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REVIEW ARTICLE

# Accentuated Eccentric Loading for Training and Performance: A Review

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**Abstract** Accentuated eccentric loading (AEL) prescribes eccentric load magnitude in excess of the concentric prescription using movements that require coupled eccentric and concentric actions, with minimal interruption to natural mechanics. This method has been theorized to potentiate concentric performance through higher eccentric loading and, thus, higher concentric force production. There is also evidence for favorable chronic adaptations, namely shifts to faster myosin heavy chain isoforms and changes in IIx-specific muscle cross-sectional area. However, research concerning the acute and chronic responses to AEL is inconclusive, likely due to inconsistencies in subjects, exercise selection, load prescription, and method of providing AEL. Therefore, the purpose of this review is to summarize: (1) the magnitudes and methods of AEL application; (2) the acute and chronic implications of AEL as a means to enhance force production; (3) the potential mechanisms by which AEL enhances acute and chronic performance; and (4) the limitations of current research and the potential for future study.

**Key Points**

Accentuated eccentric loading (AEL) prescribes eccentric load magnitude in excess of the concentric prescription using movements that require coupled eccentric and concentric actions, with minimal interruption to natural mechanics.

The current research concerning both the acute responses and chronic adaptations to AEL is inconclusive, but suggests it may be a superior method by which to enhance strength and power performance.

Due to the potential benefits, but inconsistency and paucity of current literature, it would be advantageous for future research to first examine the acute response to practically applicable means and magnitudes of AEL.

## 1 Introduction

It has been well documented that progressive resistance training programs enhance force and power production capabilities [1, 2]. These improvements are largely attributed to changes in skeletal muscle cross-sectional area (CSA) and an array of neuromuscular adaptations [3–6]. Traditional loading prescribes equivalent absolute loads for the concentric and eccentric portion of an exercise, but it should be noted that skeletal muscle is capable of as much as 50% more force production during maximum eccentric contractions compared to concentric contractions [7–9]. Therefore, loads encountered during traditional resistance

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exercise loading are limited by concentric strength, leading practitioners to turn to alternative methods in order to more optimally prescribe intensity relative to the force generation capabilities of eccentric muscle action.

Researchers and practitioners have employed eccentric-only training in an attempt to properly load the eccentric action by eliminating the limitation of concentric force production. The skeletal muscle response is largely proportional to the magnitude of mechanical stimulus and a larger response has been observed in eccentric-only training, especially with regard to strength and size changes [10, 11]. Further, selective recruitment of high-threshold motor units has been observed in eccentric-only training [12]. However, eccentric-only training may be limited in its transfer to sport due to a lack of task-specificity and limited involvement of the stretch-shortening cycle (SSC) [10, 13].

Therefore, it is logical for researchers and coaches to seek a training means that applies an overload during eccentric action, but also enhances specificity and employs the SSC, especially considering the involvement of the SSC in a wide variety of sporting actions. Accentuated eccentric loading (AEL) prescribes eccentric loads in excess of the concentric prescription of movements that require coupled eccentric and concentric actions, while creating minimal interruption in the natural mechanics of the selected exercise. For example, a coach may load a back squat to a prescribed weight for the eccentric portion, and then manually remove the weight prior to the initiation of the concentric action. This method has been theorized to enhance adaptation through higher eccentric loading and, thus, higher eccentric and concentric force production. With this method of training, there is evidence for shifts to faster myosin heavy chain (MHC) isoforms and more favorable changes in IIx-specific muscle CSA [14, 15]. These changes have often been accompanied by improvements in force and power production [15–21]. Furthermore, previous findings report favorable changes in jumping and throwing actions, suggesting AEL may transfer well to sport tasks and performance when applied to both strength and plyometric training exercises [22–29]. However, research concerning the acute and chronic responses to AEL is currently inconclusive, likely due to inconsistencies in subjects, exercise selection, load prescription, and method of providing AEL loading strategy [14, 15, 17, 20–23, 27, 29–34].

Therefore, the purpose of this review is to examine potential mechanisms and applications of AEL as a training intervention. The review summarizes: (1) the magnitudes and method of loading; (2) the acute and chronic implications of AEL as a means to enhance maximal strength and explosive performance; (3) the potential mechanisms by which AEL enhances acute and chronic performance; and (4) the limitations of current research and the potential for future study.

## 2 Literature Search Methods

The search was conducted in December 2016 using the following databases: EBSCO, Google Scholar, PubMed, ScienceDirect, and SPORTDiscus. There were no limitations regarding publication date. Three authors independently and separately conducted the search and retrieval of manuscripts through the search terms “accentuated eccentric load,” “eccentric accentuated load,” “enhanced eccentric load,” and “eccentric overload.” Only original empirical articles published in peer-reviewed journals with full document availability were considered for review. A total of 30 original papers met these criteria, with papers utilizing flywheel resistance excluded from consideration. This exclusion was due to the inherent dependency of the flywheel eccentric load on concentric output and the current lack of research quantifying progressive load under this method.

## 3 Loading Considerations

Prior studies have utilized various implements to apply AEL, including elastic bands, counterbalance weight systems, weight releaser devices, computer-driven adjustments, and manual adjustments by either the athlete or practitioner. The chosen implementation appears dependent on practicality, the magnitude of eccentric load prescription, or desired outcome. For example, lower magnitude AEL prescriptions tend to use manual adjustments by either the coach or the athlete, while higher magnitude AEL prescriptions use weight releasers or are technology driven. However, there has been little consistency in the existing literature regarding the magnitude of eccentric overload or the resulting rate of eccentric phase descent for the exercise prescribed. Differences in these loading considerations likely alter the stimulus of AEL and may have implications for acute performance and chronic adaptations. Therefore, a discussion of loading considerations—primarily the magnitude and the means of application—and their effects is warranted. Theoretically, AEL should increase the subsequent concentric action following acute application of eccentric overload, but changes will likely be directly related to the characteristics and context of application. Further, it is plausible that the magnitude of the load may have a more profound influence on adaptation based on previously established neuromuscular and architectural changes observed from high intensity eccentric contractions [10, 12, 35–39].

Supramaximal loading, which prescribes an eccentric load in excess of concentric 1RM, is the most commonly utilized strategy of AEL. The rationale is based upon the higher force generation capabilities and selective recruitment of high threshold motor units during eccentric muscle actions, potentially eliciting neuromuscular responses leading to desired adaptations, which will be discussed later in further detail [12, 39]. Saxton and associates provide a theoretical basis for supramaximal eccentric loading to potentially induce greater changes in muscle CSA through increased tension or metabolic damage [40]. Several investigations have attempted to substantiate the potential implications of supramaximal AEL to improve strength, force output, or muscle CSA [14–20, 30, 33, 34].

Despite a theoretical basis, supramaximal AEL has yielded inconsistent results regarding acute responses and chronic adaptations. Favorable acute changes in maximal strength performance have been demonstrated [16, 17]. For example, Doan and associates found significantly enhanced concentric performance in the bench press using supramaximal AEL in moderately trained males [17]. They used weight releasers to impart an eccentric overload equivalent to 105% concentric 1RM [17]. The concentric prescriptions started at 100% of preliminarily tested concentric 1RM, followed by attempts with progressively increased concentric loads of 2.27, 4.55, and 6.82 kg if prior attempts were successful. Doan and colleagues provide some of the earliest evidence of the potentiating effect that supramaximal AEL may have on subsequent concentric performance. Some theoretical mechanisms that may contribute to performance improvements resulting from supramaximal eccentric loading include attenuated reflex inhibition or increased myosin light chain (MLC) phosphorylation [41, 42]; however, supramaximal eccentric loading may require careful consideration. Contractile history can have both fatiguing and potentiating effects on skeletal muscle performance [43]. Providing a stimulus that elicits potentiating effects without fatiguing the athlete is one of the challenges facing supramaximal AEL prescription [44]. Ojasto and Häkkinen reported that subsequent 1RM and concentric force production both significantly decreased using a range of supramaximal AEL (105–120% eccentric overload) in the bench press [20]. They proposed this decline in performance was partially due to fatigue and suggest the potential need to use smaller eccentric loads [20]. These inconsistent results and methods in the literature using supramaximal AEL require further investigation, but also have led to the study of other AEL strategies, particularly in more recent studies.

The magnitude of the eccentric load during submaximal AEL is prescribed relative to the concentric movement; however, the eccentric overload does not exceed concentric 1RM. This relative loading strategy is often used in situations where changes in explosive and plyometric performance are anticipated [20, 22–26]. Submaximal AEL may also include movements more common in sports and has more consistently yielded favorable performance enhancements compared to supramaximal AEL, especially in acute interventions. Ojasto and Häkkinen found peak power and neuromuscular activity were both enhanced through submaximal AEL, but was not related to a specific submaximal prescription [20]. Though a range of submaximal AEL conditions were used (eccentric/concentric: 60/50% 1RM, 70/50% 1RM, 80/50% 1RM, 90/50% 1RM), the load condition where the highest peak power outputs and muscle activation were subject specific [20]. Therefore, there may be an individualized response to AEL, with factors such as training experience, age, strength-level, or physiological characteristics influencing the outcomes. Sheppard and Young, instead of prescribing relative percentages, prescribed submaximal AEL with fixed absolute loads of 20, 30, and 40 kg over a 40-kg concentric load [29]. Subsequent bar displacement and peak acceleration values of the bench throw were both significantly higher following AEL [29]. In accordance with the findings of Ojasto and Häkkinen, a notable finding of this study [29] is that the AEL prescription yielding the greatest performance enhancement appears to be dependent on maximal strength, with stronger subjects requiring greater eccentric overload to elicit optimal concentric performance.

Increased velocity during the eccentric phase enhances force production and power output during the subsequent concentric phase [45, 46]. The rapid eccentric phase of plyometric exercises may be further enhanced via AEL, with observed improvements in concentric force production, jump height, and throw performance [25, 29, 47]. Accentuated eccentric loading strategies that overload the eccentric portion of plyometric exercises, though fitting within the scope of the operational definition of AEL of the present review, may potentiate concentric performance primarily via increasing the rate of the eccentric phase [48], which could be considered an interruption to the natural mechanics of the movement. Increasing the eccentric load during plyometric movements may increase the rate of eccentric force production and impulse of the SSC, subsequently enhancing concentric force and power output [49, 50]. Overloading plyometric exercises is an advanced application of AEL, as the athlete needs to have the capability to store and return elastic energy quickly during the concentric portion of the jump with minimal amortization phase [51, 52]. This may require higher levels of strength and connective tissue development, and therefore such an application of AEL may be more appropriate for more advanced athlete populations.

One potential implementation involves elastic bands, which can be used to increase eccentric velocity during countermovement (CMJ) and drop jumps [22, 23]. Accentuated eccentric loading estimated to provide an additional resistance equivalent to 30% of body mass during the eccentric phase of the CMJ increased peak power (23.21%), peak concentric force (6.34%), peak concentric velocity (50.00%), and jump height (9.52%) compared to standard CMJ in resistance and plyometric trained subjects [23]. Elastic bands providing downward tension during the drop and eccentric phases of the drop jump increased eccentric impulse, eccentric rate of force development (RFD), and quadriceps muscle activity in a manner similar to increased drop jump height [22]. Aboodarda and colleagues suggest that the use of elastic bands during drop jumps may substitute for increases in drop height, theoretically minimizing injury risk associated with high drop heights [48]. However, if the center of mass is still accelerating similarly due to the elastic bands when compared to a higher drop height, the ground reaction forces may still be similar. Moore and associates provide a more precise AEL application in the jump squat, examining the potentiating effects eccentric overloads of 20, 50, and 80% of back squat 1RM coupled with a concentric phase held constant at 30% of back squat 1RM [31]. The load spectrum used by this group failed to provide supporting evidence that AEL acutely enhanced force, velocity, or power outputs of the concentric phase of the jump squat [31]. The lack of observed potentiation may be due to the subjects' lack of familiarity with jumping tasks. Though the subjects were resistance trained, there was no indication as to whether plyometric training was included in their training prior to participation in the study [31]. This is in contrast to the subjects in the study by Aboodarda and colleagues, who were participating in both resistance training and plyometric training prior to study involvement [22].

Like supramaximal AEL, the lack of consensus using submaximal AEL may be due to subject and methodological differences between studies, such as means (e.g., weight releasers, manual adjustment) or magnitude of eccentric overload. From a practical standpoint, decisions regarding implementation of AEL may be driven by feasibility just as much as supporting evidence. Some methods may be financially restrictive, overly cumbersome, or have little application or transfer to athletic performance. These limitations notwithstanding, existing research suggests the magnitude of AEL should, to some extent, reflect the strength level of the subject and exercise selection in addition to the desired effects. Researchers have typically used supramaximal eccentric overloads during strength and hypertrophy training, yielding mixed results. With similar levels of consistently favorable outcomes, submaximal eccentric overloads are typical in studies examining explosive performance or power output. Therefore, identifying and determining the influence of potential factors may allow for more precise and individualized submaximal AEL prescription. Coaches and practitioners, then, must first consider the most practical and suitable method and load prescription strategy for the desired performance outcome given the population being trained.

## 4 Performance Implications for Accentuated Eccentric Loading (AEL)

### 4.1 Maximum Strength

As previously discussed, AEL has been suggested as a potential training modality for athletes due to an association with improvements in force production [17, 21], RFD, [23] velocity [27], power [23], athletic performance, [23, 27] and injury prevention [53]. Force production underpins all of the aforementioned enhancements to performance and completion of both general and specific skills [54]. The limited number of studies using AEL to improve force production have provided varying results apparently due to differing protocols used in the investigations (Tables 1, 2). In a 7-day study by Hortobagyi and colleagues, the investigators demonstrated twofold greater strength gains in the knee extensors using an additional 40–50% eccentric overload compared to traditional loading in untrained females [47]. The drastic strength gains (27%) observed during this study may be due to the novelty of stimulus applied to an untrained population. Such results should be explored further as the adaptive responses may have been similar between AEL and traditional loading with a longer training period. Doan and colleagues provided additional evidence, finding increases in bench press 1RM of 2.27–6.80 kg in the subjects using supramaximal AEL of 105% of concentric 1RM during the eccentric phase compared to the traditional loading [17]. As previously discussed, the acute enhancement of force production capabilities observed may be induced via several potential mechanisms, including increased calcium sensitivity and increased neural drive due to the eccentric overload provided by AEL [42]. However, AEL conditions during attempts to potentiate force production acutely must consider the fatigue elicited by the selected AEL strategy [43, 44].

Demonstrating the potential importance of load prescription as it relates to maximal strength expression, Ojasto and Häkkinen performed a bench press protocol that employed AEL in the bench press with physically active males [20]. This protocol compared four different loading schemes for the eccentric portion with 100, 105, 110, and 120% of the concentric 1RM and failed to show improvements in concentric 1RM with AEL compared to an isokinetic loading protocol. Though relatively strong subjects were used, it appears that the eccentric overload spectrum employed by Ojasto and Häkkinen elicited a detrimental effect on maximal strength expression, likely

**Table 1** Acute performance responses to accentuated eccentric loading. Cohen's *d* effect size indicated in parentheses in the Results columns

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|
| Aboodarda et al. [23] | 15 males (22.6 ± 5.3 years) | 6 months | Elastic bands | +20/30% body mass | BW CMJ | CMJ | Jump height<br>Peak velocity<br>Peak force<br>Peak power | Jump height / Peak velocity<br>ACMJ20: +5.3% (0.67) / +0% (0.0)<br>ACMJ30: +10.5% (1.33) / +16.7 (0.38)<br>Peak force / Peak power<br>ACMJ20: +0.6% (0.04) / +6.4% (0.41)<br>ACMJ30: +2.9% (0.06) / +30.2% (0.66) |
| Aboodarda et al. [22] | 15 males (24.7 ± 5.7 years) | 6 months 2× BW back squat | Elastic bands | +20–30% body mass | BW drop jump | Drop jump | Jump height<br>Takeoff velocity | Jump height<br>20 cm—DJ20: 0%, (0.0), DJ30: −2.4% (−0.14)<br>35 cm—DJ20: +2.5% (0.14), DJ30: +2.5% (0.14)<br>50 cm—DJ20: +2.6% (0.14), DJ30: +2.6% (0.14)<br>Takeoff Velocity<br>20 cm—DJ20: −0.4% (−0.04), DJ30: −0.7% (−0.08)<br>35 cm—DJ20: +0.4% (0.04), DJ30: 0% (0.0)<br>50 cm—DJ20: +1.1% (0.12), DJ30: +1.1% (0.12) |

**Table 1** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Variables analyzed | Results | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bridgeman et al. [24] | 8 males (26.3 ± 5.1 years) | >2 years | Manual adjustment by athlete | +20% body mass | Pre/post | Drop jump (52 cm box) | Static jump | CMJ jump height | | |
| | | | | Session 1: 5 × 6 | | | CMJ | | 5 × 6 | 5 × 10 |
| | | | | Session 2: 5 × 10 | | | Squat force | Post | −5% (−0.43) | +0.1% (0.01) |
| | | | | | | | | 1 h | −2.2% (−0.19) | +1.9% (0.19) |
| | | | | | | | | 24 h | −0.2% (−0.02) | +5.2% (0.52) |
| | | | | | | | | 48 h | +3.3% (0.29) | +3.2% (0.32) |
| | | | | | | | | Static jump height | | |
| | | | | | | | | | 5 × 6 | 5 × 10 |
| | | | | | | | | Post | −4.0% (−0.27) | +0.3% (0.02) |
| | | | | | | | | 1 h | −1.7% (−0.12) | +4.1% (0.35) |
| | | | | | | | | 24 h | +1.3% (0.09) | +6.1% (0.52) |
| | | | | | | | | 48 h | +4.6% (0.31) | +10.5% (0.89) |
| | | | | | | | | CON squat force | | |
| | | | | | | | | | 5 × 6 | 5 × 10 |
| | | | | | | | | Post | −4.3% (−0.14) | −5.4% (−0.19) |
| | | | | | | | | 1 h | −7.3% (−0.25) | −9.5% (−0.34) |
| | | | | | | | | 24 h | +1.7% (0.06) | +6% (0.21) |
| | | | | | | | | 48 h | +1.5% (0.05) | +10.2% (0.37) |
| | | | | | | | | ECC squat force | | |
| | | | | | | | | | 5 × 6 | 5 × 10 |
| | | | | | | | | Post | −10.2% (−0.35) | +2.4% (0.09) |
| | | | | | | | | 1 h | −4.4% (−0.15) | −0.2% (−0.01) |
| | | | | | | | | 24 h | −4.6% (−0.16) | +6.9% (0.25) |
| | | | | | | | | 48 h | −7.2% (−0.25) | +14.8% (0.54) |

**Table 1** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|
| Bridgeman et al. [25] | 12 males (25.4 ± 3.5 years) | >2 years<br>1.5 BW back squat | Manual adjustment by athlete | +10/20/30% body mass additional | Unloaded DJ, CMJ | Drop jump | Drop jump height<br>Drop jump flight time<br>CMJ jump height | Drop jump height<br>BW > 10%/30% (0.39, 0.34)<br>20% > 10%/30% (0.37, 0.32)<br>Drop jump flight time<br>BW > 10/30% (0.38, 0.34)<br>20% > 10/30% (0.36, 0.32)<br>CMJ jump height<br>20% > Pre/BW/10/30% (0.47, 0.48, 0.37, 0.34) |
| Doan et al. [17] | 8 males (23.9 years) | Moderately trained | Weight releaser | CON—100% 1RM<br>ECC—105% 1RM | 1RM | Bench press | Concentric 1RM | +3.2% 1RM |
| Moore et al. [31] | 13 males (22.8 ± 2.9 years) | >6 months squat training, squat 1RM >1.5 BM | Weight releaser | 30% CON/+20, 50, 80% back squat 1RM ECC | Squat jump—30% 1RM | Jump squat | Peak velocity<br>Peak force<br>Peak power | Peak velocity<br>ECC20%: (−0.14)<br>ECC50%: (−0.14)<br>ECC80%: (0.05)<br>Peak force<br>ECC20%: (0.01)<br>ECC50%: (−0.08)<br>ECC80%: (−0.09)<br>Peak power<br>ECC20%: (0.02)<br>ECC50%: (0.00)<br>ECC80%: (0.14) |
| Ojasto and Hakkinen [20] | 11 males (32.4 ± 4.3 years) | Bench press relative strength = 1.2–1.4 × body mass | Weight releaser | Max Str<br>105%/100%, 110%/100%, 120%/100%<br>Explosive Str<br>70%/50%, 80%/50%, 90%/50% | Max Str<br>100%/100%<br>Explosive Str<br>50%/50%, 60%/50% | Bench press | Mean ECC force<br>Mean CON force<br>CON peak Power<br>CON mean power | Higher ECC load decreased mean CON force<br>Higher ECC load increased mean ECC force<br>Mean and peak CON power ~77.3 ± 3.2%/50% |
| Sheppard and Young [29] | 14 males (25.0 ± 1.0 years) | N/A | Weight releaser | +20, 30, 40 kg ECC, 40 kg CON | 40 kg Bench throw | Bench throw | Barbell Displacement | Barbell displacement vs. 40/40<br>20: (0.30)<br>30: (0.25)<br>40: (0.33) |
| Sheppard et al. [27] | 11 males (18.9 ± 2.6) | Trained high-performance volleyball players familiar with AEL | Manual adjustment by athlete | Athletes held 20 kg (10 kg/hand) and dropped weight when initiating jump | Volleyball block jump allowing arm swing during concentric action | Block jump | Jump height<br>Peak power<br>Peak force<br>Peak velocity | Jump height: +4.3% (0.20)<br>Peak power: +9.4% (0.39)<br>Peak force: +3.9% (0.19)<br>Peak velocity: +3.1% (0.25) |

*ACMJ20* Accentuated countermovement jump +20% body mass, *ACMJ30* Accentuated countermovement jump +30% body mass, *AEL* accentuated eccentric loading, *BW* body weight, *CMJ* countermovement jump, *CON* concentric, *DJ20* accentuated drop jump +20% body mass, *DJ30* accentuated drop jump +30% body mass, *ECC* eccentric, *ECC20%* eccentric overload of 20% in excess of concentric load, *ECC50%* eccentric overload of 50% in excess of concentric load, *ECC80%* eccentric overload of 80% in excess of concentric load

**Table 2** Chronic performance responses to accentuated eccentric loading. Cohen's *d* effect size indicated in parentheses in the Results columns

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Study duration | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|---|
| Barstow et al. [30] | 8 males<br>31 females | >3 months | Negator (counterbalance weight system providing concentric assistance) | AEL<br>CON—66% 1RM<br>ECC—100% 1RM<br>Weeks 1–4:<br>3 × 7–10 RM<br>Weeks 5–8:<br>3 × 6–8 RM<br>Weeks 9–12:<br>4–6 RM | TRAD<br>Weeks 1–4:<br>3 × 7–10 RM<br>Weeks 5–8:<br>3 × 6–8 RM<br>Weeks 9–12:<br>4–6 RM | Arm curl | 12 wk<br>2×/wk | Concentric 1RM<br>Isometric force (10°, 25°, 60°, 85°, 110°)<br>Isokinetic force (40°/s) | 1RM<br>AEL: +15.5%,<br>TRAD: +13.8%<br>Isometric force<br>Non-statistically significant change<br>Isokinetic force<br>Non-statistically significant change |
| Brandenburg and Docherty [16] | 18 males (university aged) | >1 year bench press ≥ BM | Manual adjustment by coach | 3 × 10 75% CON/ 110–120% CON 1RM IN ECC | 4 × 10 75% 1RM | Arm curl<br>Arm extension | 9 wk<br>Wk 1–2: 2<br>Wk 3–9: 3 | Strength: elbow flexion/ extension | Strength:<br>TRAD—flexion: +11%, extension: +15%<br>AEL—flexion: +9%, extension: +24% |
| Friedmann et al. [14] | 16 males | No RT within 1 year | Computer-driven | 3 × 25 ea leg, 30% CON/ +70% equivalent ECC (30% ECC 1RM, 2.32 × higher load) | 6 × 25 ea leg, 30% 1RM (45 s/ set) | Leg extension | 4 wk<br>3×/wk | Strength<br>Str-End | STR<br>TRAD: non-statistically significant change<br>AEL: +5%<br>STR-END<br>TRAD: +8%<br>AEL: non-statistically significant change |
| Friedmann-Bette et al. [15] | 25 males (±years) | > 1 year strength training | Computer-driven | 5 × 8 RM<br>CON: 8 RM<br>ECC: ~1.9 × CON | 6 × 8 RM | Leg extension | 6 wk<br>3×/wk | Concentric 1RM leg extension<br>Squat jump | Concentric 1RM leg extension<br>Non-significant difference between groups<br>Squat jump<br>AEL significantly greater than TRAD |
| Godard et al. [18] | 16 males<br>12 females<br>(22.4 ± 3.7 years) | N/A | Computer-driven | 80% CON/ +40% ECC | 8–12 reps<br>80% CON 1RM<br>Control Group | Leg extension | 10 wk<br>2×/wk | Strength<br>(CON 1RM torque) | Strength:<br>TRAD: +95.1% (3.50)<br>AEL: +93.6% (3.94)<br>Control: +6.4% (0.21) |

**Table 2** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Study duration | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|---|
| Hortobagyi et al. [47] | 30 females (20.9 ± 1.2 years) | Untrained (exercised no more than 1 day/wk for prior year) | Manual adjustment by coach | plus 40–50% from CON load (60% 1RM CON) | 5–6 × 10–12<br>60% 1RM | Leg extension | 7 days | Maximal isometric strength, maximal isokinetic strength, 3 RM leg extension (CON and ECC) | 3 RM—eccentric<br>TRAD—+11%<br>AEL—+27%<br>3RM—concentric<br>TRAD—+26%<br>AEL—+27%<br>Max isometric/isokinetic strength<br>TRAD—ECC: +9.9%, CON: +13.1%, ISO: +6.0%<br>AEL—ECC: +23%, CON: +14.6%, ISO: +12.9% |
| Johnson [73] | Male and female (20 years) | Students | Manual adjustment by coach (push/pull during ECC phase) | Enough force to make ECC last 5 s | N/A | Pushups<br>Dips<br>Pull ups | 13 wk<br>3×/wk | Repetition maximums | Men / Women<br>Push-ups: +18.6 reps / +12.9 reps<br>Chin-ups: +3 reps / +1.6 reps<br>Dips: +5.4 reps / +2.1 reps<br>Overall: +3.23% / +12.3% |
| Kaminski et al. [19] | 27 males (22.9 ± 3.2) | No lower body RT in previous 6 months | Negator (counterbalance weight system) | 2 × 8 RM<br>40% CON/100% ECC 8 RM | 2 × 8 RM<br>80% CON 1RM | Leg curl | 6 wk<br>2×/wk | Strength (1RM/BW), isokinetic peak torque (60, 180) | Strength:<br>TRAD: +19.0%, AEL: 28.8%<br>ECC isokinetic PT 60<br>TRAD: NS, AEL: +37.7%<br>ECC isokinetic PT 180<br>TRAD: NS, AEL: +22%<br>CON isokinetic PT 60<br>TRAD: +13.9% (0.73), AEL: +17.4% (2.22)<br>CON isokinetic PT 180<br>TRAD: +2.5% (0.15), AEL: +25% (1.24) |

**Table 2** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Study duration | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|---|
| Sheppard et al. [27] | 10 males<br>6 females<br>(21.8 ± 4.9 years) | >2 years | Athlete dropped weights prior to concentric phase | Overloaded CMJ<br>Male: 40 kg<br>Female: 20 kg | BW CMJ | CMJ | 5 wk<br>3×/wk | Jump height<br>Peak velocity<br>Peak force<br>Peak power | Jump height<br>BMJ: −2%, AEJ: +11%<br>Peak velocity<br>BMJ: −3%, AEJ: +16%<br>Peak force<br>BMJ: +3%, AEJ: +4%<br>Peak power<br>BMJ: +1%, AEJ: +20% |
| Walker et al. [21] | 28 males<br>(21 ± 3 years) | 0.5–6 years | Weight releaser (leg press); Manual adjustment by coach (leg extension) | Session 1: 6 RM CON/+40% ECC<br>Session 2: 10 RM CON/ +40% ECC | Session 1: 3 × 6 RM<br>Session 2: 3 × 10 RM | Leg press and leg extension | 2 × 5 wk<br>2×/wk | Strength (1RM), Repetitions to failure, CON/ ECC/ISO Torque | 1RM<br>TRAD: +35.8% (1.71), AEL: +29.6% (1.91)<br>Reps to failure (volume)<br>TRAD: +19.6% (0.76), AEL: +25.2% (0.87)<br>Torque<br>CON—TRAD: +8% (0.39), AEL: +9.4% (0.66)<br>ECC—TRAD: N/A, AEL: +9.1% (0.60)<br>ISO—TRAD: +10.2% (0.53), AEL: +17.7% (1.17) |
| Yarrow et al. [34] | 22 males<br>(22.1 ± 0.8 years) | Untrained (no RT within 6 months) | MaxOut (counterbalance weight system in which electric motors assist during the concentric action) | AEL (3 × 6): 40/100%, 41/103%, 43/107%, 45/112%, 46/117%, 49/121% | TRAD (4 × 6): 52.5, 58, 64, 69 73% | Bench press and back squat | 5 wk<br>3×/wk | Bench press 1RM<br>Back squat 1RM | Bench press 1RM<br>TRAD: +10.1% (1.77)<br>AEL: +9% (1.39)<br>Back squat 1RM<br>TRAD: +25.4% (3.39)<br>AEL: +18.6% (4.15) |

*1RM/BM* one-repetition maximum to body mass ratio, *AEJ* accentuated eccentric jump, *AEL* accentuated eccentric loading, *BM* body mass, *BMJ* body mass jump, *BW* body weight, *CMJ* countermovement jump, *CON* concentric, *ECC* eccentric, *ISO* isometric, *PT* peak torque, *RM* repetition maximum, *RT* resistance training, *TRAD* traditional/isokinetic loading due to fatigue. In this design, subjects first had to determine their bench press 1RM under traditional loading, then proceed to the prescribed AEL condition to ascertain if that enhanced their maximal strength levels for that day. By completing two separate maximal strength evaluations within the same session, it is likely that the potentiating effects observed by Doan and colleagues would not be present, and subjects instead saw a decrease in maximal strength performance related to acute fatigue [17, 20, 44]. Overall, acute intervention with AEL (Table 1) has yielded inconsistent results regarding maximal concentric force production, at least in part due to study design, load prescription, or population used. Acute maximal strength enhancement via AEL has sound theoretical basis and should be further explored. Further study of acute interventions using AEL may elucidate optimal loading strategies to potentiate maximal strength and may provide a framework by which to explore chronic adaptations.

Longer term studies exploring the effects of AEL on strength (Table 2) have also yielded multiple outcomes depending on protocol, duration, and subjects' characteristics. Godard and colleagues found non-statistically significant increases in concentric knee extensor strength favoring AEL (eccentric/concentric: 120/80% 1RM) compared to traditional loading (80% 1RM) [18]. Further, significant changes in thigh girth were observed under both isokinetic and AEL conditions. Due to the greater observed changes in strength, such findings may suggest that AEL imparted greater degrees of neural adaptation while eliciting similarly favorable changes in muscle morphology. However, it is difficult to assign sound rationale or practical application to the changes observed, as the subject pool consisted of untrained males and females that were not grouped for analysis, thereby limiting the depth of the observations. Also using untrained subjects, Kaminski and colleagues provided evidence that AEL may impart greater strength gains in the hamstrings, using an eccentric overload equivalent to 100% concentric 1RM paired with a concentric load equivalent to 40% 1RM [19]. After only 6 weeks of training, significant improvements in relative and absolute strength levels were observed in the leg curl compared to traditional loading. Due to the brevity of the study and the improvement in relative strength, it is likely that subjects experienced minimal changes in morphology and the favorable strength outcomes may be primarily explained by neural alterations.

Supporting such a hypothesis, Brandenburg and Docherty made similar comparisons of strength and muscle morphology changes between AEL and isokinetic loading in moderately trained males over 9 weeks [16]. The AEL condition used an eccentric load of 110–120% 1RM and a concentric load of 75% 1RM, performing three sets of ten repetitions to concentric failure. The isokinetic loading protocol, however, used four sets of ten repetitions to concentric failure at an absolute intensity of 75% 1RM [16]. Unlike the findings of Godard and colleagues, Brandenburg and Docherty observed no changes in muscle CSA within either training group, suggesting that the strength changes can likely be attributed to decreased neural inhibition and subsequent increases in motor unit discharge rate, leading to higher levels of voluntary activation and increased strength capabilities without changes in morphology [55]. This is supported by the findings of Walker and associates, who observed significant increases in voluntary muscle activation under AEL in the vastus lateralis, vastus medialis, and superficial quadriceps with no differences in CSA following a 10-week protocol [21]. The increase in voluntary activation may explain the higher percent change in isometric strength with AEL compared to traditional loading in the leg extension [21].

Despite the seemingly robust application of the potential mechanisms and adaptations to AEL, exercise selection may limit the transfer of training effects to sporting actions and athlete populations [16, 21]. An investigation by Yarrow and associates is one of the only examples of AEL using exercises that typically appear in sport training regimens (i.e., back squat and bench press), albeit with untrained male subjects [34]. The researchers found similar increases of 10% for the bench press concentric 1RM and 22% for the squat concentric 1RM under both AEL (100–121% eccentric overload) and traditional loading. Though the outcomes are similar when considered superficially, Yarrow and colleagues used atypical concentric loads within the AEL condition (up to 49% 1RM), where the traditionally loaded condition had more appropriate loads (up to 75% 1RM) [56]. Therefore, considering the findings of other investigations, it is reasonable to speculate that strength improvements for the AEL condition would have been greater had the concentric workloads been equalized [16, 18, 21]. It is also noteworthy that the AEL group achieved similar results with a lower total volume load—this difference resulted from the completion of one less set per session in the AEL group compared to the traditional loading group. Nevertheless, it is possible that AEL may be more work efficient compared to traditional loading and may elicit similar strength gains compared to traditional loading. Thus, one potential application of AEL may be to retain maximum strength while emphasizing higher movement velocities or reducing volume load due to other training stressors. Overall, chronic training studies using AEL have elicited favorable changes in strength, primarily due to advantageous changes in neural drive and secondarily to changes in muscle morphology. However, due to the inconsistent nature of study design and the paucity of literature using exercise selection typical of athletic populations, further investigations are warranted to determine the chronic effects of AEL. Given the varying nature of the findings, it is important first to identify the acute responses and potential mechanisms that would support the chronic changes in maximal strength observed in the longer term studies.

### 4.2 Explosive Performance

AEL has been used to examine changes in explosive performance and is commonly investigated using static jumps, CMJs, drop jumps, and throws. Sheppard and Young [29] demonstrated that greater concentric performance in the bench throw can be achieved through the addition of eccentric loading. Regarding explosive performance, the main finding of this investigation comes in the significant changes in peak acceleration across all eccentric overload conditions [29]. Aboodarda and associates [23] used three different CMJ conditions to assess the effects of enhanced eccentric loading on CMJ performance. Only the CMJ condition using an additional 30% of body mass provided via band-induced tensile force, increased vertical ground reaction forces (6.34%), power output (23.21%), net impulse (16.65%), and jump height (9.52%) compared to the body weight CMJ condition. In a follow-up study, this time investigating drop jumps, Aboodarda and associates [22] found greater eccentric impulse and RFD using an additional 30% of body mass provided via band-induced tensile force, but no difference in drop jump performance compared to traditional drop jumps. Aboodarda and colleagues [22, 23] observed different outcomes despite virtually identical protocols. One potential cause may be the difference in exercise selection, where Aboodarda and associates [22] utilized drop jumps instead of CMJs [23] in the initial investigation. In this regard, differences in participant strength levels were not considered in either study, which would greatly influence jump performance, especially in the drop jump, where stronger subjects are more likely to be able to store and reutilize elastic energy as well as have a shorter amortization phase [22, 23, 52, 57–59]. Further, the latter study implemented an aerobic-emphasis warm-up, possibly affecting the potentiation effects of the intervention.

The ability to quickly return stored elastic energy is an especially important consideration in using AEL for explosive performance. Moore and colleagues [31] used jump squats equal to 30% of the subjects' back squat 1RM with additional eccentric loading of 20, 50, and 80% of the back squat 1RM, failing to produce acute changes in force, velocity, or power in resistance-trained men. The large range of motion required in jump squats paired with the high magnitude eccentric load selection may have been inappropriate in eliciting favorable explosive performance outcomes, possibly due to lengthening the amortization phase and subsequently limiting the use of the SSC for concentric potentiation [51, 52]. In a study of elite male volleyball players, Sheppard, Newton, and McGuigan [28] compared the effects of AEL on a countermovement volleyball block jump versus traditional volleyball block jump performance, where arm swing was limited. Contrary to Moore and colleagues [31], the investigators found statistically greater jump height, peak power, and peak velocity ($p < 0.05$) for the AEL group, with moderate magnitude effect sizes (ES = 0.1–0.4). The difference in findings may be due to the aforementioned influence of exercise selection and loading methodology on the SSC. Sheppard and colleagues [28], using an absolute eccentric overload of 20 kg, allowed for minimal interruption in the natural mechanics of the block jump through their chosen AEL application of dropping dumbbells, which allow for a rapid return of stored energy and enhanced jump performance [51, 52].

Bridgeman and colleagues also used AEL drop jumps to potentiate jump performance [25]. Considering each subject's optimal drop height, five drop jump repetitions were completed under each of four dumbbell loading conditions, consisting of no load, 10, 20, or 30% additional eccentric load [25]. After each loading condition the athletes completed three CMJs at 2, 6, and 12 min rest. Bridgeman and colleagues found that drop jumps with additional load equivalent to 20% body mass produced significantly greater CMJ height and peak power after 2 and 6 min compared to the 12-min trials [25]. This indicates that not only are there optimal loading conditions for potentiating effects on power performance, but there may be a time-dependent window that these effects can be realized. In the lone study exploring chronic explosive performance changes with AEL, Sheppard and associates demonstrated increases in displacement (11%), velocity (16%), and power (20%) in high-achieving volleyball players following AEL CMJs compared to bodyweight CMJs [27]. Despite the paucity of investigations regarding the chronic adaptations to AEL related to explosive performance, it has been previously demonstrated that higher eccentric velocities elicit greater changes in power and SSC utilization [60, 61]. Eccentric overload prescribed for plyometric movements may add to the gravitational forces, causing a shorter eccentric duration, and thus causing more favorable explosive performance adaptations. As is the case with acute changes in explosive performance, there would likely be a requisite relative strength level necessary to maintain the efficacy of advanced means like AEL in this context.

## 5 Potential Mechanisms to Acute AEL

### 5.1 Neural

The exact contributions of the nervous system during AEL that acutely improve performance have yet to be fully elucidated, but several have been postulated. Lesser recruitment and discharge rates have been observed during eccentric action when compared to concentric under similar absolute loading conditions, which provides justification for higher magnitude eccentric loading [62, 63]. Additionally, higher loading of the eccentric phase may increase force production during the concentric phase via enhanced neural drive [31]. Enhanced neural drive may be due in part to enhanced motor cortex activation compensating for spinal inhibition during eccentric action [64]. This response is similar under both maximal and submaximal loading conditions, indicating that the nervous system employs unique activation strategies during eccentric contractions [36].

For example, higher or faster eccentric loading via AEL may allow for the incorporation and selective recruitment of high threshold motor units during the eccentric contraction leading to a greater force production during the subsequent concentric muscle action. It has been documented that during eccentric contractions, selective recruitment of high threshold motor units may be possible, leading to greater eccentric force production by contribution of larger motor unit pools [12]. Further, muscle may function closer to its optimal length and at reduced shortening velocities through tendon elongation during the eccentric phase, which minimizes muscle fiber lengthening [65, 66]. It is also likely that elastic energy stored in the series and parallel elastic components during the eccentric phase may be used during the concentric phase [46, 49, 67]. This increased tension and stretch initiates another favorable neuromuscular mechanism by which AEL acts—stimulation of Type Ia afferent nerves, inducing a myotatic reflex that enhances the subsequent concentric contraction [49].

In addition to increased neural drive and selective recruitment of high threshold motor units, eccentric lengthening may lead to other alterations in recruitment strategies compared to concentric muscle actions [31, 36, 38]. These strategies may be related to smaller motor-evoked potentials, delayed motor-evoked potentials, delayed motor-evoked potential recovery time, and reduced H-reflex responses [68]. Due to reduced activity in the motor cortex and the spinal cord during active muscle lengthening, the resultant response is decreased motor-evoked potentials and H-reflex responses [37, 69]. Furthermore, during submaximal and maximal contractions the electromyographic muscle activity displays a specialized motor unit activation pattern during lengthening compared with shortening [37]. These altered patterns associated with lengthening suggest a task-specific difference between concentric and eccentric actions [6]. Moreover, due to task-specific differences in contraction type, the inclusion of AEL may provide a unique stimulus leading to greater neural adaptation compared with traditional loading. This task-specific neural adaptation may transfer favorably to sporting movements involving eccentric muscle action, such as SSC.

### 5.2 Metabolic and Endocrine

Existing literature on the hormonal and metabolic responses to AEL is also limited. Yarrow and associates [33, 34] found no differences in concentrations or responses for total and bioavailable testosterone or growth hormone following either AEL (eccentric/concentric: 100/40% 1RM) or traditional loading (52.5% 1RM concentric) of bench press and squat exercise in a pair of studies [33, 34]. However, there was an observed statistically significant decrease in bioavailable testosterone at all time points (15, 30, 45, and 60 min) in the initial design [33] and at all but one time point (15 min) post-training in the follow-up study [34] under both loading conditions. This may indicate that more testosterone was bound to androgen receptors, which would subsequently stimulate protein synthesis and is consistent with previous findings regarding resistance training [70]. Metabolically, Yarrow and colleagues first observed a statistically greater increase in blood lactate concentration after AEL compared to traditional loading [33]. This finding supports the results of Ojasto and Häkkinen [32], who reported a trend for higher blood lactate concentrations with progressively higher AEL loads ranging from 80–100% concentric 1RM prescribed in the eccentric phase with concentric prescription held constant at 70% 1RM. Although these results did not reach statistical significance, this group also discussed the potential of an individualized response to different AEL intensities based on maximal strength level, as a significant correlation was found between the loading condition that yielded the highest lactate response and relative strength ratio [32]. Though higher lactate accumulations have been consistently observed, Yarrow and associates [34] expanded their consideration to lactate recovery in their follow-up design, observing a statistically significant improvement at 45 and 60 min post-training in AEL compared to isokinetic loading, all while completing less total mechanical work. The findings of Ojasto and Häkkinen [32] paired with those of Yarrow and associates [33, 34] suggest AEL may provide a primarily glycolytic stimulus, providing potential value in training of strength and power athletes.

Bridgeman and associates measured creatine kinase (CK) as a marker of exercise induced muscle damage following drop jumps with AEL equivalent to 20% of subjects' body mass provided via dumbbells [24]. CK levels peaked 24 h after both an initial session and a subsequent bout two weeks later, with smaller effect sizes for all but one measured time point of the subsequent bout compared to the initial session [24]. Interestingly, CK levels were reported as smaller during the initial bout versus the subsequent bout, even at rest [24]. However, this is likely due to a dose-response relationship and little to do with AEL itself, as the first bout included 5 × 6 whereas the subsequent bout included 5 × 10, thus changing the volume applied from session to session. Such an acute increase in volume may explain the greater CK concentration, which, if taken as an index of muscle damage, may indicate the need for careful prescription of advanced training means. However, it is also worth noting that CK is not the only indicator of muscle damage, as other enzymes and cytokines may also need to be considered [71, 72].

When taken together, these results would indicate that AEL provides a substantial acute homeostatic disruption of the cellular environment (Table 3). The increased lactate response coupled with enhanced lactate recovery provides some indication that some AEL protocols target the glycolytic system's capacity and efficiency. Further, it appears that AEL elicits at least a similar protein synthetic endocrine response compared to traditional loading. With regard to coaching application, some AEL protocols may provide a similar metabolic stimulus to that observed in traditionally loaded, higher volume strength endurance training blocks. However, under identical volume prescription, it may do so using a higher magnitude of loading, thereby increasing force production demands and providing a specific increase in volume load that may be advantageous for strength-power athletes.

## 6 Potential Mechanisms in Chronic AEL

Longer duration training studies may be better suited to explain the potential adaptations to AEL training compared to acute studies. Unfortunately, there are few studies to date examining the effects of AEL lasting longer than 12 weeks. These available experiments shape our current understanding of AEL for practical purposes and adaptive mechanisms (Table 4). An early study [73] using manual resistance of body-weight exercises was one of the first known training studies employing AEL. The results of this study indicated relative strength may be enhanced by overloading the eccentric portion of various exercises. Although performance increased following AEL implementation, it provided little information that allowed for hypothesis generation with regard to reasons for the observed changes. This simple intervention did, however, generate interest and subsequent completion of several studies examining the chronic effects of AEL on strength and muscle size.

Muscle hypertrophy, already linked to positive changes in a variety of performance outcomes, is a possible contributor to the favorable performance changes observed in AEL. It does seem that differential hypertrophy may occur based on training [74, 75]. Thus, hypertrophy's influence on performance is potentially dependent on the specificity of the stimulus inducing the adaptation. There appears to be a regional specificity to hypertrophic changes, with eccentric training increasing muscle CSA at the distal portion of the muscle and concentric training within the muscle belly [76, 77]. Additionally, eccentric-only training has been shown to favor increases in fascicle length and hypertrophy of the distal portions of a muscle while concentric-only training results in pennation angle increases and greater hypertrophy mid-muscle [76–80]. These differential changes suggest that eccentric training may be more favorable for contraction velocity, as hypertrophy tends to be more evenly distributed throughout the muscle, while concentric training may favor force production as hypertrophy is localized centrally in the muscle where a majority of tissue resides. Due to AEL, it is plausible that greater hypertrophy will occur in the distal portion of the muscle while maintaining the proximal muscle changes associated with traditional loading. Of four studies examining anatomical cross-sectional area (aCSA) after prescribed AEL, three have found no difference between AEL and traditional loading [15, 16, 21], with one exception [14]. However, the typical measurement methodology may have influenced the interpretation of such results. For example, though all four studies considered measurements from both the distal ends of the muscle and the muscle belly, only one considered them separately for analysis [21], while the others averaged the measurements for consideration of whole muscle aCSA changes [14–16]. Of the three studies which observed no between-group differences in aCSA, AEL produced statistically greater improvements in strength [16, 21] and jump performance [15]. The changes in jump performance may be attributed to increased contraction speed via in-series specific hypertrophy from the overloaded eccentric, while the changes in strength may be due to in-parallel specific hypertrophy from the traditional loaded concentric [76]. The similarities in aCSA changes combined with favorable performance results may indicate that neural mechanisms may be affecting training outcomes following AEL, but the lack of region-specific consideration in analysis of CSA may have also influenced this interpretation [14–16].

Despite the paucity of direct evidence regarding changes in muscle morphology under AEL, there have been enhancements in factors involved in anabolic signaling. Friedmann-Bette and associates [15] found that AEL produced significantly greater changes in androgen receptor content compared to traditional loading, which can likely

**Table 3** Acute physiological responses to accentuated eccentric loading. Cohen's *d* effect size indicated in parentheses in the Results columns

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Variables analyzed | Results | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bridgeman et al. [24] | 8 males (26.3 ± 5.1 years) | >2 years | Dumbbells dropped before concentric | +20% body mass<br>(Session 1: 5 × 6<br>Session 2: 5 × 10) | Pre/post | Drop jump (52 cm) | Creatine kinase | Creatine kinase | | |
| | | | | | | | | | 5 × 6 | 5 × 10 |
| | | | | | | | | Post | −13.5% (−0.32) | +6.3% (0.15) |
| | | | | | | | | 1 h | −1.8% (−0.04) | +1.2 (0.03) |
| | | | | | | | | 24 h | +10.3% (0.25) | +18.3% (0.43) |
| | | | | | | | | 48 h | −10.7% (−0.26) | +6% (0.14) |
| Ojasto and Hakkinen [32] | 11 males (32.4 ± 4.3 years) | BP 1RM of 1.2–1.4 BM | Weight releaser | CON—70% 1RM<br>ECC—80, 90, 100% 1RM | 70% 1RM bench press | Bench press | La<br>GH<br>EMG | La | | |
| | | | | | | | | | vs. 70% | Per Rep |
| | | | | | | | | 80% | +7.4% (0.51) | +6.7 (0.29) |
| | | | | | | | | 90% | +18.5% (1.27) | +30% (1.29) |
| | | | | | | | | 100% | +15.1% (1.03) | +36.7% (1.57) |
| | | | | | | | | GH | | |
| | | | | | | | | | vs.70% | Per Rep |
| | | | | | | | | 80% | +33.1% (0.24) | +16.7 (0.08) |
| | | | | | | | | 90% | +146.2% (1.07) | +166.7% (0.75) |
| | | | | | | | | 100% | +93.8% (0.68) | +133.3% (0.60) |
| | | | | | | | | EMG—no difference between conditions, all conditions show pre/post increases | | |
| Yarrow et al. [33] | 22 males (22.09 ± 0.8 years) | Untrained (no RT within 6 months) | Max out (concentric phase motor assisted) | CON—40% 1RM<br>ECC—100% 1RM | TRAD (4 × 6): 52.5% | Bench press<br>Back squat | Total testosterone<br>Bioavailable testosterone<br>GH<br>La | No differences in total testosterone or bioavailable testosterone | | |
| | | | | | | | | GH | | |
| | | | | | | | | AEL: +3700% 15-post, TRAD: +250 15-Post | | |
| | | | | | | | | La | | |
| | | | | | | | | AEL: 130–180% higher than bout 1 and TRAD | | |

**Table 3** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|
| Yarrow et al. [34] | 22 males (22.1 ± 0.8 years) | Untrained (no RT within 6 months) | Max out (concentric phase motor assisted) | AEL (3 × 6): 40/100%, 41/103%, 43/107%, 45/112%, 46/117%, 49/121% | TRAD (4 × 6): 52.5, 58, 64, 69, 73% | Bench press<br>Back squat | Total testosterone<br>BT<br>GH<br>La<br>Blood draws taken after final session | La<br>Lower in AEL vs. TRAD at 30-min post, AEL return to baseline by 60-min post<br>Total testosterone<br>Resting—AEL vs. TRAD: +13.8% (1.13)<br>AUC—AEL vs. TRAD: +16.7% (1.38)<br>BT<br>Resting—AEL vs. TRAD: +2.9% (0.33)<br>AUC—AEL vs. TRAD: +5.9% (0.75)<br>GH<br>No difference between groups |

*AEL* accentuated eccentric loading, *BT* bioavailable testosterone, *CON* concentric, *ECC* eccentric, *EMG* electromyography, *GH* growth hormone, *La* lactate, *RT* resistance training, *TRAD* traditional/isokinetic loading

**Table 4** Chronic physiological responses to accentuated eccentric loading. Cohen's *d* effect size indicated in parentheses in the Results columns

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Study duration | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|---|
| Brandenburg and Docherty [16] | 18 males<br>(university aged) | >1 year, bench press 1RM ≥ BM | Coach removed weight for CON phase | 3 × 10<br>CON—75% 1RM<br>ECC—110–120% 1RM | 4 × 10<br>75% 1RM | Arm curl and arm extension | 9 wk<br>Wk 1–2: 2×/wk<br>Wk 3–9: 3×/wk | CSA: elbow flexor/extensor<br>Specific tension | CSA<br>TRAD—flexor: +3.1% (0.22), extensor: +1.7% (0.08)<br>AEL—flexor: −0.3% (0.02), extensor: +1.7% (0.16)<br>Specific tension<br>TRAD—flexor: +8.8% (0.93), extensor: +13.2% (0.90)<br>AEL—flexor: +8.9% (0.72), extensor: +22.4% (1.67) |
| Friedmann et al. [14] | 16 males (24.5 ± 3.4 years) | No resistance training within 1 year | Computer-driven | 3 × 25 ea leg, 30% CON/+70% equivalent ECC (30% ECC 1RM, 2.32 × higher load) | 6 × 25 each leg<br>30% 1RM<br>(45 s/set) | Leg extension | 4 wk<br>3×/wk | CSA<br>FCSA<br>mRNA expression (MHC, PFK, LDH A, LDH B) | FCSA (% FT distribution)<br>TRAD AEL<br>Type I +1% (0.04) −14.2% (−0.67)<br>Type IIa +5.7% (0.32) +25.7% (0.89)<br>Type IIx −19.4% (−0.26) +3.8% (0.06)<br>FCSA (µm$^2$)<br>TRAD AEL<br>Type I +28.5% (0.72) +15.3% (0.68)<br>Type IIa +13.5% (0.29) +26.5% (0.88)<br>Type IIx +12.2% (0.24) +12.6% (0.39)<br>MHC mRNA<br>Type I: no change for either group<br>Type IIA—TRAD: −25% (−37 to +54%), AEL: +30% (+4 to +84%)<br>Type IIX—TRAD: −24% (−98 to +634%), AEL: +320% (−7 to +463)<br>PFK mRNA<br>No difference of change<br>LDH A mRNA<br>TRAD: −58 to +66%<br>AEL: 70% (+20 to +122%)<br>LDH B mRNA<br>No significant group or test effect |

**Table 4** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Study duration | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|---|
| Friedmann-Bette et al. [15] | 25 males (24.4 ± 3.9 years) | >1 year strength training | Computer-driven | 5 × 8 RM<br>CON: 8 RM<br>ECC: ~1.9× CON | 6 × 8 RM | Leg extension | 6 wk<br>3×/wk | CSA<br>FCSA<br>Fiber type distribution<br>mRNA expression | CSA<br>Both groups significant increase<br>FCSA<br>AEL: statistically significant in IIx, non-statistically significant changes in I and IIa<br>TRAD: No change<br>Fiber type distribution (%)<br>No difference<br>mRNA<br>AEL: statistically significant different response of MHC 4, and androgen receptor (change in AR negatively correlated with changes in Type II fiber changes)<br>Statistically significant changes pre/post in AEL only: LDH A, MCT 4, IGFBP4, EIF2B5, MRF4, Myostatin, HGF, MHCneo |
| Godard et al. [18] | 16 males<br>12 females<br>(22.4 ± 3.7 years) | N/A | Manual adjustment by coach | 80% CON/+40% ECC | 8–12 reps 80% CON 1RM | Leg extension | 10 wk<br>2×/wk | Thigh Girth | Thigh girth<br>CON/ECC: +6.2% (0.71)<br>CON/ECC+ : +5.0% (0.50)<br>Control: +0.6% (0.07) |
| Walker et al. [21] | 28 males (21 ± 3 years) | 0.5–6 years | Weight releaser (leg press); manual adjustment by coach (leg extension) | Session 1: 6 RM CON/+40% ECC<br>Session 2: 10 RM CON/+40% ECC | Session 1: 3 × 6 RM<br>Session 2: 3 × 10 RM | Leg press and Leg extension | 2 × 5 wk<br>2×/wk | CSA<br>Muscle activation | CSA<br>VL50—TRAD: +9.7% (0.50), AEL: +11.3% (0.36)<br>VM33—TRAD: +15.4% (0.84), AEL: +9.4% (0.42)<br>VLVI67—no changes within/between groups<br>Muscle activation<br>TRAD AEL<br>ECC (abs) +12.5% (0.25) +28.6% (0.60)<br>ECC (rel) +8.3% (0.25) +8.3% (0.25)<br>CON (abs) +14.6% (0.60) +35.7% (1.5)<br>CON (rel) +0%, (0.00) +0%, (0.00) |

**Table 4** continued

| Study | Subjects | Training status | Loading strategy | Loading magnitude | Comparison methodology | Exercise selection | Study duration | Variables analyzed | Results |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | ISO (abs) +20.7% (0.60) +23.5% (0.80)<br>ISO (rel) +0%, (0.00) +0%, (0.00)<br>M-wave<br>VL—AEL: +54.8% (1.13)<br>VM—AEL: +26% (0.87) |
| Yarrow et al. [34] | 22 males (22.1 ± 0.8 years) | Untrained (no RT within 6 months) | MaxOut (counterbalance weight system in which electric motors assist during the concentric action) | ECC (3 × 6): 40/100%, 41/103%, 43/107%, 45/112%, 46/117%, 49/121% | TRAD (4 × 6): 52.5%, 58%, 64%, 69% 73% | Bench press and back squat | 5 weeks<br>3×/week | BM<br>Body fat<br>La<br>Total testosterone<br>BT<br>GH | BM<br>TRAD: −0.4% (0.10)<br>AEL: +1.2% (0.19)<br>BF<br>TRAD: +2.1% (0.19)<br>AEL: +1.5% (0.12)<br>La<br>Lower in AEL by 30-min post<br>Total Testosterone, BT, GH<br>No difference between groups |

*AEL* accentuated eccentric loading, *BF* body fat, *BM* body mass, *BT* bioavailable testosterone, *CON* concentric, *CSA* cross-sectional area, *ECC* eccentric, *FCSA* fiber cross-sectional area, *GH* growth hormone, *ISO* isometric, *La* LACTATE, *LDH A* lactate dehydrogenase A, *LDH B* lactate dehydrogenase B, *MHC* myosin heavy chain,, *PFK* phosphofructokinase, *TRAD* traditional/isokinetic loading, *TT* total testosterone, *VL50* vastus lateralis at 50% femur length, *VLVI67* vastus lateralis + intermedius at 67% femur length, *VM33* vastus medialis at 33% femur length be attributed to the overloaded eccentric phase and may influence the effects of hormones like testosterone in stimulating muscle protein synthesis [81]. Though no differences were observed between traditional loading and AEL, increased androgen receptor content may explain the observations of Yarrow and associates [33, 34] regarding diminished bioavailable testosterone levels following training. Additionally, AEL produced increases in several insulin-like growth factors, including IGF-1. The mechanical load-induced anabolic effects of IGF-1 are robust and include satellite cell activation and proliferation, which also may explain the increases in factors related to muscle growth and regeneration observed by Friedmann-Bette and colleagues [15, 82]. Specifically, several myogenic regulatory factors (myoD, myogenin, MYF5, MRF4, HGF, and myostatin) were significantly increased under the AEL condition, while some were not changed under traditional loading [15]. The increases in such factors further suggest an increase in satellite cell proliferation, which may be provided by both the increased mechanical tension and stretch of the overloaded eccentric as well as the stimulation of the concentric action [15, 83].

The increased anabolic signaling may be primarily within faster muscle fiber types (i.e., Type IIa and IIx), leading to changes to specific CSA and intrinsic muscle properties, which could have positive implications for strength and power performances [84–87]. Friedmann and colleagues [14] observed decreases in Type I fiber-type percentage and increases in Type IIa and Type IIx fiber-type percentages in the vastus lateralis following AEL using 45-s timed sets of 25 leg extensions (eccentric/concentric: 70/30% 1RM), but only statistically significant changes occurred in the Type IIa fibers. Conversely, in the traditionally loaded group, a slight nonsignificant increase in Type IIa fiber-type percentage and slight decrease in Type IIx fiber-type percentage was noted, which is consistent with previous research using traditional loading [88, 89]. Relatively no change was observed in Type I fibers, which may be due to the high movement rate required [14]. The fiber CSA (fCSA) results did not reach significance for any variable; however, more pronounced increases were observed in Type I fCSA for the traditionally loaded group. Though both traditional loading and AEL yielded favorable changes in Type IIa fCSA, more marked increases of Type IIa fCSA were observed under the AEL condition [14]. Though the changes in this fiber type have been vastly noted in traditional loading conditions [84, 90–92], the greater changes in glycolytic fiber types under AEL may be due to the potentially greater stress applied to the glycolytic system, evidenced by the increased lactate response observed by Yarrow and associates as well as Ojasto and Häkkinen [32–34]. Moreover, the findings of Friedmann and colleagues [14] suggest the favorable changes in maximal strength due to AEL are highly related to Type IIa fCSA ($r = 0.966$) [14].

A later study from Friedmann-Bette and associates [15] also comparing AEL to traditional loading using 10-s timed sets of eight repetitions of leg extensions, noted significant increases in Type IIx fCSA for AEL but not traditional loading. This study also presented significant correlations between maximal strength and Type IIx and Type IIa fCSA ($R = 0.612$ and $R = 0.600$, respectively) for AEL only. These correlations for AEL only suggest additional underlying mechanisms and intrinsic muscle properties may influence fiber-type specific hypertrophy and subsequently maximum strength and power performances. One such mechanism may be MHC content. The mRNA of MHC4 isoforms, which is associated with faster muscle phenotypes, were observed to be significantly increased following AEL, while a slight decrease was observed following traditional loading [15, 93]. No other MHC or MLC mRNA differences were observed in this study [15]. However, a different study revealed statistically greater MHC IIa mRNA after AEL compared to traditional loading [14]. Additionally, a non-significant average increase of 320% in Type IIx mRNA concentration following AEL and a 24% decrease following traditional loading were observed, although high variability may impact the interpretation of these results. The increases in Type IIx mRNA, combined with statistically greater increases in LDH A isoform indicate that AEL may elicit unique skeletal muscle adaptations, particularly in faster, more explosive muscle isoforms [14]. Such changes may explain the findings of other studies, particularly Yarrow and associates [34]. As previously discussed, this group found greater increases in lactate concentration following AEL compared to traditional loading. Further, Yarrow and colleagues found that lactate clearance abilities were also enhanced via AEL, which is supported by the significant increase in LDH A mRNA content following AEL but not traditional loading [14, 34]. These studies suggest that AEL may impart chronic training adaptations similar to traditional resistance training, and it is plausible that AEL may have additional benefits towards strength and power-specific gains such as Type IIx-specific shifts in MHC concentration and bioenergetic anaerobic adaptations.

## 7 Conclusions and Direction of Future Research

A paucity of peer-reviewed literature currently exists regarding AEL, especially involving trained subjects or athletic populations. Within the current literature, there is a great deal of inconsistency in loading means and magnitude, which makes it difficult to apply the findings of such research, especially pertaining to acute applications of AEL.

Furthermore, chronic interventions vary in duration and often employ exercise selection and AEL means dissimilar to those encountered in training athletic populations, which may be where AEL is most logically applied. Despite these limitations, AEL has shown promise in a variety of acute and chronic applications. Acutely, AEL has demonstrated the ability to enhance concentric force and power production [15–21]. Through chronic application of AEL, the ability to shift MHC towards faster isoforms and elicit favorable changes in Type IIx specific muscle cross sectional area have been demonstrated [14, 15]. Due to the potential benefits, but high level of inconsistency and lack of current literature, it would be advantageous for future research to first examine the acute response to practically applicable means and magnitudes of AEL. Such findings would allow for a more precise and logical implementation to investigations regarding chronic adaptations.

### Compliance with Ethical Standards

**Conflicts of interest and study funding** John P. Wagle, Christopher B. Taber, Aaron J. Cunanan, Garett E. Bingham, Kevin M. Carroll, Brad H. DeWeese, Kimitake Sato, and Michael H. Stone declare that they have no conflicts of interest. No financial support was received for the conduct of the study or preparation of this manuscript.

## References

1. Hakkinen K, Pakarinen A, Alen M, Kauhanen H, Komi P. Neuromuscular and hormonal adaptations in athletes to strength training in two years. J Appl Physiol. 1988;65(6):2406–12.
2. Kraemer WJ, Ratamess NA, French DN. Resistance training for health and performance. Curr Sports Med Rep. 2002;1(3):165–71.
3. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol. 2002;93(4):1318–26.
4. Pensini M, Martin A, Maffiuletti N. Central versus peripheral adaptations following eccentric resistance training. Int J Sports Med. 2002;23(08):567–74.
5. Sale DG. 5 Influence of exercise and training on motor unit activation. Exerc Sport Sci Rev. 1987;15(1):95–152.
6. Tesch P. Skeletal muscle adaptations consequent to long-term heavy resistance exercise. Med Sci Sports Exerc. 1988;20(5 Suppl):S132–4.
7. Jorgensen K. Force-velocity relationship in human elbow flexors and extensors. Int Ser Biomech. 1976;1:145–51.
8. Westing SH, Seger JY, Karlson E, Ekblom B. Eccentric and concentric torque-velocity characteristics of the quadriceps femoris in man. Eur J Appl Physiol Occup Physiol. 1988;58(1–2):100–4.
9. Katz B. The relation between force and speed in muscular contraction. J Physiol. 1939;96(1):45.
10. Hortobagyi T, Barrier J, Beard D, Braspennincx J, Koens P, Devita P, et al. Greater initial adaptations to submaximal muscle lengthening than maximal shortening. J Appl Physiol. 1996;81(4):1677–82.
11. Vikne H, Refsnes PE, Ekmark M, Medbø JI, Gundersen V, Gundersen K. Muscular performance after concentric and eccentric exercise in trained men. Med Sci Sports Exerc. 2006;38(10):1770–81.
12. Nardone A, Schieppati M. Selective recruitment of high threshold human motor units during voluntary isotonic lengthening of active muscles. J Physiol. 1989;409:451–71.
13. Higbie EJ, Cureton KJ, Warren GL III, Prior BM. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. J Appl Physiol. 1996;81(5):2173–81.
14. Friedmann B, Kinscherf R, Vorwald S, Muller H, Kucera K, Borisch S, et al. Muscular adaptations to computer-guided strength training with eccentric overload. Acta Physiol Scand J. 2004;182:77–88.
15. Friedmann-Bette B, Bauer T, Kinscherf R, Vorwald S, Klute K, Bischoff D, et al. Effects of strength training with eccentric overload on muscle adaptation in male athletes. Eur J Appl Physiol. 2010;108(4):821–36.
16. Brandenburg JP, Docherty D. The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. J Strength Cond Res. 2002;16(1):25.
17. Doan BK, Newton RU, Marsit JL, Triplett-McBride NT, Koziris LP, Fry AC, et al. Effects of increased eccentric loading on bench press 1RM. J Strength Cond Res. 2002;16(1):9–13.
18. Godard MP, Wygand JW, Carpinelli RN, Catalano S, Otto RM. Effects of accentuated eccentric resistance training on concentric knee extensor strength. J Strength Cond Res. 1998;12(1):26–9.
19. Kaminski TW, Wabbersen CV, Murphy RM. Concentric versus enhanced eccentric hamstring strength training: clinical implications. J Athl Train. 1998;33(3):216–21.
20. Ojasto T, Hakkinen K. Effects of different accentuated eccentric load levels in eccentric-concentric actions on acute neuromuscular, maximal force, and power responses. J Strength Cond Res. 2009;23(3):996–1004.
21. Walker S, Blazevich AJ, Haff GG, Tufano JJ, Newton RU, Hakkinen K. Greater strength gains after training with accentuated eccentric than traditional isoinertial loads in already strength-trained men. Front Physiol. 2016;7:149.
22. Aboodarda SJ, Byrne JM, Samson M, Wilson BD, Mokhtar AH, Behm DG. Does performing drop jumps with additional eccentric loading improve jump performance? J Strength Cond Res. 2014;28(8):2314–23.
23. Aboodarda SJ, Yusof A, Osman NAA, Thompson MW, Mokhtar AH. Enhanced performance with elastic resistance during the eccentric phase of a countermovement jump. Int J Sports Physiol Perform. 2013;8:181–7.
24. Bridgeman LA, Gill ND, Dulson DK, McGuigan MR. The effect of exercise-induced muscle damage after a bout of accentuated eccentric load drop jumps and the repeated bout effect. J Strength Cond Res. 2017;31(2):386–94.
25. Bridgeman LA, McGuigan MR, Gill ND, Dulson DK. The effects of accentuated eccentric loading on the drop jump exercise and the subsequent postactivation potentiation response. J Strength Cond Res. 2017;31(6):1620–26.
26. Hughes JD, Massiah RG, Clarke RD. The potentiating effect of an accentuated eccentric load on countermovement jump performance. J Strength Cond Res. 2016;30(12):3450–5.
27. Sheppard J, Hobson S, Barker M, Taylor K, Chapman D, McGuigan M, et al. The effect of training with accentuated eccentric load counter-movement jumps on strength and power characteristics of high-performance volleyball players. Int J Sports Sci Coach. 2008;3(3):355–63.
28. Sheppard J, Newton R, McGuigan M. The effect of accentuated eccentric load on jump kinetics in high-performance volleyball players. Int J Sports Sci Coach. 2007;2(3):267–73.

29. Sheppard JM, Young K. Using additional eccentric loads to increase concentric performance in the bench throw. J Strength Cond Res. 2010;24(10):2853–6.
30. Barstow IK, Bishop MD, Kaminski TW. Is enhanced-eccentric resistance training superior to traditional training for increasing elbor flexor strength? J Sports Sci Med. 2003;2:62–9.
31. Moore CA, Weiss LW, Schilling BK, Fry AC, Li Y. Acute effects of augmented eccentric loading on jump squat performance. J Strength Cond Res. 2007;21(2):372–7.
32. Ojasto T, Hakkinen K. Effects of different accentuated eccentric loads on acute neuromuscular, growth hormone, and blood lactate responses during a hypertrophic protocol. J Strength Cond Res. 2009;23(3):946–53.
33. Yarrow JF, Borsa PA, Borst SE, Sitren HS, Stevens BR, White LJ. Neuroendocrine responses to an acute bout of eccentric-enhanced resistance exercise. Med Sci Sports Exerc. 2007;39(6):941–7.
34. Yarrow JF, Borsa PA, Borst SE, Sitren HS, Stevens BR, White LJ. Early-phase neuroendocrine responses and strength adaptations following eccentric-enhanced resistance training. J Strength Cond Res. 2008;22(4):1205–14.
35. Colliander EB, Tesch PA. Effects of eccentric and concentric muscle actions in resistance training. Acta Physiol Scand J. 1990;140:31–9.
36. Duchateau J, Enoka RM. Neural control of lengthening contractions. J Exp Biol. 2016;219(Pt 2):197–204.
37. Enoka RM. Eccentric contractions require unique activation strategies by the nervous system. J Appl Physiol. 1996;81(6):2339–46.
38. Kay D, St Clair Gibson A, Mitchell MJ, Lambert MI, Noakes TD. Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. J Electromyogr Kinesiol. 2000;10:425–31.
39. Nardone A, Schieppati M. Shift of activity from slow to fast muscle during voluntary lengthening contractions of the triceps surae muscles in humans. J Physiol. 1988;395:363–81.
40. Saxton JM, Clarkson PM, James R, Miles M, Westerfer M, Clark S, et al. Neuromuscular dysfunction following eccentric exercise. Med Sci Sports Exerc. 1995;27(8):1185–93.
41. Dietz V, Schmidtbleicher D, Noth J. Neuronal mechanisms of human locomotion. J Neurophysiol. 1979;42(5):1212–22.
42. Sweeney H, Bowman B, Stull J. Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. Am J Physiol Cell Physiol. 1993;264(5):C1085–95.
43. Sale DG. Postactivation potentiation: role in human performance. Exerc Sport Sci Rev. 2002;30(3):138–43.
44. Rassier D, Macintosh B. Coexistence of potentiation and fatigue in skeletal muscle. Braz J Med Biol Res. 2000;33(5):499–508.
45. Cavagna GA, Dusman B, Margaria R. Positive work done by a previously stretched muscle. J Appl Physiol. 1968;24(1):21–32.
46. Komi PV, Bosco C. Muscles by men and women. Med Sci Sports Exerc. 1978;10:261–5.
47. Hortobagyi T, Devita P, Money J, Barrier J. Effects of standard and eccentric overload strength training in young women. Med Sci Sports Exerc. 2001;33(7):1206–12.
48. Bobbert MF, Huijing PA, Van Ingen Schenau GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. Med Sci Sports Exerc. 1987;19(4):339–46.
49. Bobbert MF, Gerritsen KG, Litjens MC, Van Soest AJ. Why is countermovement jump height greater than squat jump height? Med Sci Sports Exerc. 1996;28:1402–12.
50. Komi PV, Bosco C. Muscles by men and women. Med Sci Sport. 1978;10:261–5.
51. Thys H, Faraggiana T, Margaria R. Utilization of muscle elasticity in exercise. J Appl Physiol. 1972;32(4):491–4.
52. Komi PV. Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. Exerc Sport Sci Rev. 1984;12(1):81–122.
53. LaStayo PC, Woolf JM, Lewek MD, Snyder-Mackler L, Reich T, Lindstedt SL. Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. J Orthop Sports Phys Ther. 2003;33(10):557–71.
54. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. Sports Med. 2016;46(10):1419–49.
55. Aagaard P. Training-induced changes in neural function. Exerc Sport Sci Rev. 2003;31(2):61–7.
56. Häkkinen K. Research overview: factors influencing trainability of muscular strength during short term and prolonged training. Strength Cond J. 1985;7(2):32–7.
57. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. J Strength Cond Res. 2009;23(1):177–86.
58. Cormie P, McGuigan MR, Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. Med Sci Sports Exerc. 2010;42(8):1566–81.
59. Stone MH, O'bryant HS, Mccoy L, Coglianese R, Lehmkuhl M, Schilling B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. J Strength Cond Res. 2003;17(1):140–7.
60. Farthing JP, Chilibeck PD. The effects of eccentric and concentric training at different velocities on muscle hypertrophy. Eur J Appl Physiol. 2003;89(6):578–86.
61. Liu C, Chen C-S, Ho W-H, Füle RJ, Chung P-H, Shiang T-Y. The effects of passive leg press training on jumping performance, speed, and muscle power. J Strength Cond Res. 2013;27(6):1479–86.
62. Pasquet B, Carpentier A, Duchateau J, Hainaut K. Muscle fatigue during concentric and eccentric contractions. Muscle Nerve. 2000;23(11):1727–35.
63. Tesch P, Dudley G, Duvoisin M, Hather B, Harris R. Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. Acta Physiol. 1990;138(3):263–71.
64. Gruber M, Linnamo V, Strojnik V, Rantalainen T, Avela J. Excitability at the motoneuron pool and motor cortex is specifically modulated in lengthening compared to isometric contractions. J Neurophysiol. 2009;101(4):2030–40.
65. Gans C, Gaunt AS. Muscle architecture in relation to function. J Biomech. 1991;24:53–65.
66. Griffiths R. Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. J Physiol. 1991;436:219.
67. Cronin J, McNair PJ, Marshall RN. Velocity specificity, combination training and sport specific tasks. J Sci Med Sport. 2001;4(2):168–78.
68. Balshaw TG. Acute neuromuscular, kinetic, and kinematic responses to accentuated eccentric load resistance exercise. University of Stirling; 2013.
69. Abbruzzese G, Morena M, Spadavecchia L, Schieppati M. Response of arm flexor muscles to magnetic and electrical brain stimulation during shortening and lengthening tasks in man. J Physiol. 1994;481(Pt 2):499.
70. Vingren JL, Kraemer WJ, Ratamess NA, Anderson JM, Volek JS, Maresh CM. Testosterone physiology in resistance exercise and training. Sports Med. 2010;40(12):1037–53.
71. Brancaccio P, Lippi G, Maffulli N. Biochemical markers of muscular damage. Clin Chem Lab Med. 2010;48(6):757–67.
72. Sorichter S, Mair J, Koller A, Gebert W, Rama D, Calzolari C, et al. Skeletal troponin I as a marker of exercise-induced muscle damage. J Appl Physiol. 1997;83(4):1076–82.

73. Johnson RM. Effects of manual negative accentuated resistance on strength and/or muscular endurance. 1974.
74. Antonio J. Nonuniform response of skeletal muscle to heavy resistance training: can bodybuilders induce regional muscle hypertrophy? J Strength Cond Res. 2000;14(1):102–13.
75. Fisher J, Steele J, Smith D. Evidence-based resistance training recommendations for muscular hypertrophy. Sports Med. 2013;17(4):217–35.
76. Franchi MV, Atherton PJ, Reeves ND, Flück M, Williams J, Mitchell WK, et al. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. Acta Physiol. 2014;210(3):642–54.
77. Seger JY, Arvidsson B, Thorstensson A, Seger JY. Specific effects of eccentric and concentric training on muscle strength and morphology in humans. Eur J Appl Physiol Occup Physiol. 1998;79(1):49–57.
78. Abe T, Kawakami Y, Kondo M, Fukunaga T. Comparison of ultrasound-measured age-related, site-specific muscle loss between healthy Japanese and German men. Clin Physiol Funct Imaging. 2011;31(4):320–5.
79. Abe T, Kumagai K, Brechue WF. Fascicle length of leg muscles is greater in sprinters than distance runners. Med Sci Sports Exerc. 2000;32(6):1125–9.
80. Reeves ND, Maganaris CN, Longo S, Narici MV. Differential adaptations to eccentric versus conventional resistance training in older humans. Exp Physiol. 2009;94(7):825–33.
81. Bamman MM, Shipp JR, Jiang J, Gower BA, Hunter GR, Goodman A, et al. Mechanical load increases muscle IGF-I and androgen receptor mRNA concentrations in humans. Am J Physiol Endocrinol Metab. 2001;280(3):E383–90.
82. Matheny RW Jr, Nindl BC, Adamo ML. Minireview: Mechano-growth factor: a putative product of IGF-I gene expression involved in tissue repair and regeneration. Endocrinology. 2010;151(3):865–75.
83. Jacobs-El J, Zhou M-Y, Russell B. MRF4, Myf-5, and myogenin mRNAs in the adaptive responses of mature rat muscle. Am J Physiol Cell Physiol. 1995;268(4):C1045–52.
84. Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. Sports Med. 2004;34(10):663–79.
85. Fry AC, Schilling BK, Staron RS, Hagerman FC, Hikida RS, Thrush JT. Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. J Strength Cond Res. 2003;17(4):746–54.
86. Gehlert S, Suhr F, Gutsche K, Willkomm L, Kern J, Jacko D, et al. High force development augments skeletal muscle signalling in resistance exercise modes equalized for time under tension. Pflügers Archiv Eur J Physiol. 2015;467(6):1343–56.
87. Yan Z, Biggs R, Booth FW. Insulin-like growth factor immunoreactivity increases in muscle after acute eccentric contractions. J Appl Physiol. 1993;74(1):410–4.
88. Campos GE, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. Eur J Appl Physiol. 2002;88(1–2):50–60.
89. Staron R, Karapondo D, Kraemer W, Fry A, Gordon S, Falkel J, et al. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. J Appl Physiol. 1994;76(3):1247–55.
90. Baumann H, Jäggi M, Soland F, Howald H, Schaub MC. Exercise training induces transitions of myosin isoform subunits within histochemically typed human muscle fibres. Pflügers Archiv Eur J Physiol. 1987;409(4):349–60.
91. Pette D, Staron RS. Myosin isoforms, muscle fiber types, and transitions. Microsc Res Tech. 2000;50(6):500–9.
92. Pette D, Staron RS. Transitions of muscle fiber phenotypic profiles. Histochem Cell Biol. 2001;115(5):359–72.
93. Smerdu V, Karsch-Mizrachi I, Campione M, Leinwand L, Schiaffino S. Type IIx myosin heavy chain transcripts are expressed in type IIb fibers of human skeletal muscle. Am J Physiol Cell Physiol. 1994;267(6):C1723–8.