and 4), ECC_{max} exercise had a more detrimental effect on force-generating capacity in the days following the exercise than did CON_{max} exercise.[26,46,47] All studies that measured muscle soreness in the days following exercise reported greater muscle soreness after ECC_{max} than CON_{max} exercise, with CON_{max} exercise typically causing little or no muscle soreness.[9,10,21,26,27,46–48] The more prolonged loss in muscle strength after ECC_{max} exercise was likely the result of muscle damage[38,45] rather than sustained central or peripheral fatigue. Thus, because little to no muscle damage is present in the days following CON_{max} exercise,[9,21,26,46–48] the acute strength loss present at the end of CON_{max} exercise is likely not due to muscle damage. However, because muscle damage occurs in the days following ECC_{max} exercise,[26,46,47] the acute strength loss at the end of ECC_{max} exercise might be caused by a combination of both muscle damage and the same physiological factors that underlie the acute strength loss at the end of CON_{max} exercise. Thus, future research that seeks to clarify the mechanisms of muscle fatigue from ECC_{max} exercise, should consider participants' previous exposures to ECC exercise of the muscle investigated, as the "repeated bout effect"[38,45] might protect against damage-induced strength loss.

TABLE 2 Strength loss at the end of acute bouts of maximal eccentric (ECC_{max}) and concentric (CON_{max}) resistance exercise of *upper*-body and lumbar extensor muscles.

Muscle group Reference	Sample *n* M	F	Age (yr)	RE history	Protocol for ECC_{max} and CON_{max} exercise Sets	Reps	Velocity (°/s)	Inter-set rest (s)	Post test	% mean ± SD change in ECC, CON, or ISO strength at the end of exercise: ECC_{max} exercise ECC	ECC_{max} exercise CON	ECC_{max} exercise ISO	CON_{max} exercise ECC	CON_{max} exercise CON	CON_{max} exercise ISO
Elbow flexors															
Komi[9]	5	0	NR	NR	1	40	VV	n/a	LR	−46 ± 5	NR	NR	NR	−17 ± 8	NR
Linnamo[26] & Bottas[46]	8	0	21–33	NR	1	100	115	n/a	LR	−53 ± 10	−38 ± 11	NR	−31 ± 18	−50 ± 19	NR
Caruso[88]	4	12	NR	NR	4	12	60	60	LR	−88 ± 12	NR	NR	NR	−81 ± 14	NR
Loscher[89]	5	3	34	NR	1	143	45	n/a	LR	−66 ± NR	NR	NR	NR	−66 ± NR	NR
Piitulainen[27]	24	0	27	Yes	3	20	60	NR	IP	−35 ± NR	−34 ± NR	−30 ± 18	−19 ± NR	−22 ± NR	−22 ± 12
Muthalib[47]	7	3	29	No	10	6	90	120	IP	NR	NR	−55 ± 11	NR	NR	−20 ± 8
Beck[49]	13	0	24	Yes	6	10	30	NR	IP	−25 ± NR	NR	NR	NR	−26 ± NR	NR
Ye[52]	25	0	24	Yes	6	10	60	60	IP	−21 ± NR	NR	NR	NR	−17 ± NR	NR
Ye[53]	15	0	24	Yes	6	10	60	60	IP	NR	NR	−26 ± NR	NR	NR	−26 ± NR
Ochi[28]	12	0	28	No	5	6	30	90	IP	−29 ± NR	NR	−33 ± 14	NR	−21 ± NR	−23 ± 13
Latella[90]	11	3	27	Yes	3	10	40	180	IP	NR	NR	−31 ± NR	NR	NR	−23 ± NR
Shelley[71]	40	0	Y 24 O 68	No	5	10	180	10	IP	Y ~ −15 O ~ −10	NR	NR	NR	Y ~ −35 O ~ −18	NR
Nuzzo[5]	11	9	~30	Yes	4	20	VV	60	LR	M 56 ± 14 F 56 ± 11	NR	NR	NR	M − 56 ± 6 F −35 ± 9	NR
Yoshida[29]	15	0	22	Yes	1	30	30	n/a	IP	−32 ± 7	NR	−40 ± 9	NR	−50 ± 11	−43 ± 14
Elbow extensors															
Shelley[71]	40	0	Y 24 O 68	No	5	10	180	10	IP	Y ~ −15 O ~ −11	NR	NR	NR	Y ~ −40 O ~ −22	NR
Shoulder int rotat															
Mullaney[14]	9	1	33	NR	3	32	120	60	LR	−25 ± NR	NR	−11 ± NR	NR	−26 ± NR	−5 ± NR
Shoulder ext rotat															
Mullaney[14]	9	1	33	NR	3	32	120	60	LR	−24 ± NR	NR	−15 ± NR	NR	−32 ± NR	−7 ± NR
Lumbar extensors															
Hermann[48]	20	0	26	NR	1	50	30	n/a	LR	−30 ± NR	NR	NR	−24 ± NR	NR	NR

Abbreviations: CON, concentric; ECC, eccentric; F, female participants; IP, immediate post; ISO, isometric; LR, last repetitions; M, male participants; NR, not reported; RE, resistance exercise; SD, standard deviation; VV, variable velocity.

TABLE 3 Strength loss at the end of acute bouts of maximal eccentric (ECC_{max}) and concentric (CON_{max}) resistance exercise of *lower*-body muscles.

Muscle group	Sample				Protocol for ECC_{max} and CON_{max} exercise					% mean ± SD change in ECC, CON, or ISO strength at the end of exercise					
	n									ECC_{max} exercise			CON_{max} exercise		
Reference	M	F	Age (yr)	RE history	Sets	Reps	Velocity (°/s)	Inter-set rest (s)	Post test	ECC	CON	ISO	ECC	CON	ISO
Knee extensors															
Komi[10]	4	0	~24	NR	1	40	VV	n/a	LR	−35 ± NR	NR	NR	NR	−13 ± NR	NR
Gray[24]	0	16	24	NR	1	40	180	n/a	LR	−0.3 ± 18	NR	NR	NR	−48 ± 5	NR
Tesch[25]	14	0	33	NR	1	32	180	60	LR	+6 ± NR	NR	NR	NR	−60 ± NR	NR
DeNuccio[51]	3	12	23	NR	1	40	180	n/a	LR	−14 ± NR	NR	NR	NR	−30 ± NR	NR
Bilcheck[54]	0	16	26	No	3	39	120	60	LR	−3 ± NR	NR	NR	NR	−5 ± NR	NR
Crenshaw[21]	8	0	21–40	NR	1	Quit	50	n/a	LR	−23 ± NR	NR	NR	NR	−37 ± NR	NR
Hortobagyi[91]	0	42	22	No	1	40	60	n/a	LR	−8 ± 12	NR	NR	NR	−49 ± 24	NR
Grabiner[12]	10	2	~24	NR	3	25	50	60	IP	−13 ± 6	NR	NR	NR	−39 ± 7	NR
Kay[20]	11	1	25	NR	1	100 s	60	n/a	LR	+9 ± NR	NR	NR	NR	−58 ± NR	NR
Baroni[92]	17	0	17	NR	10	10	90	30	LR	−18 ± 8	NR	NR	NR	−36 ± 10	NR
Denis[22]	9	4	27	NR	1	Quit*	60	n/a	LR, IP	−30 ± NR	NR	−26 ± NR	NR	−50 ± NR	−20 ± NR
Shelley[71]	40	0	Y 24 O 68	No	5	10	180	10	IP	Y ~ −12 O ~ −12	NR	NR	NR	Y ~ −20 O ~ −50	NR
Knee flexors															
Shelley[71]	40	0	Y 24 O 68	No	5	10	180	10	IP	Y ~ −17 O ~ −20	NR	NR	NR	Y ~ −41 O ~ −35	NR
Ankle plantar															
Hortobágyi[13]	7	5	24	NR	5	10	30	60	LR	+2 ± NR	NR	NR	NR	−32 ± NR	NR
Ankle dorsiflex															
Pasquet[50]	8	2	22–44	NR	5	30	50	60	LR	−24 ± NR	NR	−34 ± NR	NR	−32 ± NR	−37 ± NR
Baudry[11]	22	16	Y 31 O 77	NR	5	30	50	60	LR	Y −27 ± NR O −42 ± NR	NR	NR	NR	Y −41 ± NR O −50 ± NR	NR

Abbreviations: CON, concentric; ECC, eccentric; F, female participants; IP, immediate post; ISO, isometric; LR, last repetitions; M, male participants; NR, not reported; O, older adults; SD, standard deviation; VV, variable velocity; Y, younger adults. *In this study, the mean quit time or time to exhaustion was greater for the ECC_{max} protocol (468 s) than CON_{max} protocol (287 s).

TABLE 4 Weighted means of acute strength change after maximal eccentric (ECC_{max}) and concentric (CON_{max}) resistance exercise of upper- and lower-body muscle groups.

Body area and mode of exercise	Acute strength change (%)					
	Specific to muscle action used in exercise (ECC or CON)			Not specific to muscle action used in exercise (ISO)		
	n	Mean	SD	*n*	Mean	SD
Upper-body muscles						
ECC_{max} exercise	266	−31.4	20.4	110	−30.5	11.3
CON_{max} exercise	266	−33.6	17.5	110	−22.6	10.5
Lower-body muscles						
ECC_{max} exercise	303	−13.6	12.2	33	−29.5	4.1
CON_{max} exercise	303	−39.7	13.3	33	−27.4	8.6

Abbreviations: CON, concentric; ECC, eccentric; ISO, isometric; SD, standard deviation.

3.1.3 | Physiological outcomes

Oxygen consumption[9,10] and blood lactate levels[10,26,27,46] were elevated during both ECC_{max} and CON_{max} resistance exercise. Blood lactate levels were usually elevated to the same extent with both types of exercise,[10,27,46] though one study reported greater levels after CON_{max} than ECC_{max} exercise.[26] Amplitudes of electromyographic (EMG) signals were similar between ECC_{max} and CON_{max} muscle actions,[9,20,26,27,48,49] though two studies reported greater EMG amplitudes during CON_{max} than ECC_{max} muscle actions.[25,50] EMG amplitudes decreased with repeated ECC_{max} and CON_{max} muscle actions in some studies[9,11,27,29,49–52] but not in others.[10,20,25,26,48,53] When reductions in EMG amplitude were present, usually there was no difference in the magnitude of decrease between ECC_{max} and CON_{max} exercise,[9,11,27,29,49,51,52] although one study reported a greater decrease in EMG after CON_{max} exercise.[50] Moreover, irrespective of whether EMG amplitude was reduced after ECC_{max} or CON_{max} exercise, this reduction (or lack thereof) was sometimes,[11,48,51] though not always,[49–51] less than the large reductions in strength that occurred with these fatiguing protocols. The incongruency between acute strength and EMG loss was likely due, in part, to the fact that EMG was often reported from just one muscle, whereas joint actions were performed by multiple muscles. Finally, Pasquet et al.[50] and Baudry et al.,[11] who measured various physiological outcomes (e.g., passive muscle twitch properties, voluntary activation, surface EMG), concluded that the mechanisms of force loss from ECC_{max} and CON_{max} exercise of the ankle dorsiflexors were largely peripheral (e.g., Ca^{2+} excitation-contraction coupling) rather than neural in origin.

3.2 | Coupled ECC_{max}-CON_{max} resistance exercise

We identified seven studies[5,6,23,29,54–56] that examined changes in ECC and CON phase muscle strength during *coupled* ECC_{max}-CON_{max} resistance exercise (Table 5). Four of these studies were of the elbow flexors,[5,6,29,55] one was of the knee extensors,[54] and two were of the ankle plantarflexors.[23,56] Some of these studies included comparative groups of ECC_{max} and/or CON_{max} exercise, though results from these comparative groups are not presented in Table 5.

The first finding was that coupled ECC_{max}-CON_{max} exercise typically caused similar levels of strength loss in the ECC and CON phases. Exceptions to this were the studies by Nuzzo and colleagues,[5,6] who found greater acute strength loss in the CON than ECC phase. The studies by Nuzzo and colleagues[5,6] involved exercise and strength testing on a connected adaptive resistance exercise machine, whereas all other studies[23,29,54–56] involved exercise and strength testing on isokinetic dynamometers. The reason why the connected adaptive resistance exercise machine induced greater acute strength loss in the CON than the ECC phase during coupled ECC_{max}-CON_{max} exercise is unclear. With isokinetic dynamometers, the velocity of movement is constant throughout the ECC and CON phases, whereas with the connected adaptive resistance exercise machine, muscle actions occur within a range of velocities that are not necessarily the same in the ECC and CON phases. How this might explain the above findings is uncertain other than to note that velocity of movement impacts acute strength loss.[57–59]

The second finding was that, in the elbow flexors, acute strength loss in the CON phase was greater after ECC_{max}-CON_{max} exercise than from CON_{max} exercise.[5,29] However, with regard to *ECC phase* acute strength loss, Nuzzo et al.[5] observed little difference between ECC_{max}-CON_{max} and ECC_{max} exercise of the elbow flexors, whereas Yoshida et al.[29] observed greater ECC phase acute strength loss after ECC_{max}-CON_{max} exercise than ECC_{max} exercise. A notable difference between the studies was, again, the exercise equipment used (connected adaptive resistance exercise machine[5] versus isokinetic dynamometer[29]).

In other muscle groups, too few studies have been conducted to make firm conclusions. In the knee extensors, Bilcheck[54] observed little or no acute strength loss at the end of coupled ECC_{max}-CON_{max} exercise and from separate ECC_{max} and CON_{max} exercise protocols. In the ankle plantarflexors, Svantesson et al.[56] observed a 33% acute strength loss in the CON phase of ECC_{max}-CON_{max} exercise and a 25% acute strength loss in the CON phase of CON_{max} exercise, which was not different statistically.

Overall, the existing, albeit limited, literature on coupled ECC_{max}-CON_{max} exercise suggests that when the exercise is performed at a constant velocity using isokinetic dynamometry, similar levels of acute strength loss can be expected in the ECC and CON phases. However, the magnitude of acute strength loss experienced during the CON phase can be expected to be greater after ECC_{max}-CON_{max} exercise than CON_{max} exercise when the exercise is performed by the elbow flexors.

3.3 | Submaximal ECC and CON resistance exercise with equal *relative* loads

In the studies summarized above, fatigue was quantified as the percent loss in strength from before to after *maximal* exercise. A second way to examine fatigue from ECC and CON resistance exercise is to first measure the ECC and CON one-repetition maximums (1RM) and then compare the number of ECC and CON repetitions that can be completed when repetitions are performed to failure with equal *relative* loads. Many previous studies have documented that when the same *absolute* load is lifted, the following occurs: (a) more repetitions are completed during ECC than CON exercise,[60] (b) time-to-exhaustion is longer during ECC than CON exercise,[61] and (c) measures of cardiovascular demand/stress (e.g., heart rate, blood pressure, oxygen consumption) and perceived exertion are lower during ECC than CON exercise.[61–66] However, because ECC strength is approximately 40% greater than CON strength,[18] when a participant lifts the same *absolute* loads, the load is heavier in relative terms (i.e., %1RM) during the CON than ECC exercise. Maximal ECC strength assessments are challenging to administer with traditional resistance exercise equipment but emerging technologies appear to make these assessments more feasible.[4–7] Thus, exercise prescriptions based on the ECC maximum might be more common in the future, and the %1RM-repetition relationship should not be assumed to be the same for ECC and CON resistance exercise.

We identified three studies that examined ECC versus CON repetitions-to-failure with equal *relative* loads.[67–69] These studies were of the barbell bench press,[68] dumbbell bicep curl,[69] and isokinetic knee extension.[67] The loads tested ranged from 60 to 95% of the muscle action-specific 1RM. In the study by Kelly et al.,[68] 30 healthy men completed ECC and CON repetitions-to-failure tests in the bench press with loads equal to 60, 70, 80, and 90% of 1RM. For the 90% 1RM load comparison, participants completed, on average, three more repetitions during ECC (8 repetitions) than CON tests (5 repetitions). However, no statistically significant difference in the number of repetitions completed in the two conditions was observed for the 80% (~11 repetitions), 70% (~18 repetitions), and 60% 1RM tests (~27–30 repetitions).

In the study by Shibata et al.,[69] 16 healthy men completed ECC and CON repetitions-to-failure tests for the biceps curl with dumbbells equal to 70%, 80%, 90%, and 95% 1RM. In general, participants performed more ECC than CON repetitions. With the 70% 1RM load, the mean number of ECC and CON repetitions completed by participants was 34 and 21, respectively. With the 80% 1RM load, the mean ECC and CON repetitions completed by participants were 22 and 12, respectively. With the 90% 1RM load, the mean ECC and CON repetitions completed by participants were 10 and 5, respectively. With the 95% 1RM load, the mean ECC and CON repetitions completed by participants were 7 and 3, respectively.

In the study by Cherouveim et al.,[67] 10 healthy men completed ECC and CON repetitions-to-fatigue tests for the isokinetic knee extension exercise with a resistance equal to 60% of the maximum. The dynamometer provided torque feedback, and participants were encouraged to reach the 60% of maximum target. The fatigue test ended when participants could not achieve the 60% target on three consecutive repetitions. The participants completed significantly more ECC than CON repetitions (means: 122 vs 78 repetitions, respectively).

Overall, the existing, albeit limited, literature on the number of ECC and CON repetitions that can be completed with equal *relative* loads has shown that equal or more ECC repetitions can be performed depending on the exercise and the magnitude of the relative load. More ECC than CON repetitions can be performed during the biceps curl at 70–95% 1RM, the knee extension at 60% of peak torque, and the bench press at 90% 1RM. However, no difference appears to exist in the number of ECC versus CON bench press repetitions that can be performed at 60–80% 1RM, and perhaps this relates to greater coordination requirements for the ECC phase of the bench press compared to the single-joint exercises.

TABLE 5 Strength loss at the end of acute bouts of maximal eccentric, maximal concentric (ECC_{max}-CON_{max}) resistance exercise of the elbow flexors, knee extensors, and ankle plantarflexors.

	Sample			Protocol for ECC_{max} and CON_{max} exercise						% mean ± SD change in ECC, CON, or ISO strength at the end of exercise		
	n											
Muscle group Reference	M	F	Age (yr)	RE history	Sets	Reps	Velocity (°/s)	Inter-set rest (s)	Post test	ECC	CON	ISO
Elbow flexors												
Kawakami[55]	10	0	13	NR	1	50	30	n/a	LR, IP	~ −45 ± NR	~ −45 ± NR	−37 ± 13
Nuzzo[6]	12	9	~30	Yes	1	25	VV	n/a	LR	M −64 ± 12 F −44 ± 8	M −78 ± 7 F −63 ± 13	NR
Nuzzo[5]	11	9	~30	Yes	4	10	VV	60	LR	M −63 ± 8 F −49 ± 16	M −77 ± 5 F −66 ± 12	NR
Yoshida[29]	15	0	22	Yes	1	30	30	n/a	LR, IP	−59 ± 9	−62 ± 9	−57 ± 9
Knee extensors												
Bilcheck[54]	0	16	26	No	3	30	120	60	LR	−1 ± NR	−3 ± NR	NR
Ankle plantarflex												
Svantesson[56]	0	10	24	NR	1	~48	60	n/a	LR	−36 ± 16	−33 ± 16	NR
Svantesson[23]	C 7 SP 7	0	51–64	NR	1	Quit	60	n/a	LR	C −30 ± 11 SP −30 ± 13	C −31 ± 8 SP −32 ± 13	NR

Abbreviations: C = controls; CON, concentric; ECC, eccentric; F, female participants; IP, immediate post; ISO, isometric; LR, last repetitions; M, male participants; NR, not reported; SD, standard deviation; SP, stroke patients; VV, variable velocity.

3.4 | Future research

The current review has revealed that most studies on muscle fatigue from ECC_{max} and CON_{max} resistance exercise were conducted on the elbow flexors and knee extensors. The elbow flexors appear to be more susceptible to acute strength loss from ECC_{max} exercise than the knee extensors, and this is perhaps due to differences in the architectures and daily uses of these muscles. Future research can continue to explore how muscle architecture and use-history impact acute strength loss and muscle damage from ECC_{max} and CON_{max} resistance exercise. Training studies could be used to determine if muscle fatigability from ECC_{max} versus CON_{max} exercise changes after several weeks of resistance exercise.[37] Similarly, cross-sectional studies could be used to determine if muscle fatigability from ECC_{max} and CON_{max} exercise differs between individuals who have different levels of experience with resistance exercise.[36,70] In the current review, exploration of the potential impact of resistance exercise history on muscle fatigability from ECC_{max} and CON_{max} exercise was not possible as 60% of papers did not report information on resistance exercise history. Thus, as some evidence suggests that individuals with histories of resistance exercise are less fatigable than those without histories of resistance exercise,[36,70] we encourage information on resistance exercise experience to be collected in future research. Such information might include number of years of experience and number of days per week of current participation. Cross-sectional studies can also continue to explore whether sex[5,6] and age[11,71] correlate with muscle fatigability from these protocols, as the current literature is composed of studies involving mostly healthy male participants who are between 20 and 40 years old. Understanding the extent to which sex, age, and muscle group impact muscle fatigability during ECC and CON exercise could further inform resistance exercise guidelines for ECC and CON exercise. Other recommendations for future research include, when feasible, large sample sizes, multiple strength tests, and assessments of muscle groups other than the elbow flexors and knee extensors (e.g., knee flexors).

Finally, prescriptions for numbers of repetitions at percentages of the 1RM have historically been based on the %1RM-repetition relationship for the *CON* 1RM.[72,73] However, as the current review highlights, the number of ECC repetitions that can be completed at a given relative load is sometimes higher than the number CON repetitions that can be completed at that same relative load.[67–69,74] Thus, further research will be required to determine the %1RM-repetition relationship for ECC resistance exercise in various populations and across various exercises.

3.5 | Practical applications

Results from the current overview provide practical implications for resistance exercise prescriptions, particularly as ECC resistance exercise seems to have increased in popularity in recent years and given that there has been an emergence of exercise equipment to facilitate ECC resistance exercise prescriptions.[4,7,75] Skeletal muscles are approximately 40% stronger during ECC than CON muscle actions,[18] cardiovascular stress and perceptions of effort are lower during ECC than CON resistance exercise at equal absolute workloads,[61–66,76] and weeks of ECC resistance exercise increases muscle size and strength.[1,77–81] Thus, ECC resistance exercise is believed to be an effective way for improving health and fitness in healthy adults as well as in older adults and those who have medical conditions that might require an exercise stimulus with less cardiovascular stress and lower perceptions of effort.[75,82] ECC resistance exercise also appears to prevente and rehabilitate some muscle and tendon and injuries.[82–85] Nevertheless, isolation of the CON and ECC phases of resistance exercises with free weights, weight stack machines, and plated-loaded machines is difficult. Isokinetic dynamometers are better-suited to accomplish this, and their frequent appearance in the literature overviewed herein is evidence of this. However, isokinetic dynamometers, due to their size, cost, and other limiting factors, have not been widely adopted by exercise practitioners.[2,3] New ECC resistance exercise technologies advance some of the limitations of isokinetic dynameters, permitting independent maximal strength assessments and exercise prescriptions for the CON and ECC phases of resistance exercises.[4–7] Thus, findings from the current review have potential implications for resistance exercise prescriptions that incorporate such equipment or isokinetic dynamometry to deliver CON or ECC resistance exercise.

Perhaps the main implication of the current work is that ECC resistance exercise prescriptions should account for the muscle group being exercised. The elbow flexors are more susceptible to acute strength loss and damage from ECC exercise than are muscles of the lower limbs. Thus, volumes or intensities of ECC exercise should be lower for the elbow flexors than for the knee extensors, ankle dorsiflexors, and ankle plantarflexors, if less muscle damage and fatigue are desired. This might be particularly important for novice exercisers and individuals who have medical conditions that might be exacerbated by muscle damage and fatigue. A second implication is that cardiovascular stress during ECC exercise at a given *absolute* load will be less than during CON exercise.[61–66,76] Thus, as mentioned above, ECC resistance exercise might be well-suited for patients with cardiovascular or other medical conditions.[75,82] Third, at a given absolute load, individuals can complete more ECC than CON repetitions. Thus, predictions of the number of repetitions that can be completed at particular percentages of the *CON* 1RM (i.e., the test often used to guide prescriptions), should not be expected to be the same for ECC resistance exercise. Fourth, when prescribing target numbers of CON or ECC repetitions to be completed at the same *relative* loads, individuals, in some cases, will *still* be able to complete more ECC than CON repetitions. Fifth, acute bouts of ECC_{max}, CON_{max}, and coupled ECC_{max}-CON_{max} resistance exercise cause significant acute reductions in muscle strength. In the case of ECC_{max} resistance exercise, this strength loss is often not recovered in the hours or days following exercise due to muscle damage. Thus, prescriptions of ECC_{max} resistance exercise should consider the individual's resistance exercise history, the muscle group exercised, and the potential impact of such strength loss on performance in upcoming sport practices and games.

3.6 | Limitations

All of the above information should be considered in light of the limitations of the current work. First, the current work was a thorough overview, but it was not a systematic review or meta-analysis. Investigator bias is thought to be more likely with overviews than systematic reviews.[15] Thus, our interpretations of the findings should be considered with caution. Nevertheless, we believe that we have compiled into one source an amount of data on responses to acute ECC_{max} and CON_{max} resistance exercise that is significantly larger than any previous attempt. Moreover, a purpose of overviews and similar types of reviews, such as narrative and scoping reviews, is to provide a general sense of the methods and results associated with the current literature and to also propose new hypotheses and suggest directions for future research.[15] We believe we have accomplished that.

A second limitation of the current overview is that the average sample size across studies was 16 participants, and heterogeneity existed in terms of some of the methods used. Small sample sizes are a problem in exercise and sports science research,[86,87] and they are potentially problematic here because they likely make estimates of effects less precise than they would otherwise be with larger samples. Such problems are also likely compounded by the heterogeneity in study methods. Thus, as we did not formally assess study quality, our results and conclusions should, again, be interpreted with caution.

3.7 | Conclusion

Based on results from 30 studies that reported on acute strength loss from bouts of ECC_{max} and CON_{max} resistance exercise, we conclude the following: (a) both ECC_{max} and CON_{max} exercise cause acute strength loss by the end of exercise; (b) the acute strength loss exhibits a plateauing or strength preservation behavior, such that it rarely exceeds 60% of baseline strength; (c) acute strength loss is not exclusive to the muscle action type used during exercise, but in some studies, it is most pronounced in the muscle action type used during exercise (i.e., specificity of fatigue); and (d) the magnitude of acute strength loss from ECC_{max} exercise is less for the knee extensors than elbow flexors, likely due to the different architectural features and daily functions of these muscle groups.

Based on seven studies on coupled ECC_{max}-CON_{max} resistance exercise, we conclude the following: (a) coupled ECC_{max}-CON_{max} isokinetic muscle actions cause similar levels of acute strength loss in the ECC and CON phases of exercise; (b) when exercise is performed by the elbow flexors, the magnitude of acute strength loss experienced during the CON phase of ECC_{max}-CON_{max} exercise can be expected to be greater than experienced during the CON phase of CON_{max} exercise. Based on three studies on muscle fatigue during submaximal ECC and CON repetitions with equal *relative* loads, we conclude that equal or more ECC repetitions can be completed than CON repetitions depending on the exercise and relative load lifted. Nevertheless, most of the studies summarized in the current review have involved healthy young male participants completing isokinetic muscle actions of the elbow flexors or knee extensors. Further research can explore muscle fatigue from ECC and CON resistance exercise in different and larger samples and in different muscle groups and exercises.

4 | PERSPECTIVES

The current overview has helped to answer a research question that has remained unanswered for several decades: do repeated ECC_{max} and CON_{max} muscle actions induce similar magnitudes of acute strength loss (i.e., muscle fatigue)? The present review has clarified that the answer depends on the muscle group exercised. When ECC_{max} and CON_{max} exercise are performed by the elbow flexor muscles, both types of exercise cause significant yet similar magnitudes of acute strength loss. However, when ECC_{max} and CON_{max} exercise are performed by the knee extensor muscles, acute strength loss from ECC_{max} exercise is less than from CON_{max} exercise. We speculate that this "protection" of the knee extensors from ECC exercise-induced muscle fatigue (and damage) is due to the different architectures and daily uses of these muscles compared to the elbow flexors. We also discovered that when participants complete acute

ECC and CON resistance exercise with equal *relative* loads, equal or more ECC repetitions can be completed, depending on the exercise and relative load prescribed. Overall, the results indicate that prescriptions of ECC and CON exercise should not necessarily be the same. They should account for potential interactions between exercise mode and muscle group, relative load, exercise volume, and previous exposure to ECC exercise. Sex and age might also warrant consideration, but more research with female and older adult participants is needed.

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