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Kinetic and Kinematic Characteristics of Accentuated Eccentric Loading

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Kinetic and Kinematic Characteristics of Accentuated Eccentric Loading

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by

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ABSTRACT

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The current investigation was an examination of the kinetic and kinematic characteristics of the back squat using accentuated eccentric loading (AEL) and cluster set programming strategies. Trained male subjects (age = 26.1 ± 4.1 years, height = 183.5 ± 4.3 cm, body mass = 92.5 ± 10.5 kg, back squat to body mass ratio = 1.8 ± 0.3) volunteered to complete four different load condition sessions involving traditionally loaded straight sets (TL), traditionally loaded cluster sets (TLC), AEL cluster sets (AEC), and AEL straight sets where only the first repetition of each set used eccentric overload (AEL1). The use of AEL increased eccentric work (W_{ECC}) and eccentric rate of force development (RFD_{ECC}) but did not result in the expected potentiation of subsequent concentric output. Interrepetition rest, however, appears to have the largest influence on concentric peak power (PP), rate of force development (RFD_{CON}), and average velocity (MV). Additionally, the current study was an investigation of the efficacy of novel methods of ultrasonography technique that can be applied to monitoring training response. Compared to lying measures of the vastus lateralis (VL), standing ultrasonography measures of muscle thickness (MT), pennation angle (PA), and cross-sectional area (CSA) were more strongly and abundantly correlated with dynamic and isometric strength performance. Finally, the present study was an exploration of the genetic underpinnings of performance outcomes and muscle phenotypic characteristics. The polymorphisms of two candidate genes (*ACTN3*, *ACE*) typical of strength-power athletes were used. *ACTN3* RR tended to result in greater type II fiber CSA and

alter maximal strength, while *ACE* DD tended to influence RFD through the presence of more favorable type II-to-type I CSA ratios. Overall, the current investigation provided valuable insight into the characteristics of advanced programming tactics. Furthermore, the ultrasonography measurement and genetic aspects of the current investigation may serve as a framework to inform monitoring practice and generate hypotheses related to the training process.

DEDICATION

I would like to dedicate this dissertation to my mother, Carol A. Lewis for being the best mother, mentor, and friend that I could ever ask for.

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CHAPTER 1

INTRODUCTION

Resistance training, particularly valuable within athletic populations, is prescribed to exploit the immediate, accumulative, and long-term delayed effects of imposed training stimuli (Counsilman & Counsilman, 1991; Hakkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Kraemer, Ratamess, & French, 2002; Matveev & Zdornyj, 1981; Siff, 2003). As a means of physical preparation, resistance training is associated with enhanced athletic actions, including sprinting (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Alexander, 1989), jumping (Kraska et al., 2009), throwing (Stone et al., 2003), and change of direction (Nimphius, McGuigan, & Newton, 2012). These long-term performance changes are specific to the organization, sequencing, and manipulation of training variables – constantly managing acute alterations to the imposed relative demands to optimize the chronic adaptations (DeWeese, Hornsby, Stone, & Stone, 2015a, 2015b). Such adaptations are contingent on the initiation of adaptive mechanisms to re-establish homeostasis, and favorable adaptation is dependent on an understanding of the dose-response relationship (Stone, Stone, & Sands, 2007).

Due to the multifaceted nature of recovery-adaptation, training must be evaluated from a macro- and micro-sense. To understand the potential mechanisms underlying performance outcomes, acute response must be thoroughly understood to properly manage the training process. With respect to resistance training, one of the foundational aspects needed to be understood is the loading strategy. Traditional loading prescribes equivalent absolute loads for the concentric and eccentric portion of an exercise. However, skeletal muscle is capable of as much as 50% more force production during maximum eccentric contractions compared to concentric contractions (Jorgensen, 1976; Katz, 1939; Westing, Seger, Karlson, & Ekblom, 1988). Load prescription of traditional resistance exercise is limited by an athlete's concentric strength and therefore investigating the potential benefits of exploiting this force reserve that exists in the eccentric phase is warranted.

A logical starting point is the use of eccentric-only training to apply higher relative loading to the eccentric action thus eliminating the limitation of concentric force production. The response of skeletal muscle is proportional to the magnitude of mechanical stimulus and favorable changes in size and strength have been observed in eccentric-only training (T. Hortobágyi et al., 1996; Vikne et al., 2006). Further, the selective recruitment of high-threshold motor units during eccentric-only training make it a potentially intriguing training means for strength-power athletes (Howell, Fuglevand, Walsh, & Bigland-Ritchie, 1995; Linnamo, Moritani, Nicol, & Komi, 2003; Nardone & Schieppati, 1989). Though the physiological benefits of eccentric-only training exist (Tibor Hortobágyi, Devita, Money, & Barrier, 2001; Krentz, Chilibeck, & Farthing, 2017), a clear association to the transfer of training effects is less well-established (Higbie, Cureton, Warren III, & Prior, 1996). Increased motor potential and eventual performance enhancement depends on the transfer of training effects, meaning the shortcomings of traditional eccentric-only training may limit the extent of its utility in training athletic populations (Siff, 2003). Therefore, coaches and researchers alike have searched for loading strategies that simultaneously permit eccentric-overload and a subsequently coupled concentric action to promote higher degrees of task-specificity.

Accentuated eccentric loading (AEL) uses eccentric loads in excess of the concentric prescription of movements that require coupled eccentric and concentric actions, while allowing minimal interruption to the natural mechanics of the selected exercise (Wagle et al., 2017). 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 of shifts to faster myosin heavy chain (MHC) isoforms and more favorable changes in IIx-specific muscle CSA (Friedmann-Bette et al., 2010; Friedmann et al., 2004). These changes have often been accompanied by improvements in force and power production. (Ben-Sira, Ayalon, & Tavi, 1995; Brandenburg & Docherty, 2002; Doan et al., 2002; Friedmann-Bette et al., 2010; Godard, Wygand, Carpinelli, Catalano, & Otto, 1998; Kaminski, Wabbersen, & Murphy, 1998; Ojasto & Häkkinen, 2009; Walker et al., 2016). Furthermore, previous findings report advantageous changes in jumping and throwing actions, suggesting AEL may transfer well to sport task and performance when applied to both resistance and plyometric training exercises (Aboodarda, Yusof, Osman, Thompson, & Mokhtar, 2013; J. Sheppard, Newton, & McGuigan, 2007; J. M. Sheppard & Young, 2010). However, research concerning the acute and chronic responses to AEL is currently inconclusive, likely due to large variability in subject characteristics, exercise selection, load prescription, and means of providing eccentric overload.

Like the previous discussion of understanding the training process, chronic adaptations should be explored only following a thorough understanding of the acute responses to AEL. Therefore, the overall purpose of this series of studies is to investigate the acute neuromuscular responses to AEL, along with kinetic and kinematic differences in comparison to traditional loading strategies. An additional purpose is to explore the rarely investigated role that genetic and physiologic predisposition has on the acute responses to training and requisite force producing capabilities, which may be important in determining the appropriateness of training means for different athletic populations.

Dissertation Purposes

1. The initial purpose of the current investigation was to examine (a) the effects of eccentric overload on eccentric and concentric characteristics, (b) the effects of inter-repetition rest on eccentric and concentric characteristics, and (c) how inter-repetition rest may influence the responses to eccentric overload.
2. The secondary purpose of the current investigation was to explore the repetition-to-repetition kinetic and kinematic differences between eccentric overload and inter-repetition rest using the back squat.
3. The tertiary purpose of the current study was to (a) examine the differences between standing and lying ultrasonography measures of muscle size and architecture, and (b) to explore the relationships between lying and standing measures with isometric and dynamic force production capabilities.
4. The quaternary purpose of the current study was to provide a rationale for further investigation of (a) the potential effect that *ACTN3* and *ACE* polymorphisms have on whole muscle and fibre-specific characteristics and (b) the effect that *ACTN3* and *ACE* polymorphisms have on isometric and dynamic performance capabilities.

CHAPTER 2

REVIEW OF LITERATURE

The review of literature in this chapter has been previously published as *Accentuated Eccentric Loading for Training and Performance: A Review* [1]. Some text has been modified to include related literature published since the date of publication. The usage and adaptation of this manuscript is with permission from the publisher, Springer, Sports Medicine.

Introduction

It has been well documented that progressive resistance training programs enhance force and power production capabilities [2, 3]. These improvements are largely attributed to changes in skeletal muscle cross sectional area (CSA) and an array of neuromuscular adaptations [4-7]. 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 [8-10]. Therefore, loads encountered during traditional resistance 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 [11, 12]. Further, selective recruitment of high-threshold motor units has been observed in eccentric-only training [13]. 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) [11, 14].

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 its application to 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 [15, 16]. These changes have often been accompanied by improvements in force and power production. [16-22]. Furthermore, previous findings report favorable changes in jumping and throwing actions, suggesting AEL may transfer well to sport task and performance when applied to both strength and plyometric training exercises [23-30]. 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 [15, 16, 18, 21-24, 28, 30-35].

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.

Literature Search Methods

The search was conducted in December 2016 using the following databases: EBSCO, Google Scholar, PubMed, ScienceDirect, and SPORTDiscus. The search was subsequently updated in June 2018 using the same databases to account for updates in the relevant literature. 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 thirty 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. It is worth noting that one study was excluded from consideration despite satisfying the search criteria due to a lack of detail provided in methodology [36].

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 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 [11, 13, 37-41].

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 [13, 41]. 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 [42]. Several investigations have attempted to substantiate the potential implications of supramaximal AEL to improve strength, force output, or muscle CSA [15-21, 31, 34, 35].

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 [17, 18]. For example, Doan and associates found significantly enhanced concentric performance in the bench press using supramaximal AEL in moderately trained males [18]. They used weight releasers to impart an eccentric overload equivalent to 105% concentric 1RM [18]. The concentric prescriptions started at 100% of preliminarly 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 colleauges 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 [43, 44]; however, supramaximal eccentric loading may require careful consideration. Contractile history can have both fatiguing and potentiating effects on skeletal muscle performance [45]. Providing a stimulus that elicits potentiating effects without fatiguing the athlete is one of the challenges facing supramaximal AEL prescription [46]. 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 [21]. They proposed this decline in performance partially due to fatigue and suggest the potential need to use smaller eccentric loads [21]. The findings of Ojasto & Häkkinen disagreed with those of Munger and colleagues, who observed increases in peak power, peak force, and peak concentric velocity as supramaximal intensity (105-120% eccentric overload) increased in the front squat [21, 47]. 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 [21, 23-27]. Submaximal AEL also may 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 [21]. 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 [21]. Therefore, there may be an indivualized response to AEL, with factors such as training experience, age, strength-level, or physiological characteristics influencing the outcomes. Sheppard & Young, instead of prescribing relative percentages, prescribed submaximal AEL with fixed absolute loads of 20-kg, 30-kg, and 40-kg over a 40-kg concentric load [30]. Subsequent bar displacement and peak acceleration values of the bench throw were both significantly higher following AEL [30]. In accordance with the findings of Ojasto and Häkkinen, a notable finding of this study [30] 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 [48, 49]. 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 [26, 30, 50]. 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 [51], 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 [52, 53]. 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 [54, 55]. This may require higher levels of strength and connective tissue development, 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 [23, 24]. AEL 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 [24]. 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 [23]. 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 [51]. 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 [32]. 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 [32]. 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 [32]. 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 [23].

Like supramaximal AEL, the lack of consensus using submaximal AEL may be due to subject and methodological differences between studies, such as means (i.e. 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.

Performance Implications for AEL

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 [18, 22], RFD, [24] velocity [28], power [24], athletic performance, [24, 28] and injury prevention [56]. Force production underpins all of the aforementioned enhancements to performance and completion of both general and specific skills [57]. The limited number of studies using AEL to improve force production have provided varying results apparently due to differing protocols used in the investigations (Table 1, Table 2). In a seven day study by Hortobagyi and colleagues, the investigators demonstrated two-fold greater strength gains in the knee extensors using an additional 40-50% eccentric overload compared to traditional loading in untrained females [50]. 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 to 6.80 kg in the subjects using supramaximal AEL of 105% of concentric 1RM during the eccentric phase compared to the traditional loading [18]. As previously discussed, the acute enhancement of force production capabilities observed may be induced via several theoretical mechanisms, including increased calcium sensitivity and increased neural drive due to the eccentric overload provided by AEL [44]. However, AEL conditions during attempts to potentiate force production acutely must consider the fatigue elicited by the selected AEL strategy [45, 46].

Demonstrating the potential importance of load prescription as it relates to maximal strength expression, Ojasto and Häkkinen performed a bench press protocol which employed AEL in the bench press with physically active males [21]. 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 elicted a detrimental effect on maximal strength expression, likely 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 colleauges would not be present, and subjects instead saw a decrease in maximal strength performance related to acute fatigue [18, 21, 46]. 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.

Table 1

Acute performance responses to accentuated eccentric loading. Cohen's d effect size indicated in parentheses under Results.

Study	Subjects	Training Status	Loading Strategy	Loading Magnitude	Comparison Methodology	Exercise Selection	Variables Analyzed	Results
Aboodarda et al. [24]	15 males (22.6 ± 5.3 years)	6-months	Elastic Bands	+20/30% body mass	BW CMJ	CMJ	Jump Height Peak Velocity Peak Force Peak Power	Jump Height / Peak Velocity ACMJ20: +5.3% (0.67) / +0% (0.0) ACMJ30: +10.5% (1.33) / +16.7% (0.38) Peak Force / Peak Power ACMJ20: +0.6% (0.04) / +6.4% (0.41) ACMJ30: +2.9% (0.06) / +30.2% (0.66)
Aboodarda et al. [23]	15 males (24.7 ± 5.7 years)	6-months 2x BW Back Squat	Elastic Bands	+20-30% body mass	BW Drop Jump	Drop Jump	Jump Height Takeoff Velocity	Jump Height 20cm - DJ20: 0%, (0.0), DJ30: -2.4% (-0.14) 35cm - DJ20: +2.5% (0.14), DJ30: +2.5% (0.14) 50cm - DJ20: +2.6% (0.14), DJ30: +2.6% (0.14) Takeoff. Velocity 20cm - DJ20: -0.4% (-0.04), DJ30: -0.7% (-0.08) 35cm - DJ20: +0.4% (0.04), DJ30: 0% (0.0) 50cm - DJ20: +1.1% (0.12), DJ30: +1.1% (0.12)
Bridgeman et al. [25]	8 Males (26.3 ± 5.1 years)	>2 years	Manual Adjustment by Athlete	+20%body mass Session 1:5x6 Session 2: 5x10	Pre/Post	Drop Jump (52cm box)	Static Jump CMJ Squat Force	CMJ Jump Height 5x6 / 5x10 Post: -5% (-0.43) / +0.1% (0.01) 1-Hr: -2.2% (-0.19) / +1.9% (0.19) 24-Hrs: -0.2% (-0.02) / +5.2% (0.52) 48-Hrs: +3.3% (0.29) / +3.2% (0.32) Static Jump Height 5x6 / 5x10 Post: -4.0% (-0.27) / +0.3% (0.02) 1-Hr: -1.7% (-0.12) / +4.1% (0.35) 24-Hrs: +1.3% (0.09) / +6.1% (0.52) 48-Hrs: +4.6% (0.31) / +10.5% (0.89) CON Squat Force 5x6 / 5x10 Post: -4.3% (-0.14) / -5.4% (-0.19) 1-Hr: -7.3% (-0.25) / -9.5% (-0.34) 24-Hrs: +1.7% (0.06) / +6% (0.21) 48-Hrs: +1.5% (0.05) / +10.2% (0.37) ECC Squat Force 5x6 / 5x10 Post: -10.2% (-0.35) / +2.4% (0.09) 1-Hr: -4.4% (-0.15) / -0.2% (-0.01) 24-Hrs: -4.6% (-0.16) / +6.9% (0.25) 48-Hrs: -7.2% (-0.25) / +14.8% (0.54)
Bridgeman et al. [26]	12 Males (25.4 ± 3.5 years)	>2 years 1.5 BW Back Squat	Manual Adjustment by Athlete	+10/20/30% body mass additional	Unloaded DJ, CMJ	Drop Jump	Drop Jump Height Drop Jump Flight Time CMJ – Jump Height	Drop Jump Height: BW > 10%/30% (0.39, 0.34) 20%> 10%/30% (0.37, 0.32) Drop Jump Flight Time BW > 10/30% (0.38, 0.34) 20% > 10/30% (0.36, 0.32) CMJ Jump Height: 20% > Pre/BW/10/30% (0.47, 0.48, 0.37, 0.34)

Table 1 cont.

Acute performance responses to accentuated eccentric loading. Cohen's d effect size indicated in parentheses under Results.

Study	Subjects	Training Status	Loading Strategy	Loading Magnitude	Comparison Methodology	Exercise Selection	Variables Analyzed	Results
Doan et al. [18]	8 Males (23.9 years)	Moderately Trained	Weight Releaser	CON -100% 1RM ECC 105% 1RM	1RM	Bench Press	Concentric 1RM	+3.2% 1RM
Moore et al. [32]	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 Peak Force Peak Power	Peak Velocity ECC20%: (-0.14) ECC50%: (-0.14) ECC80%: (0.05) Peak Force ECC20%: (0.01) ECC50%: (-0.08) ECC80%: (-0.09) Peak Power ECC20%: (0.02) ECC50%: (0.00) ECC80%: (0.14)
Munger et al. [47]	20 Males (23.80 ± 1.82 years)	Resistance trained	Weight Releaser	CON – 90% 1RM ECC – 105, 110, 120% 1RM	Kinetic and kinematic characteristics	Front Squat	Peak Velocity Peak Force Peak Power Concentric RFD	Peak velocity (m/s) Pre: 0.96 ± 0.11, Post: 1.01 ±0.10, 105%: 0.99 ± 0.13, 110%: 1.01 ± 0.14, 120%: 1.03 ± 1.11 Peak Force (N) Pre: 2,275.03 ± 319.16, Post: 2,366.36 ± 337.61, 105%: 2,329.59 ± 334.86, 110%: 2,372.21 ± 365.46, 120%: 2,397.29 ± 333.54 Peak Power (W) Pre: 2,018.28 ± 348.02, Post: 2,150.92 ±412.03, 105%: 2,021.84 ± 563.53, 110%: 2,205.92 ± 461.83, 120%: 2,225.00 ± 432.37 Concentric RFD (N/s) Pre: 2,270.50 ± 494.73, Post: 2,738.12 ± 1,269.68, 105%: 2,902.36 ± 2,068.40, 110%: 2,773,78 ± 1,620.01, 120%: 2,538.22 ± 1,388.03
Ojasto & Häkkinen [21]	11 Males (32.4 ± 4.3 years)	Bench Press relative strength = 1.2-1.4 x body mass	Weight Releaser	Max Str 105%/100%, 110%/100%, 120%/100% Explosive Str 70%/50%, 80%/50%, 90%/50%	Max Str 100%/100% Explosive Str 50%/50%, 60%/50%	Bench Press	Mean ECC Force Mean CON Force CON Peak Power CON Mean Power	Higher ECC load decreased mean CON force Higher ECC load incrased mean ECC force Mean and Peak CON power ~77.3 ± 3.2%/50%
Sheppard & Young [30]	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 20: (0.30) 30: (0.25) 40: (0.33)
Sheppard et al. [28]	11 Males (18.9 ± 2.6)	Trained high-performance volleyball players familiar with AEL	Manual Adjustment by Athlete	Athletes held 20 kg (10kg/had) and dropped weight when initiating jump	Volleyball block jump allowing armswing during concentric action	Block Jump	Jump Height Peak Power Peak Force Peak Velocity	Jump Height: +4.3% (0.20) Peak Power: +9.4% (0.39) Peak Force: +3.9% (0.19) 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

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) [19]. 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 [20]. 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 [17]. 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 [17]. 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 [58]. 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 [22]. The increase in voluntary activation may explain the higher percent change in isometric strength with AEL compared to traditional loading in the leg extension [22].

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 [17, 22]. 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 [35]. 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) [59]. 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 [17, 19, 22]. 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, it may be utilized to retain maximum strength while emphasizing higher movement velocities or reducting volume load due to other training stressors. Overall, chronic training studies using AEL have elicitied 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.

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 [30] 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 [30]. Aboodarda and associates [24] 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 countermovement jump condition. In a follow-up study, this time investigating drop jumps, Aboodarda and associates [23] 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 [23, 24] observed different outcomes despite virtually identical protocols. One potential cause may be the difference in exercise selection, where Aboodarda and associates [23] utilized drop jumps instead of CMJs [24] 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 express elastic energy as well as have a shorter amortization phase [23, 24, 55, 60-62]. Further, the latter study implemented an aerobic-emphasis warm-up, possibly affecting the potentiation effects of the intervention.

The ability to quickly return stored energy is an especially important consideration in using AEL for explosive performance. Moore and colleagues [32] 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 provide 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, likely lengthening the amortization phase and subsequently limiting the use of the SSC for concentric potentiation [54, 55]. In a study of elite male volleyball players, Sheppard, Newton and McGuigan [29] 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 [32], 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 [29], though using a low-intensity 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 [54, 55].

Bridgeman and colleagues also used AEL drop0 jumps to potentiate jump performance [26]. 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 [26]. After each loading condition the athletes completed three CMJs at 2, 6 and 12 minutes' rest. Bridgeman and colleagues found that drop jumps with additional load equivalent to 20% body mass produced significantly greater CMJs height and peak power after 2 and 6 minutes compared to the 12 minute trials [26]. 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 [28]. 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 [63, 64]. 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 adequately use advanced means like AEL in this context.

Table 2

Chronic performance responses to accentuated eccentric loading. Cohen's d effect size indicated in parentheses under Results.

Study	Subjects	Training Status	Loading Strategy	Loading Magnitude	Comparison methodology	Exercise Selection	Study Duration	Variables Analyzed	Results
Barstow et al. [31]	8 males 31 females	>3 Months	Negator (counterbalance weight system providing concentric assistance)	AEL CON: 66% 1RM ECC: 100% 1RM Weeks 1-4: 3x7-10RM Weeks 5-8: 3x6-8RM Weeks 9-12: 4-6RM	TRAD Weeks 1-4: 3x7-10RM Weeks 5-8: 3x6-8RM Weeks 9-12: 4-6RM	Arm Curl	12 weeks 2x/week	Concentric 1RM Isometric force (10°, 25°, 60°, 85°, 110°), Isokinetic Force (40°/sec)	1RM AEL: +15.5%, TRAD: +13.8% Isometric force Non-statistically significant change Isokinetic Force Non-statistically significant change
Brandenburg & Docherty [17]	18 Males (university aged)	>1 Year Bench Press ≥ BM	Manual Adjustment by Coach	3x10 75% CON/110-120% CON 1RM IN ECC	4x10 75% 1RM	Arm Curl Arm Ext	9 weeks Weeks 1-2: 2 Weeks 3-9: 3	Strength: Elbow Flexion/Extension	Strength: TRAD - Flexion: +11%, Extension: +15% AEL - Flexion: +9%, Extension: +24%
Friedmann et al. [15]	16 Males	No RT within 1 year	Computer-driven	3x25 ea leg, 30% CON/+70% equivalent ECC (30% ECC 1RM, 2.32xhigher load)	6x25 ea leg, 30% 1RM (45s/set)	Leg Extension	4 weeks 3x/week	Strength Str-End	STR TRAD: Non-statistically significant change AEL: +5% STR-END TRAD: +8% AEL: Non-statistically significant change
Friedmann-Bette et al. [16]	25 Males	> 1 Year Strength Training	Computer-driven	5x8RM CON: 8RM ECC: ~1.9x CON	6x8 RM	Leg Extension	6 weeks 3x/week	Concentric 1RM Leg Extension Squat Jump	Concentric 1RM Leg Extension Non-Significant difference between groups Squat Jump AEL significantly greater than TRAD
Godard et al. [19]	16 Males 12 Females (22.4 ± 3.7 years)	N/A	Computer-driven	80% CON/+40% ECC	8-12 Reps 80% CON 1RM Control Group	Leg Extension	10 weeks 2x/week	Strength (CON 1RM torque)	Strength: TRAD: +95.1% (3.50) AEL: +93.6% (3.94) Control: +6.4% (0.21)
Hortobagyi et al. [50]	30 Females (20.9 ± 1.2 years)	untrained (exercised no more than 1 day/week for prior year)	Manual Adjustment by Coach	plus 40-50% from CON load (60% 1RM CON)	5-6x10-12 60% 1RM	Leg Extension	7 Days	Maximal Isometric Strength, Maximal Isokinetic Strength, 3RM Leg Extension (CON & ECC)	3RM - Eccentric TRAD - +11% AEL - +27% 3RM - Concentric TRAD - +26% AEL - +27% Max Isometric/Isokinetic Strength TRAD - ECC: +9.9%, CON: +13.1%, ISO: +6.0% AEL - ECC: +23%, CON: +14.6%, ISO: +12.9%

Table 2 cont.

Chronic performance responses to accentuated eccentric loading. Cohen's d effect size indicated in parentheses under Results.

Study	Subjects	Training Status	Loading Strategy	Loading Magnitude	Comparison methodology	Exercise Selection	Study Duration	Variables Analyzed	Results
Johnson [65]	Male & Female (20 years)	Students	Manual Adjustment by Coach (Push/Pull during ECC phase)	Enough force to make ECC last 5 seconds	N/A	Pushups Dips Pull Ups	13 weeks 3x/week	Repetition maximums	Men / Women Push-ups: +18.6 reps / +12.9 reps Chin-ups: +3 reps / +1.6 reps Dips: +5.4 reps / +2.1 reps Overall: +3.23% / +12.3%
Kaminski et al. [20]	27 Males (22.9 ± 3.2)	No lower body RT in previous 6 months	Negator (Counterbalance Weight System)	2x8RM40% CON/100% ECC 8 RM	2x8RM 80% CON 1RM	Leg Curl	6 weeks 2x/week	Strength (1RM/BW), Isokinetic Peak Torque (60, 180)	Strength:TRAD: +19.0%, AEL: 28.8% ECC Isokinetic PT 60 TRAD: NS, AEL: +37.7% ECC Isokinetic PT 180TRAD: NS, AEL: +22% CON Isokinetic PT 60TRAD: +13.9% (0.73), AEL: +17.4% (2.22) CON Isokinetic PT 180TRAD: +2.5% (0.15), AEL: +25% (1.24)
Sheppard et al. [28]	10 males 6 females (21.8 ± 4.9 years)	>2 years	Athlete dropped weights prior to concentric phase	Overloaded CMJ Male: 40kg Female: 20kg	BW CMJ	CMJ	5 weeks 3x/week	Jump height Peak Velocity Peak Force Peak Power	Jump Height BMJ: -2%, AEJ: +11% Peak Velocity BMJ: -3%, AEJ: +16% Peak Force BMJ: +3%, AEJ: +4% Peak Power BMJ: +1%, AEJ: +20%
Walker et al. [22]	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 Session 2: 10 RM CON/+40% ECC	Session 1: 3x6RM Session 2: 3x10RM	Leg Press & Leg Extension	2 x 5 weeks 2x/week	Strength (1RM), Repetitions to failure, CON/ECC/ISO Torque	1RM TRAD: +35.8% (1.71), AEL: +29.6% (1.91) Reps to Failure (volume) TRAD: +19.6% (0.76), AEL: +25.2% (0.87) Torque CON - TRAD: +8% (0.39), AEL: +9.4% (0.66) ECC - TRAD: N/A, AEL: +9.1% (0.60) ISO - TRAD: +10.2% (0.53), AEL: +17.7% (1.17)
Yarrow et al. [35]	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)	AEL (3x6): 40/100%, 41/103%, 43/107%, 45/112%, 46/117%, 49/121%	TRAD (4x6): 52.5%, 58%, 64%, 69% 73%	Bench Press & Back Squat	5 weeks 3x/week	Bench Press 1RM Back Squat 1RM	Bench Press 1RM TRAD: +10.1% (1.77) AEL: +9% (1.39) Back Squat 1RM TRAD: +25.4% (3.39) 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

Potential Mechanisms to Acute AEL

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 [66, 67]. Additionally, higher loading of the eccentric phase may increase force production during the concentric phase via enhanced neural drive [32]. Enhanced neural drive may be due in part to enhanced motor cortex activation compensating for spinal inhibition during eccentric action [68]. This response is similar under both maximal and submaximal loading conditions, indicating that the nervous system employs unique activation strategies during eccentric contractions [38].

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 [13]. 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 [69, 70]. 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 [49, 52, 71]. 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 [52].

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 [32, 38, 40]. 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 [72]. 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 [39, 73]. Furthermore, during submaximal and maximal contractions the electromyographic muscle activity displays a specialized motor unit activation pattern during lengthening compared with shortening [39]. These altered patterns associated with lengthening suggest a task-specific difference between concentric and eccentric actions [7]. 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.

Metabolic and Endocrine

Existing literature on the hormonal and metabolic responses to AEL is also limited. Yarrow and associates [34, 35] found no differences in concentrations or responses for total and bioavailable testosterone or growth hormone following either AEL (100% 1RM eccentric and 40% 1RM concentric) or traditional loading (52.5% 1RM concentric) of bench press and squat exercise in a pair of studies [34, 35]. However, there was an observed statistically significant decrease in bioavailable testosterone at all timepoints (15, 30, 45, 60 minutes) in the initial design [34] and at all but one timepoint (15 minutes) post-training in the follow-up study [35] under both loading conditions. This may indicate that more testosterone was bound to androgren receptors, which would subsequently stimulate protein synthesis and is consistent with previous findings regarding resistance training [74]. Metabolically, Yarrow and colleagues first observed a statistically greater increase in blood lactate concentration after AEL compared to traditional loading [34]. This finding supports the results of Ojasto & Häkkinen [33], 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 [33]. Though higher lactate accumulations have been consistently observed, Yarrow and associates [35] expanded their consideration to lactate recovery in their follow-up design, observing a statistically significant improvement at 45 and 60 minutes post-training in AEL compared to isokinetic loading, all while completing less total mechanical work. The findings of Ojasto and Häkkinen [33] paired with those of Yarrow and associates [34, 35] suggest AEL may provide a primarily glycolytic stimulus, providing potential value in training of strength and power athletes.

Bridgeman and associates measured CK as a marker of exercise induced muscle damage following drop jumps with AEL equivalent to 20% of subjects' body mass provided via dumbbells [25]. CK levels peaked 24 hours 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 [25]. Interestingly, CK levels were reported as smaller during the initial bout versus the subsequent bout, even at rest [25]. However, this is likely due to a dose-response relationship and little to do with AEL itself, as the first bout included 5x6 wheras the subsequent bout included 5x10, 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 [75, 76].

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 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.

Table 3

Acute physiological responses to accentuated eccentric loading. Cohen's d effect size indicated in parentheses under Results.

Study	Subjects	Training Status	Loading Strategy	Loading Magnitude	Comparison Methodology	Exercise Selection	Variables Analyzed	Results
Bridgeman et al. [25]	8 Males (26.3 ± 5.1 years)	>2 years	Dumbbells dropped before concentric	+20% Body Mass (Session 1: 5x6 Session 2: 5x10)	Pre/Post	Drop Jump (52cm)	Creatine Kinase	Creatine Kinase 5x6 / 5x10 Post: -13.5% (-0.32) / +6.3% (0.15) 1-Hr: -1.8% (-0.04) / +1.2 (0.03) 24-Hrs: +10.3% (0.25) / +18.3% (0.43) 48-Hrs: -10.7% (-0.26) / +6% (0.14)
Ojasto & Häkkinen [33]	11 Males (32.4 ± 4.3 years)	BP 1RM of 1.2-1.4 BM	Weight Releaser	CON - 70% 1RM ECC - 80, 90, 100% 1RM	70% 1RM Bench Press	Bench Press	La GH 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. [34]	22 males (22.09 ± 0.8 years)	Untrained (no RT within 6 months)	MaxOut (concentric phase motor assisted)	CON - 40% 1RM ECC -100% 1RM	TRAD (4x6): 52.5%	Bench Press Back Squat	Total Testosterone Bioavailable Testosterone GH 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
Yarrow et al. [35]	22 males (22.1 ± 0.8 years)	Untrained (no RT within 6 months)	MaxOut (concentric phase motor assisted)	AEL (3x6): 40/100%, 41/103%, 43/107%, 45/112%, 46/117%, 49/121%	TRAD (4x6): 52.5%, 58%, 64%, 69% 73%	Bench Press Back Squat	Total Testosterone BT GH La *Blood draws taken after final session	La Lower in AEL v TRAD at 30-min post, AEL return to baseline by 60-min post Total Testosterone Resting - AEL v TRAD: +13.8% (1.13) AUC - AEL v TRAD: +16.7% (1.38) BT Resting - AEL v TRAD: +2.9% (0.33) AUC - AEL v TRAD: +5.9% (0.75) GH 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

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 [65] 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 [77, 78]. 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 [79, 80]. 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 [79-83]. These differential changes suggest that eccentric training may favor contraction velocities, 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 [16, 17, 22], with one exception [15]. 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 [22], while the others averaged the measurements for consideration of whole muscle aCSA changes [15-17]. Of the three studies which observed no between-group differences in aCSA, AEL produced statistically greater improvements in strength [17, 22] and jump performance [16]. The changes in jump performance may be attributed to increased contraction speed via in-series specific hypertrophy from the overloaded ecentric, while the changes in strength may be due to in-parallel specific hypertrophy from the traditional loaded concentric [79]. 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 [15-17].

Of five studies examining anatomical cross-sectional area (aCSA) after prescribed AEL, three have found no difference between AEL and traditional loading [16, 17, 22], while two did observe differential changes [15, 84]. However, the typical measurement methodology may have influenced the interpretation of such results. For example, though three of the five studies considered measurements from both the distal ends of the muscle and the muscle belly, only one considered them separately for analysis [22], while the others averaged the measurements for consideration of whole muscle aCSA changes [15-17, 84]. Of the three studies which observed no between-group differences in aCSA, AEL produced statistically greater improvements in strength [17, 22] and jump performance [16]. 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 [79]. 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 [15-17].

Despite the paucity of direct evidence regarding enhanced changes in muscle morphology under AEL, there have been enhancements in factors involved in anabolic signaling. Friedmann-Bette and associates [16] found that AEL produced significantly greater changes in androgen receptor content compared to traditional loading, which can likely be attributed to the overloaded eccentric phase and may influence the effects of hormones like testosterone in stimulating muscle protein synthesis [85]. Though no differences were observed between traditional loading and AEL, increased androgen receptor content may explain the observations of Yarrow and associates [34, 35] 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 [16, 86]. 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 [16]. 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 [16, 87]. Further, Walker and colleagues observed an elevation in acute testosterone, cortisol, and growth hormone compared to traditional loading over ten weeks of training [84]. These post-session elevations at various testing timepoints indicate a unique response to AEL, which was accompanied by greater changes in muscle mass and maximal voluntary contraction in the latter half of the study [84].

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 [88-91]. Friedmann and colleagues [15] 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-second 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 [92, 93]. Relatively no change was observed in Type I fibers, which may be due to the high movement rate required [15]. 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 [15]. Though the changes in this fiber type have been vastly noted in traditional loading conditions [88, 94-96], the greater changes in glycolytic fiber types under AEL may be due to the potentially greater stress applied to the glycolyic system, evidenced by the increased lactate response observed by Yarrow and associates as well as Ojasto and Häkkinen [33-35]. Moreover, the findings of Friedmann and colleagues [15] suggest the favorable changes in maximal strength due to AEL are highly related to Type IIa fCSA (r = 0.966) [15].

A later study from Friedmann-Bette and associates [16] also comparing AEL to traditional loading using 10-second timed sets of 8 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, associated with faster muscle phenotypes, were observed to be significantly increased following AEL, while a slight decrease was observed following traditional loading [16, 97]. No other MHC or MLC mRNA differences were observed in this study [16]. However, a different study revealed statistically greater MHC IIa mRNA after AEL compared to traditional loading [15]. 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 [15]. Such changes may explain the findings of other studies, particularly Yarrow and associates [35]. 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 abilites were also enhanced via AEL, which is supported by the significant increase in LDH A mRNA content following AEL but not traditional loading [15, 35]. 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.

Table 4

Chronic physiological responses to accentuated eccentric loading. Cohen's d effect size indicated in parentheses under Results.

Study	Subjects	Training Status	Loading Strategy	Loading Magnitude	Comparison methodology	Exercise Selection	Study Duration	Variables Analyzed	Results
Brandenburg & Docherty [17]	18 Males (University Aged)	>1 Year, Bench Press 1RM ≥ BM	Coach removed weight for CON phase	3x10 CON - 75% 1RM ECC - 110-120% 1RM	4x10 75% 1RM	Arm Curl & Arm Extension	9 weeks Weeks 1-2: 2x/week Weeks 3-9: 3x/week	CSA: Elbow Flexor/Extensor Specific Tension	CSA TRAD - flexor: +3.1% (0.22), extensor: +1.7% (0.08) AEL - flexor: -0.3% (0.02), extensor: +1.7% (0.16) Specific Tension TRAD - flexor: +8.8% (0.93), extensor: +13.2% (0.90) AEL - flexor: +8.9% (0.72), extensor: +22.4% (1.67)
Friedmann et al. [15]	16 Males (24.5 ± 3.4 years)	21 ± 2 years	Computer-driven	3x25 ea leg, 30% CON/+70% equivalent ECC (30% ECC 1RM, 2.32xhigher load)	6x25 each leg 30% 1RM (45s/set)	Leg Extension	4 weeks 3x/week	CSA FCSA mRNA expression (MHC, PFK, LDH A, LDH B)	FCSA (% FT Distribution) TRAD / AEL Type I: +1% (0.04) / -14.2% (-0.67) Type IIa: +5.7% (0.32) / +25.7% (0.89) Type IIx: -19.4% (-0.26) / +3.8% (0.06) FCSA (um2) TRAD / AEL Type I: +28.5% (0.72) / +15.3% (0.68) Type IIa: +13.5% (0.29) / +26.5% (0.88) Type IIx: +12.2% (0.24) / +12.6% (0.39) MHC mRNA Type I: No change for either group Type IIA- TRAD: -25% (-37% to +54%), AEL: +30% (+4% to +84%) Type IIX - TRAD: -24% (-98% to +634%), AEL: +320% (-7% to +463) PFK mRNA No difference of change LDH A mRNA TRAD: -58% to +66% AEL: 70% (+20% to +122%) LDH B mRNA No significant group or test effect
Walker et al. [84]	18 Males (21 ± 2 years)	2.7 ± 2.3 years	Weight Releaser (Leg Press); Manual Adjustment by Coach (Leg Extension)	Session 1: 6 RM CON/+40% ECC Session 2: 10 RM CON/+40% ECC	Session 1: 3x6RM Session 2: 3x10RM	Leg Press & Leg Extension	2 x 5 weeks 2x/week	Serum concentration of: Lactate Testosterone Cortisol 22 kDa Growth Hormone	Lactate (mmol/L) Week 2-ISO: 1.2 ± 0.4, AEL: 1.3 ± 0.4 Week 9-ISO: 1.6 ± 0.6, AEL 1.8 ± 0.9 Testosterone (nmol/L) Week 2-ISO: 12.3 ± 4.3, AEL: 14.1 ± 5.7 Week 9-ISO: 12.0 ± 3.9, AEL 15.4 ± 4.7 Cortisol (mmol/L) Week 2-ISO: 290 ± 120, AEL: 307 ± 53 Week 9-ISO: 324 ± 114, AEL 352 ± 102 22 kDa GH (μg/L) Week 2-ISO: 0.2 ± 0.3, AEL: 0.3 ± 0.4 Week 9-ISO: 0.9 ± 1.1, AEL 0.3 ± 0.5

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 application 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 [16-22]. 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 [15, 16]. 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.

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CHAPTER 3

STUDY I

ACCENTUATED ECCENTRIC LOADING AND CLUSTER SET CONFIGURATIONS IN THE BACK SQUAT: A KINETIC AND KINEMATIC ANALYSIS

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Abstract

This study examined the kinetic and kinematic differences between accentuated eccentric loading (AEL) and cluster sets in trained male subjects (age = 26.1 ± 4.1 years, height = 183.5 ± 4.3 cm, body mass = 92.5 ± 10.5 kg, and back squat to body mass ratio = 1.8 ± 0.3). Four load condition sessions consisted of traditionally loaded (TL) "straight sets," TL cluster (TLC) sets, AEL cluster (AEC) sets, and AEL "straight sets" where only the first repetition had eccentric overload (AEL1). An interrepetition rest interval of 30 seconds was prescribed for both TLC and AEC. Concentric intensity for all load conditions was 80% 1 repetition maximum (1RM). Accentuated eccentric loading was applied to repetitions through weight releasers with total eccentric load equivalent to 105% of concentric 1RM. Traditionally loaded cluster had statistically greater concentric outputs than TL. Furthermore, statistically greater eccentric and concentric outputs were observed during AEC compared with TL with the exception of peak power. Statistically greater concentric characteristics were observed in TLC compared with AEL1, but statistically greater eccentric outputs were observed in AEL1. In the 2 cluster set conditions, statistically greater concentric rate of force development (RFD_{CON}) ($d = 0.470$, $p < 0.001$) and average velocity (v_{avg}) ($d = 0.560$, $p < 0.001$) in TLC compared with AEC were observed. However, statistically greater eccentric work (W_{ECC}) ($d = 2.096$, $p < 0.001$) and eccentric RFD (RFD_{ECC}) ($d = 0.424$, $p < 0.001$) were observed in AEC compared with TLC. Overall, eccentric overload demonstrated efficacy as a means of increasing eccentric work and RFD, but not as a means of potentiating concentric output. Finally, interrepetition rest seems to have the largest influence on concentric power output and RFD.

Introduction

Coaches aim to leverage the positive outcomes of resistance training in the physical preparation of athletic populations. The imposed training stimuli allow for the exploitation of immediate, accumulative, and long-term delayed training effects (8, 23). The favorable results from resistance training are robust, demonstrating utility in the enhancement of a multitude of athletic actions including change of direction (30), linear sprinting (1), jumping ability (25), and throwing ability (35). To effectively manage fatigue and realize performance potential, coaches make deliberate programming decisions to generate more predictable outcomes (9, 10). Programming tactics, then, serve to introduce variation into a periodized training program through the manipulation of one or more training variables (e.g. volume, intensity, and density). Emphasizing the importance of training variation, Hodges and associates (20) demonstrated that a novel stimulus results in more rapid performance improvement, whereas monotonous training slows adaptation. Therefore, it is especially important that coaches consider a multitude of factors to maximize preparedness and performance potential.

An increasingly popular means of providing variation within a resistance training program is manipulation of the exercise phase-specific overload. Traditional loading prescribes equivalent absolute loads for the concentric and eccentric portion of an exercise. However, skeletal muscle is capable of as much as 50% more force production during maximum eccentric muscle actions compared to concentric muscle actions (42). This disparity has led to exploration of a variety of means to apply greater loads eccentrically to exercises with a paired eccentric and concentric action (e.g. weight releasers) and has been termed accentuated eccentric loading (AEL) (39). Eccentric overload theoretically increases the active state of the muscle (24), calcium sensitivity (36), or muscle spindle excitation (37) – all of which have been previously associated with acute concentric potentiation. Previous findings report advantageous changes in jumping (32), throwing (33), and resistance training (29) performance using AEL. However, these outcomes are equivocal, likely due to the inherently sensitive nature of potentiation and high-stress nature of AEL. Therefore, the exploration of factors influencing AEL-specific alterations (e.g. concentric potentiation) could provide deterministic information to coaches who aim to use this training approach.

One aspect to consider is the inherent interrepetition rest required in most common AEL applications (e.g. replacing weight releasers on the end of a barbell). It is possible that this set configuration, commonly termed a 'cluster set' (28), is at least partly responsible for the favorable observations surrounding AEL (29). The potential influence on the outcomes observed with AEL aside, cluster sets are an effective means of providing variation within a training program. Although the rationale for implementation may be context-specific, interrepetition rest has demonstrated the ability to allow athletes to train at a higher overall intensity and power output due to the partial recovery provided. This could allow cluster sets to provide an advantageous stimulus when training emphasizes absolute strength or peak power (PP) production. Potentiating effects seem to be most effective when used by highly-trained individuals (5), which further supports the possible use of cluster sets as a means of variation during later stages of a periodized plan (17). Furthermore, lower metabolite accumulations have been observed using cluster sets (15), which may alter the recovery-adaptation relationship associated with a particular work load and provide unique advantages during peaking. To properly administer such a strategy to the benefit of the athlete, the coach must possess an intimate knowledge of the training process, the acute effects of programming tactics, and their potential ramifications for chronic adaptation.

The purpose of the current investigation was to explore the kinetic and kinematic differences between AEL and cluster sets. Specifically, this study sought to compare the factors associated with enhanced interrepetition performance when using either of these prescriptions. Using the back squat, this study aimed to determine (a) the effects of eccentric overload on eccentric and concentric characteristics, (b) the effects of interrepetition rest on eccentric and concentric characteristics, and (c) how interrepetition rest may influence the responses to eccentric overload.

Methods

Experimental approach to the problem

To compare the kinetic and kinematic differences between AEL and cluster set configurations in the back squat, subjects were asked to complete testing protocols on five separate occasions. Back squat 1RM and three sets of five repetitions of four different experimental conditions were performed in separate testing sessions. Each repetition was performed on dual force platforms affixed with linear position transducers to assess phase-specific kinetic and kinematic characteristics of each condition.

Subjects

Eleven recreationally resistance-trained males (age = 26.1 ± 4.1 years, height = 183.5 ± 4.3 cm, body mass = 92.5 ± 10.5 kg, back squat to body mass ratio = 1.8 ± 0.3) volunteered for the current investigation. Subjects were required to have spent at least the past year on a weekly resistance training program that included back squats. All subjects' hydration status (urinary specific gravity) was determined prior to any data collection using a refractometer (Atago, Tokyo, Japan) to ensure hydration status would not influence the results (4). All subjects read and signed a written informed consent, and the procedures were approved by East Tennessee State University's Institutional Review Board.

Procedures

Dynamic strength was measured using a one-repetition maximum (1RM) back squat, and the 1RM load was used to set the load for the experimental conditions. Dynamic strength testing was completed following 48 hours of rest to ensure subjects were adequately recovered (2). Prior to testing, each subject performed a general dynamic warm-up.

After the general warm-up, bar and safety bar heights in the squat rack were adjusted as needed to best accommodate each subject. Subjects warmed-up with progressively heavier loads of 30, 50, 70, 80, and 90% of their self-reported 1RM before maximal attempts. Each subject attained their back squat 1RM by attempting progressively heavier loads until they could not complete a successful repetition. For a repetition to be considered successful, the subject's hip crease must have been below the patella at the bottom of the descent during the back squat and was verified by multiple certified strength and conditioning coaches.

Experimental back squat sessions commenced at least 48-hours after participants completed 1RM testing. Experimental sessions were completed in pre-determined random order using an online randomization tool. Each session was separated by 7 days and executed at the same time of day for each subject. Between sessions, subjects could engage in training typical for their respective routines but refrained from training of any kind 48 hours before any data collection. All load conditions underwent identical data collection procedures. The general and specific warm-up was identical to that used in dynamic strength testing. Subjects completed 3 sets of 5 repetitions of the barbell back squat for the prescribed condition, each separated by three minutes of seated rest. Concentric intensity for all load conditions was 80% 1RM. Accentuated eccentric loading was applied to repetitions using weight releasers (Monster Grips, Columbus, OH) with total eccentric load equivalent to 105% of concentric 1RM. Weight releasers were adjusted for height based on the lowest descent point in each subject's back squat technique (29).Weight releasers, due to the angle of the hanging base, are designed to release from the barbell at the bottom of the back squat, meaning that the eccentric portion of the movement is overloaded in comparison to the concentric (11, 40).

Four loading conditions were used to better understand the uniqueness of AEL and cluster set configurations. Traditionally loaded "straight sets" (TL) were completed with no interrepetition rest and represented training most characteristic to that implemented with athletic populations. Subjects completed each of the 5 repetitions per set consecutively. No more than three seconds were allowed between repetitions, and the barbell remained placed on the participants' upper trapezius between repetitions. Two load conditions allowed interrepetition rest, which is the basis for a cluster set (17). Traditionally loaded cluster sets (TLC) were completed with identical procedures to TL, except 30 seconds of interrepetition standing rest was prescribed where the subjects placed the barbell on the safety hooks of the squat rack between repetitions. During the AEL cluster set condition (AEC) session, all 5 repetitions of the back squat were completed with eccentric overload with otherwise identical procedures to those of TL cluster (TLC) sets. After unracking the barbell from the safety hooks, the weight releasers were re-attached to the barbell by 2 coaches. The fourth load condition aimed to examine the effects of AEL without the effects of interrepetition rest. The AEL "straight set" condition (AEL1) added an eccentric overload to the first repetition of each set only. Subsequent repetitions were executed without eccentric overload and with procedures identical to TL.

Data were collected using a dual force plate design (2 x 91 x 45.5 cm force plates; Rough Deck HP; Rice Lake Weighing Systems, Rice Lake, WI, USA) inside a custom-built rack (Sorinex Exercise Equipment; Lexington, SC, USA) with data sampled at 1,000 Hz. Four linear position transducers (PT101-0100-H14-1120; Celesco Measurement Specalties, Chatsworth, CA, USA) were attached to the top of the custom-built rack (Figure 1), and recoil wires were attached to the each of the ends of the barbell just inside where the plates were loaded (6). The linear position transducers were synchronized with the force plates using a custom LabVIEW (version 7.1; National Instruments) program. Data were processed using RStudio (Version 1.0.153; RStudio, Inc., Boston, MA). To account for and diminish noise, a digital Butterworth second-order low-pass filter with a 10 Hz cutoff frequency determined through residual analysis was applied. Eccentric and concentric phases were confirmed by the displacement values obtained from the linear position transducers. Peak power, eccentric work (W_{ECC}), concentric work (W_{CON}), eccentric rate of force development (RFD_{ECC}), concentric rate of force development (RFD_{CON}), and concentric average velocity (v_{avg}) were assessed for each load condition. Eccentric RFD (RFD_{ECC}) was calculated as the slope between eccentric peak force and the force value 250 ms prior to eccentric peak force (34). The timepoint of 250 ms was chosen to reflect the upper limit of time in which stored eccentric energy may be used to enhance the subsequent concentric action rather than dissipated as heat (38). Concentric rate of force development

(RFD_{CON}) was calculated using the concentric peak force and the force value 250 ms prior to concentric peak force (34).

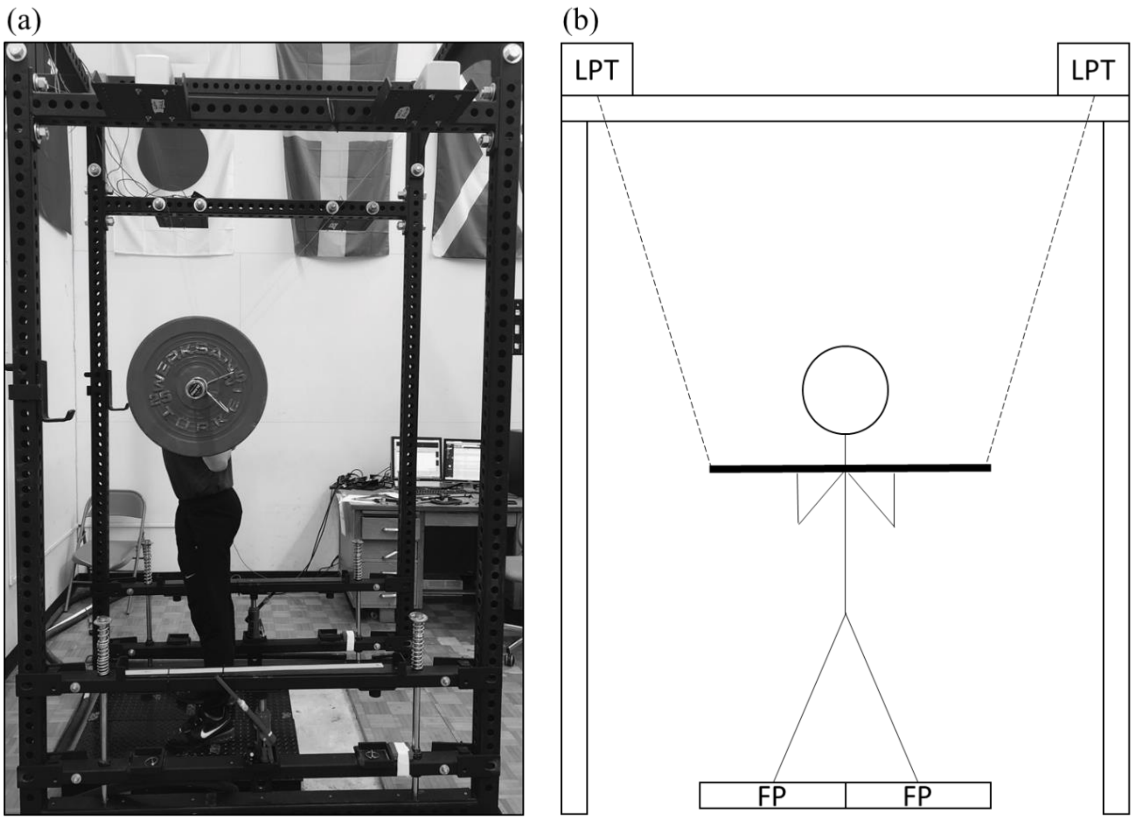

Figure 1. Custom-built rack (A) image from the lateral view and (B) schematic representation from the posterior view. LTP = linear position transducer, FP = force plate.

Statistical Analyses

Descriptive statistics including mean and SD were calculated. Within-subject reliability for each variable was assessed using intraclass correlation coefficients (ICCs) (22). Interpretation of ICC was 0-0.1, 0.1-0.3, 0.3-0.5, 0.5-0.7, 0.7-0.9, and 0.9-1.0 as trivial, small, moderate, large, very large, and nearly perfect respectively (21). Coefficient of variation (CV) was calculated for each load condition. One-way within-subject analysis of variance was performed against the independent variable of load condition for each dependent variable. Data were screened for sphericity using Mauchly's test. If the assumption of sphericity was violated, a Greenhouse-Geisser correction was performed for the dependent variable being considered prior to any further analysis. The critical alpha level was set at $p \leq 0.05$. If a main effect was observed, a Holm-Bonferroni post hoc comparison was performed to determine between which conditions the significance occurred and to account for family-wise error. Cohen's *d* effect sizes were calculated for each dependent variable to determine the magnitude and meaningfulness of the differences between dependent variables across load conditions. For practical significance, effect sizes were interpreted with magnitude thresholds of 0-0.2, 0.2-0.6, 0.6-1.2, 1.2-2.0, and 2.0 and above as trivial, small, moderate, large, and very large (21). Statistical analyses were performed using JASP (Version 0.8.1.2, Amsterdam, Netherlands).

Results

Relative reliability of all dependent variables returned at least very large ICC values (Table 1), whereas absolute reliability of the dependent variables returned CV values ranging between 1.49 and 40.94% (Table 2). There were significant between-condition main effects for PP ($p = 0.007$), W_{ECC} ($p < 0.001$), W_{CON} ($p < 0.001$), RFD_{ECC} ($p < 0.001$), RFD_{CON} ($p < 0.001$), and v_{avg} ($p < 0.001$).

Table 1. Intra-class correlation (ICC) coefficient to determine within-subject reliability.

	Load Condition			
	TL	TLC	AEL1	AEC
PP	0.98	0.99	0.96	0.98
W_{ECC}	1.00	1.00	1.00	0.99
W_{CON}	1.00	1.00	0.99	0.99
RFD_{ECC}	0.96	0.92	0.94	0.80

RFD_{CON}	0.97	0.85	0.90	0.98
v_{avg}	0.91	0.96	0.87	0.90

PP = peak power; W_{ECC} = eccentric work; W_{CON} = concentric work; RFD_{ECC} = eccentric rate of force development; RFD_{CON} = concentric rate of force development; v_{avg} = average concentric velocity; TL = traditionally loaded straight sets; TLC = traditionally loaded cluster sets; AEL1 = accentuated eccentric loaded straight sets where only first repetition had eccentric overload applied; AEC = accentuated eccentric loaded cluster sets where each repetition had eccentric overload applied.

Table 2. Descriptive statistics using mean ± standard deviation (coefficient of variation).

Variable	Load Condition			
	TL	TLC	AEL1	AEC
PP (W)	2526.10 ± 786.41 (7.12%)	2836.39 ± 993.46 (4.69%)	2546.92 ± 857.03 (7.36%)	2660.36 ± 819.61 (9.18%)
W_{ECC} (N•m)	1483.60 ± 253.92 (1.51%)	1479.41 ± 272.80 (1.49%)	1502.69 ± 253.97 (4.64%)	1627.54 ± 267.56 (2.24%)
W_{CON} (N•m)	1581.67 ± 287.94 (1.70%)	1622.39 ± 329.97 (1.77%)	1586.67 ± 305.73 (2.31%)	1604.31 ± 284.03 (2.64%)
RFD_{ECC} (N/s)	2719.97 ± 1259.78 (19.87%)	2595.35 ± 1189.66 (19.84%)	2857.69 ± 1477.50 (40.94%)	3348.43 ± 1437.19 (33.19%)
RFD_{CON} (N/s)	1486.16 ± 855.34 (19.14%)	1867.94 ± 876.51 (17.51%)	1480.92 ± 859.99 (21.58%)	1616.77 ± 942.67 (25.37%)
v_{avg} (m/s)	0.49 ± 0.07 (10.42%)	0.55 ± 0.07 (5.48%)	0.49 ± 0.09 (12.37%)	0.51 ± 0.08 (9.53%)

PP = peak power; W_{ECC} = eccentric work; W_{CON} = concentric work; RFD_{ECC} = eccentric rate of force development; RFD_{CON} = concentric rate of force development; v_{avg} = average concentric velocity; TL = traditionally loaded straight sets; TLC = traditionally loaded cluster sets; AEL1 = accentuated eccentric loaded straight sets where only first repetition had eccentric overload applied; AEC = accentuated eccentric loaded cluster sets where each repetition had eccentric overload applied.

Post hoc comparisons of load conditions without eccentric overload revealed TLC had statistically greater concentric outputs than TL (Table 3). However, post hoc comparisons showed that eccentric overload during the first repetition only during a straight (AEL1) set produced statistically greater W_{ECC} (d = 0.211, p = 0.024) compared with TL.

The next post hoc comparison examined the effect of AEL on cluster sets. Statistically greater RFD_{CON} (d = 0.470, p < 0.001) and v_{avg} (d = 0.560, p < 0.001) in TLC compared with AEC were observed. However, statistically greater W_{ECC} (d = 2.096, p < 0.001) and RFD_{ECC} (d = 0.424, p < 0.001) were observed in AEC compared with TLC. No statistical differences between TLC and AEC were present in PP (d = 0.125, p = 0.457) or W_{CON} (d = 0.161, p = 0.108).

In examining the potential difference between straight sets and the combination of interrepetition rest and eccentric overload, post hoc comparisons showed statistically greater W_{ECC} (d = 1.786, p < 0.001), W_{CON} (d = 0.225, p = 0.030), RFD_{ECC} (d = 0.342, p < 0.001), RFD_{CON} (d = 0.232, p = 0.01), v_{avg} (d = 0.201, p = 0.034) during AEC compared with TL. Statistically greater concentric characteristics were observed in TLC compared with AEL1; however, statistically greater eccentric outputs were observed in AEL1 (Table 3). The final post hoc comparison examined the difference between the 2 load conditions that used eccentric overload, AEL1 and AEC. Statistically greater W_{ECC} (d = 1.313, p < 0.001), RFD_{ECC} (d = 0.271, p = 0.006), RFD_{CON} (d = 0.262, p = 0.006), and v_{avg} (d = 0.252, p = 0.008) were observed in AEC compared with AEL1 (Table 3).

Table 3. Post hoc comparisons and effect sizes with practical interpretations (21).

Variable	Load Condition	Comparator	Cohen's *d*		p_{holm}
PP	AEL1	TL	0.018	(Trivial)	0.819
		TLC	-0.342	(Small)	< 0.001*
		AEC	-0.086	(Trivial)	0.619
	TLC	TL	0.268	(Small)	0.004*
		AEC	0.125	(Trivial)	0.457
	AEC	TL	0.100	(Trivial)	0.619
W_{ECC}	AEL1	TL	0.211	(Small)	0.024*
		TLC	0.255	(Small)	0.008*
		AEC	-1.313	(Large)	< 0.001*
	TLC	TL	-0.088	(Trivial)	0.292
		AEC	-2.096	(Very Large)	< 0.001*
	AEC	TL	1.786	(Large)	< 0.001*
W_{CON}	AEL1	TL	0.063	(Trivial)	0.448
		TLC	-0.380	(Small)	< 0.001*
		AEC	-0.186	(Small)	0.080
	TLC	TL	0.500	(Moderate)	< 0.001*
		AEC	0.161	(Trivial)	0.108
	AEC	TL	0.225	(Small)	0.030*
RFD_{ECC}	AEL1	TL	0.099	(Trivial)	0.259
		TLC	0.224	(Small)	< 0.001*
		AEC	-0.271	(Small)	0.006*
	TLC	TL	-0.127	(Trivial)	0.259
		AEC	-0.424	(Small)	< 0.001*
	AEC	TL	0.342	(Small)	< 0.001*
RFD_{CON}	AEL1	TL	-0.013	(Trivial)	0.871
		TLC	-0.886	(Moderate)	< 0.001*
		AEC	-0.262	(Small)	0.006*
	TLC	TL	0.890	(Large)	< 0.001*
		AEC	0.470	(Small)	< 0.001*
	AEC	TL	0.232	(Small)	0.012*
v_{avg}	AEL1	TL	-0.072	(Trivial)	0.389
		TLC	-0.954	(Moderate)	< 0.001*
		AEC	-0.252	(Small)	0.008*
	TLC	TL	1.035	(Moderate)	< 0.001*
		AEC	0.560	(Small)	< 0.001*
	AEC	TL	0.201	(Small)	0.034*

* = statistically significant relationship at a critical alpha of 0.05; PP = peak power; W_{ECC} = eccentric work; W_{CON} = concentric work; RFD_{ECC} = eccentric rate of force development; RFD_{CON} = concentric rate of force development; v_{avg} = average concentric velocity; TL = traditionally loaded straight sets; TLC = traditionally loaded cluster sets; AEL1 = accentuated eccentric loaded straight sets where only first repetition had eccentric overload applied; AEC = accentuated eccentric loaded cluster sets where each repetition had eccentric overload applied.

Discussion

The purpose of this investigation was to explore the kinetic and kinematic differences between potential programming tactics in the back squat. Specifically, the authors aimed to determine (a) the effects of eccentric overload on eccentric and concentric characteristics and (b) the effects of interrepetition rest on eccentric and concentric characteristics to gain insight into the potential applications of these programming tactics in resistance training. The results of the current investigation reveal that eccentric overload significantly increases the work performed during the eccentric phase compared with TL, even when applied to only the initial repetition of a set. The results demonstrate the favorable effects of interrepetition rest interval on concentric outputs, which agrees with previous literature on cluster sets (15, 19). Finally, acute potentiation of concentric outputs following application of eccentric overload was not supported.

Previous research has demonstrated the effectiveness of AEL to enhance muscle hypertrophy, particularly in the type II fibers (13, 14, 41). Greater mechanical tension experienced during AEL eccentrically compared to traditionally loaded resistance training is a potential mechanism for this effect (12). The current investigation supports this hypothesis, as the application of eccentric overload (AEL1 and AEC) significantly increased W_{ECC} compared with traditional loading (TL and TLC). The larger summation of forces experienced during AEL may therefore provide rationale for increased mechanical tension and the previously observed alterations in muscle hypertrophy with chronic exposure to AEL (13, 14, 41). Even when eccentric overload was applied for a single repetition within a given set, as in AEL1, the small effect observed in W_{ECC} compared to both traditionally loaded conditions may have valuable implications when chronically applied. This novel and practical loading tactic affords the coach the opportunity to maintain aspects of straight sets (e.g. metabolite accumulation) with the potential additional outcome of muscle hypertrophy due to higher absolute EL (12, 15). Although beyond the scope of this investigation, future studies should explore the influence that the chronic exposure to increased eccentric work in the back squat has on changes in muscle size.

Another potential rationale for prescribing AEL as a programming tactic in resistance training is to facilitate an acute potentiating effect. Accentuated eccentric loading has been demonstrated to acutely potentiate concentric outputs in previous literature (11, 29, 31). However, the potentiating effects of AEL on the squat have only been recently investigated (27, 29). When eccentric actions are rapid and forceful, it is possible that a greater muscle spindle activation (7), a greater stretch of the musculotendinous complex (16), or a pre-attachment of cross-bridges (3) occur and contribute to enhancing concentric force application. To fully exploit these potentially favorable mechanisms, a rapid eccentric action should be tightly coupled with the concentric action (38). The statistically greater RFD_{ECC} observed during AEC compared with TL conditions suggest the eccentric action immediately preceding the concentric phase was more rapid because of the presence of overload. Considering the established relationship between eccentric RFD and concentric potentiation (26), enhanced concentric outputs would be expected. However, concentric PP, W_{CON}, RFD_{CON}, and v_{avg} were all unaffected by the inclusion of eccentric overload in the current investigation. The findings agree with Munger et al. regarding 105% 1RM as an eccentric overload (29). Because there was no difference in concentric outputs as opposed to a detrimental result, it is possible that the eccentric loading was not substantial enough to induce potentiation. Potentiation has recently been demonstrated in the squat using greater magnitudes of eccentric overload, upwards of 120% (29). However, the optimal intensity prescription and other programming decisions may be more nuanced. Acute potentiation from

AEL appears to be highly individualized (31) and consideration may need to be made to both the eccentric and concentric load prescriptions (39). It is also worth noting at this point that magnitude of overload prescription may be somewhat dependent on exercise selection (11, 29, 31, 40). Ojasto and Häkkinen observed force production decrements at 105, 110, and 120% 1RM eccentric overload in the bench press (31). The concentric prescription of 100% 1RM used by Ojasto and Häkkinen may have also contributed to the observed fatiguing effect, whereas Munger et al. used 90% 1RM in the front squat (29, 31). It has also been suggested that maximal eccentric contractions could have detrimental effects on concentric outputs when coupled, albeit using isokinetic exercise (23). Nonetheless, previous work combined with the findings of the current investigation emphasize the potentially delicate nature of balancing potentiation and fatigue when using AEL as well as the myriad of programming aspects that should be considered (29, 31).

One common strategy to manage acute fatigue is to provide an athlete with interrepetition rest (15). Cluster sets have also previously demonstrated the ability to be an effective method for inducing velocity and power adaptations to specific loads (18, 28). Acutely, such a tactic allows the athlete to have consistently higher power outputs while incurring less metabolic stress and fatigue (15). The results of this investigation agree with previous research, as PP, W_{CON}, RFD_{CON}, and v_{avg} were all significantly greater in TLC compared with straight set conditions. Adding eccentric overload to a cluster appears to have a trivial negative effect on PP and W_{CON} when compared with TLC. Furthermore, RFD_{CON} and v_{avg} had small effect detriments in AEC compared to TLC. These findings suggest that when the highest potential rates of movement and force application are the desired outcome, adding eccentric overload to the existing approach of interrepetition rest may be disadvantageous.

In conclusion, the results of the current investigation demonstrate that (a) the addition of eccentric overload increases the magnitude and rate of eccentric force development. (b) Although theoretically relevant for acute potentiation, AEL may be sensitive to the magnitude of overload to elicit increases in concentric outputs. (c) Our results provide strong evidence for the inclusion of interrepetition rest in producing the greatest concentric outputs, especially considering rate-related measures. Future research should investigate the role that different combinations of eccentric and concentric loading schemes have on acute potentiation to further elucidate this point. Future research should also examine the adaptations and delayed training effects associated with chronic exposure to AEL, particularly regarding strength and power athletes based on the current findings and those of previous literature.

Practical Application

Eccentric overload demonstrated efficacy as a means of increasing eccentric work and rate of force development, but its efficacy in acute concentric potentiation was not supported by the current investigation. Therefore, strength and conditioning coaches may choose to implement AEL as a progression towards more rapid and forceful eccentric actions such as plyometrics or sprinting. The value of interrepetition rest on concentric output was also demonstrated in the current investigation. This finding supports previous literature of the potential utility of cluster sets as a means of increasing the overall power output of the athlete within a training session (15, 19). Such a strategy may potentially be useful during tapering and peaking phases of periodized resistance training plans. Lastly, the usage of interrepetition rest intervals may be programmed when the highest achievable concentric outputs are desired (e.g. peak power and RFD), but may be at the expense of potential metabolic effects present when interrepetition rest is not prescribed.

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CHAPTER 4

STUDY II

REPETITION-TO-REPETITION DIFFERENCES USING CLUSTER AND ACCENTUATED ECCENTRIC LOADING IN THE BACK SQUAT

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Abstract

The current investigation was an examination of the repetition-to-repetition magnitudes and changes in kinetic and kinematic characteristics of the back squat using accentuated eccentric loading (AEL) and cluster sets. Trained male subjects (age = 26.1 ± 4.1 years, height = 183.5 ± 4.3 cm, body mass = 92.5 ± 10.5 kg, back squat to body mass ratio = 1.8 ± 0.3) completed four load condition sessions, each consisting of three sets of five repetitions of either traditionally loaded straight sets (TL), traditionally loaded cluster sets (TLC), AEL cluster sets (AEC), and AEL straight sets where only the initial repetition had eccentric overload (AEL1). Eccentric overload was applied using weight releasers, creating a total eccentric load equivalent to 105% of concentric one repetition maximum (1RM). Concentric load was 80% 1RM for all load conditions. Using straight sets (TL and AEL1) tended to decrease peak power (PP) (d = –1.90 to –0.76), concentric rate of force development (RFD_{CON}) (d = –1.59 to –0.27), and average velocity (MV) (d = –3.91 to –1.29), with moderate decreases in MV using cluster sets (d = –0.81 to –0.62). Greater magnitude eccentric rate of force development (RFD_{ECC}) was observed using AEC at repetition three (R3) and five (R5) compared to all load conditions (d = 0.21–0.65). Large within-condition changes in RFD_{ECC} from repetition one to repetition three (ΔREP1–3) were present using AEL1 (d = 1.51), demonstrating that RFD_{ECC} remained elevated for at least three repetitions despite overload only present on the initial repetition. Overall, cluster sets appear to permit higher magnitude and improved maintenance of concentric outputs throughout a set. Eccentric overload with the loading protocol used in the current study does not appear to potentiate concentric output regardless of set configuration but may cause greater RFD_{ECC} compared to traditional loading.

Introduction

Strength-power adaptations to resistance training are primarily determined by the mode of exercise which is implemented and type of loading encountered [1]. The development of strength and power can be optimized through proper management of acute training variables such as sets, reps, rest periods and exercise order [2]. However, greater degrees of variation and novelty of stimulus are required to continue to drive changes in athletes with an advanced training status [3,4]. Novelty and variation must be systematically planned, sequenced, and with consideration of the multi-faceted nature of the demands of sporting actions. Therefore, coaches must make creative manipulations of the more nuanced variables to properly disrupt homeostasis with two of the most prevalent being accentuated eccentric loading (AEL) and inter-repetition rest.

Accentuated eccentric loading (AEL) is an advanced training tactic – aiming to exploit the muscle's ability to produce greater force during eccentric muscle actions compared to isometric and concentric actions [5,6]. This method is prescribed for movements that require coupled eccentric-concentric actions (e.g. back squat, bench press), using eccentric loads in excess of the concentric prescription. Ideally, this is achieved while imparting minimal interruption to natural mechanics of the chosen exercise [7]. Accentuated eccentric loading has been explored in several studies using both upper [8-11] and lower body [10-12] exercises. AEL has demonstrated positive effects on concentric performance compared to traditional loading patterns [8,12] though not all studies agree [9-11]. The inconsistent nature of the existing evidence may be largely due to the discrepancy in both eccentric and concentric loading, means of application, exercise selection, among other confounders. Furthermore, as AEL typically requires time between repetitions to reload the eccentric load, it is possible the inter-repetition rest may explain some of the purported benefits of AEL [13].

Inter-repetition rest – typically termed a cluster set – is an efficacious programming tactic independent from its potential influence on AEL. Previous literature has demonstrated that various cluster set arrangements can offset the loss in movement velocity and maintain power outputs [14-16]. Interestingly, the potentiating effects of cluster sets appear to be more substantial when prescribed to athletes with an advanced training age [17], suggesting clusters may be more appropriately applied as an advanced tactic [18]. Some have suggested this may be the case regarding AEL as well [7], though such a hypothesis must be explored further. To exploit the potential advantages of the aforementioned strategies, an intimate knowledge of their acute characteristics is valuable in hypothesizing the chronic response.

Though previous literature has recently elucidated foundational kinetic and kinematic characteristics of AEL and cluster sets [13], repetition-to-repetition magnitudes and maintenance have not yet been examined. Therefore, the purpose of the current investigation was to build upon previous findings [13] and explore the repetition-to-repetition kinetic and kinematic differences between potential programming tactics in the back squat. Specifically, the authors aimed to determine the effects of (1) eccentric overload and (2) inter-repetition rest on the magnitude and repetition-to-repetition changes of rate-related eccentric and concentric characteristics. The findings of the current investigation aim to inform resistance training programming decisions by providing more robust information regarding the separate and combined effects of these increasingly prevalent training strategies.

Materials and Methods

Subjects

Eleven resistance-trained males (age = 26.1 ± 4.1 years, height = 183.5 ± 4.3 cm, body mass = 92.5 ± 10.5 kg, back squat to body mass ratio = 1.8 ± 0.3) volunteered for the current investigation. To qualify, subjects were required to have spent at least the past year in a weekly resistance training program that consistently included back squats. Urinary specific gravity was determined prior to any data collection using a refractometer (Atago, Tokyo, Japan) to ensure the subjects' hydration status would not influence the results [19]. All subjects read and signed a written informed consent and the procedures were approved by the university's Institutional Review Board.

Procedures

Dynamic strength was measured using a previously established one-repetition maximum back squat (1RM) protocol [20]. The 1RM was achieved by each subject within three maximal attempts that was preceded by a standardized squat warm-up based on each subjects' self-reported 1RM back squat. The final successful 1RM attempt was subsequently used in determining load prescription for experimental loading conditions.

The initial experimental back squat session began a minimum of 48-hours following each subject's dynamic strength testing. Experimental sessions were completed in a random order using an online randomization tool [21]. Following the initial load condition, each subsequent session was separated by seven days and executed at the same time of day for each subject. Between sessions, subjects were permitted to train typical to that of their respective routines except for complete rest 48-hours prior to any data collection. The general and specific warm-up was identical to that used in dynamic strength testing [20], with loading adjusted based on the tested 1RM. Subjects performed three sets of five repetitions of the barbell back squat for each prescribed condition, with each set separated by three minutes of passive rest. Concentric intensity for all load conditions was 80% 1RM [22]. Accentuated eccentric loading totaled 105% of 1RM [8,22,23] and was applied to prescribed repetitions via weight releasers (Monster Grips, Columbus, OH, USA) [12,23,24]. Subjects were strongly verbally encouraged in the same manner during each session to perform the concentric phase of the squat as explosively as possible.

Four loading conditions which were typical of athletic populations were used to better understand the uniqueness of different programming strategies. Traditionally loaded "straight sets" (TL) were completed with no intra-set rest, completing each of the five back squat repetitions per set consecutively. No more than three seconds were allowed between repetitions. Two load conditions allowed intra-set rest, which is the basis for a cluster set [18]. Traditionally loaded cluster sets (TLC) were completed with identical load to TL, but 30-seconds of intra-set standing rest was prescribed where the subjects placed the barbell on the safety hooks of the squat rack between repetitions. During the accentuated eccentric load cluster set condition (AEC), all five repetitions of the back squat were completed with eccentric overload (105% 1RM) with otherwise identical procedures to those of TLC. The accentuated eccentric load "straight set" condition (AEL1) added an eccentric overload to the first repetition of each set only and subsequent repetitions were completed using procedures identical to TL. The AEL1 condition aimed to examine the effects of AEL without intra-set rest.

Data were collected using a dual force plate design (2 x 91 cm x 45.5 cm force plates, Roughdeck HP, Rice Lake, WI) inside a custom-built apparatus with data sampled at 1,000 Hz

[13]. Four linear position transducers (PT101-0100-H14-1120, Celesco, Chatsworth, CA, USA) were attached to the top of the custom-built apparatus and recoil wires were attached to the each of the ends of the barbell just inside where the plates were loaded [13]. The linear position transducers were synchronized with the force plates using a custom LabVIEW (version 7.1, National Instruments) program. Data were processed using RStudio (Version 1.0.153, RStudio, Inc., Boston, MA). To account for and diminish noise, a digital Butterworth 2nd order low-pass filter was applied. Eccentric and concentric phases were confirmed by the displacement values obtained from the linear position transducers. Repetition-to-repetition values and changes in peak power (PP), eccentric rate of force development (RFD_{ECC}), concentric rate of force development (RFD_{CON}), and concentric average velocity (MV) were assessed for each load condition. The slope between eccentric peak force and the force value 250 ms prior to eccentric peak force was used to determine RFD_{ECC} [25]. The timepoint of 250 ms was chosen to reflect the upper limit of time in which stored eccentric energy may be used to enhance the subsequent concentric action rather than dissipated as heat [26]. Concentric rate of force development was determined using the concentric peak force and the force value 250 ms prior [27].

Statistical Analyses

Descriptive statistics including mean and 90% confidence interval (CI) were calculated for the first (R1), third (R3), and fifth (R5) repetitions as well as the change from R1 to R3 ($\Delta REP_{1\text{-}3}$) and change from R1 to R5 ($\Delta REP_{1\text{-}5}$) (Table 1-4). Within subject reliability for each dependent variable was assessed using coefficient of variation (CV) and intraclass correlation coefficients (ICC (2,1)), with every repetition performed being considered in determining reliability [28,29]. Coefficient of variation was calculated using the mean and standard deviation of each dependent variable. Within-condition Cohen's d effect sizes (ES) and 90% CI were calculated for $\Delta REP_{1–3}$ and $\Delta REP_{1–5}$ using the average of each individual's effect statistic [30]. Between-condition Cohen's d ES and 90% CI were calculated for each dependent variable [30]. Effect sizes were interpreted with magnitude thresholds of 0–0.2, 0.2–0.6, 0.6–1.2, 1.2–2.0, and 2.0 and above as trivial, small, moderate, large, and very large [31]. Statistical analyses were performed using Microsoft ExcelTM (Version 1806, Redmond, WA, USA).

Results

Descriptive statistics for each dependent variable are displayed in Tables 1–4. Relative reliability of all dependent variables returned at least very large ICC (2,1) values, while absolute reliability of the dependent variables returned CV values ranging between 1.49–40.94% when considering all repetitions collected [13]. Within- and between-condition ES are presented in Figure 1 and Table 5, respectively. Concentric outputs tended to decrease in both straight-set configurations (TL and AEL1): peak power (d = –1.90 to –0.76), RFD_{CON} (d = –1.59 to –0.27), and MV (d = –3.91 to –1.29). Additionally, moderate decreases were observed for MV during both cluster conditions (d = –0.81 to –0.62).

Accentuated eccentric clusters elicited greater RFD_{ECC} magnitudes in R3 and R5 compared to all other load conditions (d = 0.21–0.65). Conversely, small-to-moderate effect sizes indicated RFD_{CON} was greater during TLC than all other load conditions at R3 and R5 (d = 0.33–0.64). Consistent with concentric RFD, MV was greatest in the TLC condition. Relative to straight-set configurations (TL and AEL1), between-condition effect magnitudes became larger throughout the set, at R1 (d = 0.27–0.31, small), R3 (d = 0.67–0.72, moderate), and R5 (d = 1.34–1.51, large). Interestingly, the effect magnitudes between both cluster configurations (TLC and AEC) remained similar throughout the set, slightly favoring TLC (d = 0.30–0.42, small). Small-to-moderate effects indicated greater PP (d = 0.52) and MV (d = 0.61) during TLC compared to TL. However, only trivial effects were observed between TLC and AEC considering PP and MV changes.

Table 1. Concentric peak power presented as mean (M) ± 90% confidence interval (CI).

Repetition	PP (W)											
	TL			TLC			AEL1			AEC		
R1	2638.12	±	241.45	2869.44	±	300.62	2704.62	±	272.97	2797.67	±	295.10
R3	2496.74	±	221.79	2844.20	±	282.82	2525.61	±	244.91	2627.10	±	228.15
R5	2364.68	±	203.80	2791.61	±	276.63	2415.14	±	228.50	2651.61	±	212.77
$\Delta REP_{1–3}$	–141.38	±	52.67	–25.24	±	31.98	–179.01	±	56.18	–170.57	±	169.53
$\Delta REP_{1–5}$	–273.44	±	83.10	–77.83	±	56.94	–289.48	±	60.62	–146.06	±	151.38

PP = peak power; R1 = first repetition; R3 = third repetition; R5 = fifth repetition; $\Delta REP_{1–3}$ = change from first repetition to third repetition; $\Delta REP_{1–5}$ = change from first repetition to fifth repetition.

Table 2. Eccentric rate of force development presented as mean (M) ± 90% confidence interval (CI).

Repetition	RFD_{ECC} (N/s)											
	TL			TLC			AEL1			AEC		
R1	2515.93	±	329.17	2752.57	±	336.82	2766.49	±	528.00	3115.18	±	372.94
R3	2735.06	±	373.72	2412.35	±	316.22	2943.66	±	403.30	3237.90	±	409.44
R5	2764.42	±	358.83	2448.90	±	324.01	2816.68	±	375.33	3270.97	±	461.88
$\Delta REP_{1–3}$	219.13	±	170.26	–340.21	±	235.77	177.17	±	660.08	122.72	±	314.70
$\Delta REP_{1–5}$	248.49	±	103.48	–303.67	±	227.92	50.19	±	684.15	155.80	±	414.89

RFD_{ECC} = eccentric rate of force development; R1 = first repetition; R3 = third repetition; R5 = fifth repetition; $\Delta REP_{1–3}$ = change from first repetition to third repetition; $\Delta REP_{1–5}$ = change from first repetition to fifth repetition.

Table 3. Concentric rate of force development presented as mean (M) ± 90% confidence interval (CI).

Repetition	RFD_{CON} (N/s)											
	TL			TLC			AEL1			AEC		
R1	1518.94	±	223.43	1863.61	±	260.99	1704.26	±	311.61	1629.89	±	289.27
R3	1440.05	±	234.43	1906.43	±	297.33	1401.40	±	230.31	1583.12	±	265.56
R5	1386.14	±	260.16	1901.80	±	306.73	1318.00	±	206.97	1542.21	±	255.12
$\Delta REP_{1–3}$	–78.90	±	61.15	42.82	±	81.31	–302.86	±	114.53	–46.77	±	179.36
$\Delta REP_{1–5}$	–174.81	±	75.17	38.19	±	89.11	–386.27	±	128.38	–87.68	±	199.46

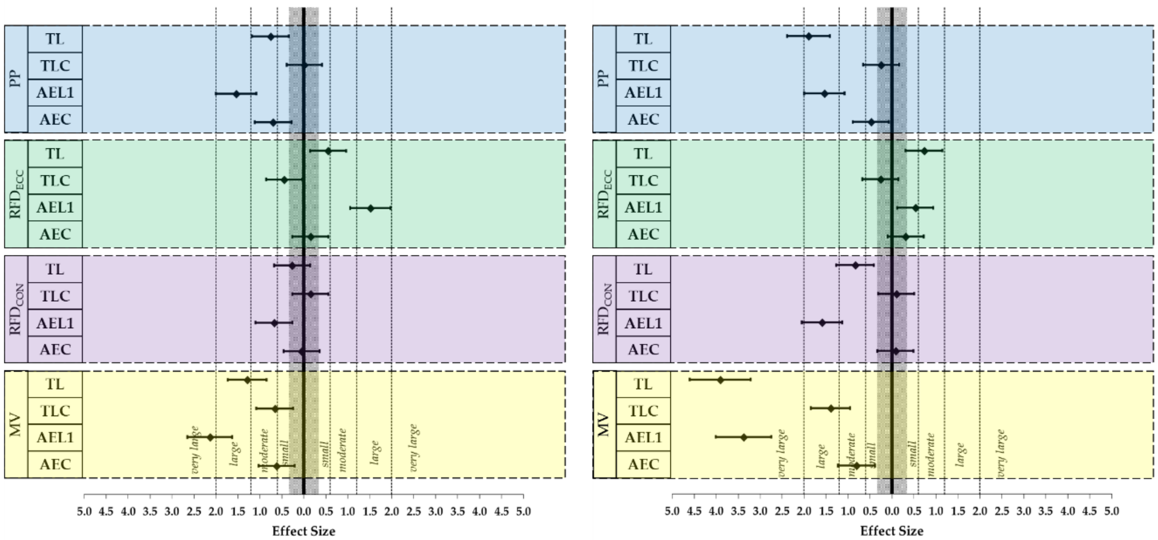
RFD_{CON} = concentric rate of force development; R1 = first repetition; R3 = third repetition; R5 = fifth repetition; $\Delta REP_{1–3}$ = change from first repetition to third repetition; $\Delta REP_{1–5}$ = change from first repetition to fifth repetition.

Table 4. Concentric average velocity presented as mean (M) ± 90% confidence interval (CI).

Repetition	MV (m/s)											
	TL			TLC			AEL1			AEC		
R1	0.54	±	0.02	0.56	±	0.02	0.54	±	0.02	0.54	±	0.02
R3	0.49	±	0.02	0.54	±	0.02	0.48	±	0.03	0.51	±	0.02

R5	0.43	±	0.02	0.52	±	0.02	0.42	±	0.02	0.49	±	0.02
ΔREP_{1-3}	–0.05	±	0.01	–0.02	±	0.00	–0.06	±	0.01	–0.03	±	0.02
ΔREP_{1-5}	–0.11	±	0.01	–0.04	±	0.01	–0.12	±	0.01	–0.05	±	0.02

MV = average concentric velocity; R1 = first repetition; R3 = third repetition; R5 = fifth repetition; ΔREP_{1-3} = change from first repetition to third repetition; ΔREP_{1-5} = change from first repetition to fifth repetition.



(**a**) (**b**)

Figure 1. Within-condition Cohen's *d* effect sizes ± 90% confidence interval for (**a**) the magnitude of change from repetition one to repetition three (ΔREP_{1-3}) and (**b**) the magnitude of change from repetition one to repetition five (ΔREP_{1-5}).

Table 5. Between-condition Cohen's *d* effect sizes ± 90% confidence interval.

Repetition			PP	RFD$_{ECC}$	RFD$_{CON}$	MV
R1	AEL1	TL	0.09 ± 0.41	0.16 ± 0.41	0.20 ± 0.41	0.02 ± 0.40
		TLC	–0.16 ± 0.41	0.01 ± 0.40	–0.16 ± 0.41	–0.27 ± 0.41
		AEC	–0.09 ± 0.41	–0.22 ± 0.41	0.07 ± 0.41	0.03 ± 0.40
	TLC	TL	0.30 ± 0.41	0.20 ± 0.41	0.41 ± 0.41	0.31 ± 0.41
		AEC	0.07 ± 0.41	–0.29 ± 0.41	0.24 ± 0.41	0.30 ± 0.41
	AEC	TL	0.21 ± 0.41	0.49 ± 0.41	0.12 ± 0.41	–0.01 ± 0.40
R3	AEL1	TL	0.04 ± 0.41	0.15 ± 0.41	–0.05 ± 0.41	–0.18 ± 0.41
		TLC	–0.34 ± 0.41	0.42 ± 0.41	–0.54 ± 0.41	–0.72 ± 0.42
		AEC	–0.12 ± 0.41	–0.21 ± 0.41	–0.21 ± 0.41	–0.34 ± 0.41
	TLC	TL	0.39 ± 0.41	–0.27 ± 0.41	0.50 ± 0.41	0.67 ± 0.42
		AEC	0.24 ± 0.41	–0.65 ± 0.42	0.33 ± 0.41	0.42 ± 0.41
	AEC	TL	0.17 ± 0.41	0.37 ± 0.41	0.16 ± 0.41	0.21 ± 0.41
R5	AEL1	TL	0.07 ± 0.41	0.04 ± 0.41	-0.08 ± 0.41	–0.06 ± 0.41
		TLC	–0.42 ± 0.41	0.30 ± 0.41	-0.64 ± 0.42	–1.34 ± 0.45
		AEC	–0.31 ± 0.41	–0.31 ± 0.41	-0.28 ± 0.41	–0.88 ± 0.42
	TLC	TL	0.50 ± 0.41	–0.26 ± 0.41	0.52 ± 0.41	1.51 ± 0.46
		AEC	0.16 ± 0.41	–0.59 ± 0.41	0.36 ± 0.41	0.40 ± 0.41
	AEC	TL	0.39 ± 0.41	0.35 ± 0.41	0.17 ± 0.41	0.95 ± 0.43

PP = peak power; RFD_{ECC} = eccentric rate of force development; RFD_{CON} = concentric rate of force development; MV = average concentric velocity; R1 = first repetition; R3 = third repetition; R5 = fifth repetition.

Discussion

The purpose of this investigation was to explore the repetition-to-repetition kinetic and kinematic differences between potential programming tactics in the back squat. Specifically, the authors aimed to determine the effects of (1) eccentric overload and (2) inter-repetition rest on the magnitude and repetition-to-repetition changes of rate-related eccentric and concentric characteristics. In agreement with previous literature [32], the results of the current investigation suggest that the use of inter-repetition rest elicits a higher magnitude of peak power between conditions, paired with an increased ability to maintain peak power within a set compared to all load conditions through the initial three repetitions. This influence appears to be mainly driven by kinematic factors (i.e. MV). Accentuated eccentric loading does not appear to provide a potentiating effect on concentric output in straight-set or cluster-set configurations but may impart higher magnitude RFD_{ECC} compared to traditional loading.

Cluster sets have demonstrated efficacy as a method of inducing velocity and power adaptations [33,34]. Following a training program that included squats and weightlifting derivatives, Hansen and colleagues [34] demonstrated that the use of cluster sets throughout training caused greater changes in PP and peak velocity characteristics of a jump squat compared to the use of straight sets. Such chronic responses are likely related to the acute characteristics of cluster sets with higher velocity magnitudes within a session [35] and power output magnitudes within a set [36] observed using cluster set compared to straight set configurations. In agreement with previous literature, TLC resulted in greater concentric PP, RFD_{CON}, and MV compared to straight set load conditions at R3 and R5. Interestingly, TLC also produced higher MV at R1 compared to all experimental conditions, potentially indicating that using TLC allows the carryover of less fatigue from set-to-set. Although, this may be the result of longer total rest compared to straight sets. Alternatively, this may indicate that intent is influenced by an athlete knowing whether an inter-repetition rest will be provided. Rationale aside, TLC permits the athlete an opportunity to express greater concentric outputs potentially advantageous in the later stages of a periodized training plan where such an emphasis is typically prescribed [37]. Moreover, ΔREP_{1-3} and ΔREP_{1-5} decreases were the least substantial in cluster configurations (TLC and AEC), further emphasizing its utility in maintaining concentric outputs across a set. This agrees with previous literature [32] and supports the efficacy of inter-repetition rest in acute management of fatigue. The application of eccentric overload during a cluster set (i.e. AEC) at least of the magnitude used in the current study caused a unique response. Higher magnitude MV were observed at R1, R3, and R5 using TLC compared to AEC. However, the ΔREP_{1-5} effect magnitude was less negative during AEC, indicating once again that intent may be influenced by the details of the loading strategy. The results comparing TLC and AEC suggest that the athletes may have been adjusting concentric intent to ensure sufficient energy was available to undertake the eccentric overload. Therefore, TLC may be most advantageous compared to AEC in maximizing the magnitude of concentric output, but AEC may be applied if maintenance within a set is desired.

A typical and theoretically-sound rationale for prescribing AEL in resistance training is to acutely potentiate the concentric output and has demonstrated effectiveness in the previous literature using bench press and squats [8,12,23]. However, evidence that AEL does not elicit a potentiating response is similarly prevalent [38] though the relative inconsistency in loading means and magnitude makes drawing definitive conclusions problematic. The current investigation is the first to consider repetition-to-repetition magnitudes and within-set changes using two different AEL strategies, though these strategies have been explored from the training session-level in prior study [13]. As previously discussed, considering R1 before significant accumulation of fatigue would theoretically be experienced and immediately preceded by full recovery, the application of eccentric overload induced small detrimental effects on MV magnitude compared to TLC. Interestingly, RFD_{CON} was greater at R1 when eccentric overload was prescribed during straight sets, but lower when applied to a cluster set. Though initially appearing to add to the convoluted nature of the evidence regarding the potentiating effects of AEL, the between-condition effects on RFD_{CON} and MV worsened at R3 and R5 compared to traditionally loaded conditions, suggesting a fatiguing effect from AEL. Providing further support, within-condition $\Delta REP_{1–3}$ decreases in RFD_{CON} and MV were also larger when eccentric overload was applied to straight sets. However, because $\Delta REP_{1–3}$ and $\Delta REP_{1–5}$ were similar between TLC and AEC, changes in intent should again be considered as a rationale.

Though the current investigation presented evidence supporting the potentially fatiguing nature of AEL, this may be due to a sensitivity in concentric or eccentric load prescription rather than a generalizable conclusion regarding eccentric overload. More important may be the presence of kinetic characteristics that have demonstrated efficacy in potentiating concentric outputs. For example, when high RFD_{ECC} is present, it is possible that a greater muscle spindle activation [39] or a pre-attachment of cross-bridges via Ca2+ influx [40] occur both of which contribute to acute concentric potentiation so long as the eccentric and concentric action are tightly coupled [26]. Higher magnitude RFD_{ECC} were observed in AEC compared to TLC, providing a mechanistic rationale for induction of acute potentiation via AEL. Further, large within-condition ΔREP_{1-3} for RFD_{ECC} were present using AEL1. This suggests that despite overload being applied during R1 only, the enhancement in RFD_{ECC} may continue for at least three repetitions. The effect at ΔREP_{1-5} reduced to small and a lower magnitude RFD_{ECC} was produced at R5 compared to R3, meaning that if this eccentric facilitation were desired, three repetitions within a set may be more optimal. This provides important practical considerations for coaches, as weight releasers may not need to be reapplied at each repetition to enhance RFD_{ECC} within a set. Despite convincing evidence that RFD_{ECC} is enhanced using AEL, this did not correspond with the expected comparatively higher concentric outputs (i.e. PP, RFD_{CON}, MV). It is possible then, that the eccentric overload prescription produced the desired outcome, but the concentric load prescription may need to be lowered to produce acute concentric potentiation. Previous investigations have explored the effects of different magnitudes of eccentric overload on potentiation at a fixed concentric load [8,12]. However, future investigations should consider the opposite – how manipulating the concentric prescription accompanied by a fixed eccentric overload influences acute potentiation.

Conclusions

The results of the current investigation demonstrate that inter-repetition rest permits higher magnitude and improved maintenance of kinetic and kinematic concentric outputs throughout a set. Further, AEL does not appear to provide a potentiating effect on concentric output in straight-set or cluster-set configurations but may impart higher magnitude RFDECC compared to traditional loading therefore providing the mechanistic characteristics to theoretically potentiate concentric outputs. Though potentiation was not observed in the current investigation, future study should focus on different concentric and eccentric load prescriptions using AEL to determine if concentric potentiation is prescription, rather than method-sensitive, in the back squat. Finally, important practical considerations were elucidated in applying eccentric overload for the initial repetition of the set. The results of the current investigation suggest that applying eccentric overload for the initial repetition of a set only may alter RFDECC substantially for at least two subsequent traditionally loaded repetitions. There were limitations to the current investigation that may have influenced the outcomes including differences in work and work-to-rest ratios between load conditions. However, this was a purposeful aspect of the design in order to make it a more practical comparison.

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CHAPTER 5

STUDY III

COMPARISON OF THE RELATIONSHIP BETWEEN LYING AND STANDING ULTRASONOGRAPHY MEASURES OF MUSCLE MORPHOLOGY WITH ISOMETRIC AND DYNAMIC FORCE PRODUCTION CAPABILITIES

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Abstract

The purpose of the current study was (1) to examine the differences between standing and lying measures of vastus lateralis (VL), muscle thickness (MT), pennation angle (PA), and cross-sectional area (CSA) using ultrasonography; and (2) to explore the relationships between lying and standing measures with isometric and dynamic assessments of force production—specifically peak force, rate of force development (RFD), impulse, and one-repetition maximum back squat. Fourteen resistance-trained subjects (age = 26.8 ± 4.0 years, height = 181.4 ± 6.0 cm, body mass = 89.8 ± 10.7 kg, back squat to body mass ratio = 1.84 ± 0.34) agreed to participate. Lying and standing ultrasonography images of the right VL were collected following 48 hours of rest. Isometric squat assessments followed ultrasonography, and were performed on force platforms with data used to determine isometric peak force (IPF), as well as RFD and impulse at various time points. Forty-eight hours later, one-repetition maximum back squats were performed by each subject. Paired-samples t-tests revealed statistically significant differences between standing and lying measurements of MT ($p < 0.001$), PA ($p < 0.001$), and CSA ($p \leq 0.05$), with standing values larger in all cases. Further, standing measures were correlated more strongly and abundantly to isometric and dynamic performance. These results suggest that if practitioners intend to gain insight into strength-power potential based on ultrasonography measurements, performing the measurement collection with the athlete in a standing posture may be preferred.

Introduction

Ultrasonography is commonly used to assess muscle size (e.g., muscle thickness, cross-sectional area) and architecture (e.g., pennation angle) [1-3], and has been shown to be valid against the gold standards magnetic resonance imaging [4-6] and dual energy X-ray absorptiometry [7,8]. Ultrasonography measurements are typically taken in a lying, and/or resting position, meaning that the muscle is likely evaluated in a position non-specific to upright activities. This could result in large alterations in measurements of muscle size and architecture due to the influence of gravity [9,10]. However, ultrasonography provides a level of versatility (e.g., subject positioning) that other methods do not. The adaptability of ultrasonography may be exploited to allow practitioners to develop techniques that capture muscle size and architecture in positions that maintain its functional configuration.

Muscle thickness (MT) and cross-sectional area (CSA) have previously shown moderate-to-strong relationships with magnitude of force production (r = 0.32–0.85) [10,11], while pennation angle (PA) has been more commonly associated with rate of force development (RFD) (r = 0.34–0.44) [12-14] when measurements are collected using ultrasonography. The non-specific nature of typical athlete positioning in ultrasonography assessment makes it plausible that the selected posture may influence the magnitude of relationship observed between muscle measurements and physical outputs. Ultrasonography techniques used to assess musculature as they relate to performance potential may be more appropriate if they closely reflect the positioning found in athletic maneuvers (e.g., standing). Standing assessments provide greater ecological validity, potentially yielding more precise associations between measures of muscle architecture and upright performance outcomes. To the authors' knowledge, the potential influence that subject positioning may have on the relationship between muscle function and architecture has not yet been explored.

Therefore, the purpose of the current study was (1) to examine the differences between standing and lying measures of MT, PA, and CSA using ultrasonography, and (2) to explore the relationships between lying and standing measures with isometric and dynamic assessments of force production. We hypothesized that standing measurements of muscle size and architecture would have comparatively greater relationships to such measures of physical output. This may be important for practitioners that work with athletic populations, as standing ultrasonography measurements may capture the muscle in a state that more closely represents its functional configuration.

Materials and Methods

Muscle Size and Architecture

Fourteen resistance-trained subjects (age = 26.8 ± 4.0 years, height = 181.4 ± 6.0 cm, body mass = 89.8 ± 10.7 kg, back squat to body mass ratio = 1.84 ± 0.34) volunteered for the current investigation. Subjects were required to have spent at least the past year on a resistance-training program that involved back squats. Subjects were assessed for MT, CSA, and PA of the right vastus lateralis (VL) in both lying and standing postures using ultrasonography (LOGIQ P6, General Electric Healthcare, Wauwatosa, WI, USA) [10,15]. All subjects' hydration status was determined using a refractometer (Atago, Tokyo, Japan) to ensure hydration status would not affect the ultrasound measurements [16]. Further, to ensure that there were minimal alterations in muscle size due to swelling, ultrasonography collection was performed at least 48 h after the most recent physical activity [17]. To determine anatomical landmark on the VL, subjects were positioned in the left lateral recumbent position with an internal knee angle of 160° ± 10°. A location half the distance between the greater trochanter and lateral epicondyle of the right femur was identified and marked. A distance 5 cm medial to the mid-femur marking was also identified and marked [9,18]. This medial marking was used for the measurement of MT. The same markings were used for both lying and standing ultrasonography measurements. All landmarks for all subjects were determined by a single practitioner, and images were collected in a repeated measures manner, and therefore any potential error would be systematic. All subjects gave informed consent, and the procedures were approved by the university's Institutional Review Board.

Lying Cross-Sectional Area Measurement

Lying ultrasonography measures began with the application of a water-soluble transmission gel to the measurement site and a 16 Hz probe oriented in the short-axis, perpendicular to the VL muscle, while not depressing the skin [19]. Lying cross-sectional area (LCSA) was obtained using a panoramic image sweep in the transverse plane perpendicular to the muscle [9]. A straight-edge was placed along the skin to ensure that the probe remained along the previously established midline. Three images were obtained and saved for subsequent analysis using the software provided within the ultrasonography device [10,18].

Lying Muscle Thickness and Pennation Angle Measurement

The measurement site location for MT and PA measurement was the point 5 cm medial to the mid-femur mark. The ultrasonography probe was then placed in the long axis, oriented parallel to the VL muscle. The probe was held at a 90° angle to the skin surface to maintain consistent images across subjects. Consistent with CSA measurement, three images were captured and saved for subsequent analysis to determine lying muscle thickness (LMT) and lying pennation angle (LPA). Analysis was performed using the software provided within the ultrasonography device [10,18].

Standing Ultrasonography Measurement

Following lying measures of LMT, LPA, and LCSA, standing measurements of muscle thickness (SMT), pennation angle (SPA), and cross-sectional area (SCSA) were collected. These methods were consistent with lying measures with one exception: for standing measures, the subject was upright and bearing weight on the opposite leg, which was positioned on a 5 cm tall platform, unweighting the measured leg and creating an internal knee angle of 160° ± 10° (Figure 1). Three separate long-axis images and three separate short-axis images were saved for subsequent analysis, the same as were used for the lying measurements [9].

Figure 1. Standing ultrasonography collection position.

Isometric Strength Assessment

Subjects completed a standardized general warm-up sequence before beginning the isometric strength assessment. After completing the dynamic warm-up, participants completed one set of five repetitions of the back squat with a 20 kg barbell followed by three sets of five repetitions at 60 kg, each separated by a 60 s rest. The isometric squat (ISQ) testing used an adapted protocol from McBride and colleagues [20,21]. Data were collected using a dual force platform design (2 × 91 cm × 45.5 cm force platforms, RoughDeck HP, Rice Lake, WI, USA) inside a custom-built apparatus, with data sampled at 1000 Hz. Participants’ bar height was set on an individual basis, to the point allowing the subject to have an internal knee angle of 100°, which was assessed using a goniometer (Figure 2) [20].

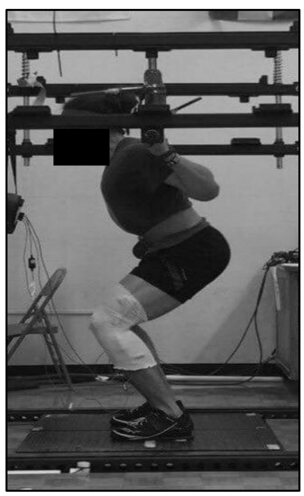

Figure 2. Isometric squat testing position.

Following bar-height adjustments, participants executed ISQ trials at 50% and 75% of their perceived maximal effort. Each subject performed a minimum of two maximal effort trials. If a countermovement of greater than 200 N was observed, or trials differed by more than 250 N, subjects were required to complete an additional trial [22]. When executing maximal effort trials, subjects were first instructed to apply steady pressure on the bar before imparting maximal effort to reduce the likelihood of a countermovement. Participants were further instructed to push ‘as fast and hard as possible’ and strongly verbally encouraged during trials [20,22]. A three-minute seated rest interval was prescribed between each of the ISQ trials. LabVIEW (Version 7.1, National Instruments, Austin, TX, USA) was used for collecting and ForceDecks (Version 1.2.6464, NMP Technologies Ltd., London, UK) for processing kinetic data [24]. Isometric peak force (IPF), rate of force development over 50 ms (RFD50), 100 ms (RFD100), 200 ms (RFD200), impulse over 50 ms (IMP50), 100 ms (IMP100), and 200 ms (IMP200) were calculated from the collected data.

Dynamic Strength Assessment

Dynamic strength testing was conducted using a one-repetition maximum (1RM) back squat, aimed at establishing dynamic peak strength capabilities. Dynamic strength testing was completed 48 h after isometric strength assessment to allow subjects to recover from any residual effects of the previous testing [24]. Prior to testing, each subject performed a general dynamic warm-up identical to that used in ISQ testing.

Following the warm-up, the bar height and safety bar heights in the squat rack were adjusted as needed to best accommodate each subject. Subjects then performed a 1RM back squat test using a protocol modified from Suchomel and associates [25], with warm-up set intensities based on each subject’s self-reported 1RM back squat (Table 1). All subjects attempted progressively heavier loads per the protocol in Table 1 until their 1RM back squat was attained. For a repetition to be considered successful, the subject’s hip crease must have been below the patella at the bottom of the descent during the back squat, as verified by multiple certified strength and conditioning professionals.

Table 1. Back squat warm-up.

Sets × Repetitions × Intensity (% 1RM)	Rest Interval
1% × 5% × 30%	1 min
1% × 3% × 50%	1 min
1% × 2% × 70%	2 min
1% × 1% × 80%	3 min
1% × 1% × 90%	3 min
1RM attempts	3 min

Statistical Analyses

Descriptive statistics, including mean and 95% confidence interval (CI) were calculated. Normality was evaluated for each variable using the Shapiro-Wilk assessment. Within-subject reliability for each muscle morphology variable was assessed using coefficient of variation (CV) and intraclass correlation coefficients (ICC) [26]. Due to the high reliability observed for each variable (Table 2), the average of the three images was used for statistical analysis. Good reliability was also observed for all variables considered from isometric performance testing (ICC = 0.79–1.00), so the averages of two trials were used for statistical analysis. Paired-samples t-Tests were calculated for standing versus lying measures of the same morphological variable to determine differences between the two subject positions. Correlations between all measurements of muscle morphology and isometric and dynamic performance capabilities were calculated using Pearson's *r*. Based on the current sample size, correlation of at least 0.53 was needed to establish a statistically significant relationship. For practical significance, Pearson's *r* values were interpreted with magnitude thresholds previously established by Hopkins [27]. Statistical analyses were performed using JASP (Version 0.8.1.2, JASP, Amsterdam, The Netherlands) and statistical significance was set at $p \leq 0.05$.

Table 2. Reliability for each muscle size and architecture variable in lying and standing postures.

Measure	**CV**	**ICC**
LMT	2.03%	0.98
SMT	1.40%	0.99
LPA	6.65%	0.90
SPA	6.18%	0.84
LCSA	1.93%	0.95
SCSA	3.63%	0.91

CV = coefficient of variation; ICC = intraclass correlation coefficient; LMT = lying muscle thickness; SMT = standing muscle thickness; LPA = lying pennation angle; SPA = standing pennation angle; LCSA = lying cross-sectional area; SCSA = standing cross-sectional area.

Results

Each variable was normally distributed according to the Shapiro-Wilk assessment. Paired-samples *t*-Tests revealed statistically significant differences between standing and lying measurements of MT ($p < 0.001$), PA ($p < 0.001$), and CSA ($p \leq 0.05$) (Figure 3). Standing measures resulted in greater values for all variables, presented as mean ± 95% CI: SMT was 14.5% ± 6.67% greater than LMT, SPA was 49.0% ± 16.0% greater than LPA, and SCSA was 3.4% ± 3.13% greater than LCSA. Additionally, standing measures related more strongly to measures of isometric and dynamic performance. The relationships between standing and lying measures of muscle morphology with isometric and dynamic performance, as well as their practical interpretation, are displayed in Table 3.

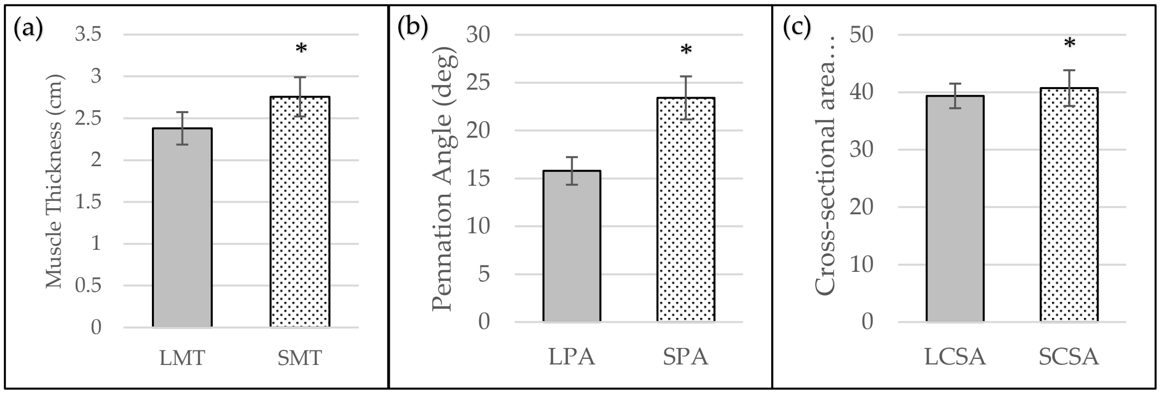

Figure 3. Lying and standing ultrasonography measurement differences for (**a**) Muscle Thickness; (**b**) Pennation Angle, and (**c**) Cross-Sectional Area presented as mean ± 95% CI. * = statistically significant difference compared to lying measure ($p \leq 0.05$).

Table 3. Relationships between muscle size and architecture with measures of isometric and dynamic performance.

Measure	Outcome	IPF	RFD50	RFD100	RFD200	IMP50	IMP100	IMP200	1RM
LMT	Pearson's *r*	0.46	0.29	0.27	0.18	0.32	0.33	0.32	0.56 *
	p-value	0.10	0.31	0.35	0.55	0.26	0.25	0.26	0.04
	Interpretation	Moderate	Small	Small	Small	Moderate	Moderate	Moderate	Large
SMT	Pearson's *r*	0.73 *	0.59 *	0.53 *	0.52	0.54 *	0.58 *	0.59 *	0.55 *
	p-value	<0.01	0.03	0.05	0.06	0.04	0.03	0.03	0.04
	Interpretation	Very Large	Large	Large	Large	Large	Large	Large	Large
LPA	Pearson's *r*	0.20	−0.04	0.02	−0.03	0.13	0.11	0.09	0.46
	p-value	0.49	0.90	0.95	0.91	0.67	0.72	0.76	0.10
	Interpretation	Small	Trivial	Trivial	Trivial	Small	Small	Trivial	Moderate
SPA	Pearson's *r*	0.49	0.59 *	0.66 *	0.54 *	0.38	0.47	0.53 *	0.32
	p-value	0.08	0.03	0.01	0.05	0.18	0.09	0.05	0.26
	Interpretation	Moderate	Large	Large	Large	Moderate	Moderate	Large	Moderate
LCSA	Pearson's *r*	0.38	0.33	0.25	0.27	0.52	0.49	0.44	0.60 *
	p-value	0.18	0.25	0.38	0.36	0.06	0.08	0.11	0.03
	Interpretation	Moderate	Moderate	Small	Small	Large	Moderate	Moderate	Large
SCSA	Pearson's *r*	0.58 *	0.50	0.48	0.46	0.62 *	0.63 *	0.61 *	0.77 *
	p-value	0.03	0.07	0.08	0.10	0.02	0.02	0.02	<0.01
	Interpretation	Large	Large	Moderate	Moderate	Large	Large	Large	Very Large

* = statistically significant relationship ($p \leq 0.05$). LMT = lying muscle thickness; SMT = standing muscle thickness; LPA = lying pennation angle; SPA = standing pennation angle; LCSA = lying cross-sectional area; SCSA = standing cross-sectional area; IPF = isometric peak force; RFD50 = rate of force development at 50 ms; RFD100 = rate of force development at 100 ms; RFD150 = rate of force development at 150 ms; RFD200 = rate of force development at 200 ms; IMP50 = impulse at 50 ms; IMP100 = impulse at 100 ms; IMP150 = impulse at 150 ms; IMP200 = impulse at 200 ms; 1RM = one-repetition maximum back squat.

Discussion

The current investigation is the first study intended to determine the relationship between lying and standing measures of VL muscle morphology with upright isometric and dynamic performances. Although standing postures have been used in evaluating dynamic fascicle and tendon behavior [17,28], lying muscle measurements have been commonly used when the primary interest is static muscle morphology. We hypothesized that data collected using an upright posture would provide a stronger relationship to measures of standing isometric and dynamic performance. Our results indicated that (1) collection position significantly altered ultrasonography measurements of VL muscle size and architecture, and (2) standing ultrasonography measures were more strongly and more abundantly associated with measures of upright isometric and dynamic performance compared to lying ultrasonography measures.

Measures of standing muscle size (i.e., MT, CSA) and PA were statistically larger than the lying posture, providing evidence that body position substantially influenced the muscle measurements. Though a statistical change was found between the different postures with respect to CSA measures, there was a noticeably smaller percent difference compared to those of MT and PA. This indicates that while the measurements were quite different at the muscle belly, the measurements of whole muscle CSA were not influenced to the same degree. This may be due to a redistribution of the observed or neighboring muscle tissue and fluid between measurement positions due to gravity. Greater magnitude changes at the muscle belly may also be influenced by changes to fascicle orientation and/or rotation, creating a bulging effect [29]. Nonetheless, the observed increase in all measures of muscle morphology using an upright posture warrants an examination into the meaningfulness of such a difference. Most athletic actions are executed from standing postures, and therefore the potential exists that lying ultrasonography measures may not accurately capture the muscle in its functional configuration [30].

Lying measures yielded moderate correlations between LMT-1RM and LCSA-1RM, which is in agreement with previous findings [3,31-33]. Nevertheless, the correlations observed between standing measurements of whole muscle CSA and maximal dynamic strength were greater in magnitude, yielding a very large association between SCSA-1RM compared to a large association between LCSA-1RM. Standing CSA and SMT generated large and very large associations with IPF respectively, whereas LMT and LCSA were both considered moderate. While the relationship between muscle size as measured by ultrasonography and maximal strength has been well established [3,31-33], the results of the current investigation suggest that the selected posture in which muscle size is measured may influence the magnitude of its association with maximal strength. We speculate that this observation may be due to an underrepresentation of muscle size and architecture captured in a lying posture. When concerned with dynamic strength outcomes (i.e., 1RM), the relationship with MT was not considerably influenced by body position, as evidenced by both postures generating large correlations. The lack of influence position has on dynamic strength correlations could potentially be attributed to muscle-length changes during dynamic movements compared to isometric tests. Therefore, standing measures may better reflect muscle shape and architecture as they relate to upright isometric tests such as the isometric squat. It is possible that measurement of muscle architecture at a variety of joint angles may capture the changes in muscle length associated with changes in joint angle, thus better reflecting the changes in muscle length that occur during dynamic assessments. Practitioners may consider the positioning and nature of their physical assessment when determining the most appropriate ultrasonography technique in measuring muscle size.

Consideration of muscle architecture may give a more complete indication of the influence of body position on muscle imaging and the resulting associations with physical output. Pennation angle indicates fascicle orientation with respect to the aponeurosis and has been previously associated with both maximal strength and RFD [34,35]. The substantially larger SPA compared to LPA reflects the influence of gravity on muscle shape and resulting PA. Though the present investigation did not yield a significant relationship between SPA-IPF, the difference in relative magnitude of the relationships LPA-IPF and SPA-IPF should be noted. The difference in correlation coefficients further suggests that lying measures may not be accurately capturing muscle architecture as it relates to its maximal strength.

Maximal strength has been suggested to underpin RFD [36,37], as stronger athletes exhibit higher RFD and force at critical time points [35]. However, it may be valuable to assess RFD separately, as it has been found to correlate strongly with sport-specific tasks [38]. Muscle architecture is one of the major contributors to an athlete's RFD capabilities [39,40], along with fiber-type distribution [41-44] and efferent neural drive [35,45]. In the present investigation, SPA yielded large correlations with all of the considered spectrum of RFD time points, while lying measures yielded trivial relationships. Further, large associations were observed between SMT and all RFD time points, with only small associations observed with LMT and RFD. Rate of force development during later time intervals (i.e. >100 ms) are closely related to maximal strength [36], which may also explain the observed relationship with standing measures of muscle size. The very strong correlation with SPA may be due to the greater pennation angle observed, which may be due to a more compacted arrangement of series elastic elements (e.g., actin-myosin filaments, titin, cross-bridges) [46-48]. The findings of the current investigation, especially considering the relationship between SPA-RFD50, suggest that standing fiber orientation may also be considered when investigating the intrinsic muscle properties influencing early-phase RFD [35,36]. Therefore, lying measures of VL muscle architecture may misrepresent the functional configuration and RFD potential entirely, limiting ultrasonography's usefulness as a monitoring tool for strength-power athletes. Because of RFD's implication for sporting success [35], practitioners should instead consider standing measures of muscle architecture.

Impulse combines elements of magnitude and rate of force production, as increases in either would result in an increase in impulse. Impulse has well-established relationships to sprint [49-51] and change-of-direction performance [52], making it potentially the most important kinetic characteristic to consider in evaluating the overall success and potential transfer of effects resulting from a training intervention. Within the current investigation, the results suggest that standing ultrasonography measures may provide a more useful representation of VL architecture in predicting impulse potential across a range of time points. All impulse variables considered (IMP50, IMP100, IMP200) elicited statistically large associations with SMT and SCSA, but no statistical significance was reached with any lying measures of muscle size. Additionally, SPA returned substantially larger correlation magnitudes compared to LPA, further suggesting that standing measurements more accurately capture the functional configuration of VL architecture as it relates to the physical potential of strength-power athletes.

Conclusions

The results of the current investigation demonstrated that ultrasonography measurements of VL muscle size and architecture were significantly larger during standing ultrasonography imaging. This is valuable considering the desire for practitioners to capture the muscle in a state that more precisely represents its configuration during performance. Further, standing ultrasonography measures were overall more strongly associated with measures of isometric and dynamic performance. This suggests that, if practitioners intend to gain insight into strength-power potential based on ultrasonography measurements, performing collection with the athlete in a standing posture is preferred.

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CHAPTER 6

STUDY IV

A PRELIMINARY INVESTIGATION INTO THE EFFECT OF ACTN3 AND ACE POLYMORPHISMS ON MUSCLE AND PERFORMANCE CHARACTERISTICS

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Abstract

The purpose of this investigation was to explore the phenotypic and performance outcomes associated with *ACTN3* and *ACE* polymorphisms. Ten trained males (age = 25.8 ± 3.0 years, height = 183.3 ± 4.1 cm, body mass = 92.3 ± 9.3 kg, back squat to body mass ratio = 1.8 ± 0.3) participated. Blood samples were analysed to determine *ACTN3* and *ACE* polymorphisms. Standing ultrasonography images of the vastus lateralis (VL) were collected to determine whole muscle cross-sectional area (CSA-M) and a percutaneous muscle biopsy of the VL was collected to determine type I-specific CSA (CSA-T1), type II-specific CSA (CSA-T2), and type II-to-type I cross-sectional area ratio (CSA-R). Isometric squats were performed on force platforms with data used to determine peak force (IPF), allometrically scaled peak force (IPFa), and rate of force development (RFD) at various timepoints. One-repetition maximum back squats (1RM) were performed whereby allometrically scaled dynamic strength (DSa) was determined. Cohen's *d* effect sizes revealed *ACTN3* RR and *ACE* DD tended to result in greater CSA-M but differ in how they contribute to performance. *ACTN3* RR's influence appears to be in the type II fibers, altering maximal strength, *ACE* DD may influence RFD capabilities through a favorable CSA-R. Though the findings of the current investigation are limited by the sample size, the findings demonstrate the potential influence of *ACTN3* and *ACE* polymorphisms on isometric and dynamic strength testing. This study may serve as a framework to generate hypotheses regarding the effect of genetics on performance.

Introduction

Athletic potential and performance outcomes are thought to be the result of a combination of several factors related to training and recovery strategies. Genotype, however, is likely the largest contributor to athletic potential and performance, with heritability estimated to be responsible for as much as 66% of performance (7). Human gene mapping has been especially insightful in the identification of candidate genes related to certain phenotypic characteristics. Two of the most extensively explored in athletics are the α-actinin-3 (*ACTN3*) and angiotensin converting enzyme (*ACE*) genes.

ACTN3 encodes for the skeletal muscle α-actinin-3, which is expressed predominantly in sarcomeres of fast-twitch, glycolytic muscle fibers (8, 16). The expressed protein is believed to enhance structural integrity of the Z-line within these sarcomeres, consequently enhancing its force-production capabilities. A polymorphism of the *ACTN3* gene that may influence the performance outcomes occurs at amino acid 577 (16). The replacement of arginine (R) with a stop codon (X) at that location within chromosome 11 creates the most notable gene variants pertaining to strength-power performance outcomes (6). The R allele and the RR polymorphism have well-established relationships to strength-power performance outcomes in a variety of populations, including soccer players (24), rowers (6), and sprinters (21). Further, in *ACTN3* knockout mouse models, a decreased fiber-specific cross-sectional area (CSA) was observed in type II fibers with a concomitant reduction in strength (17).

ACE has several polymorphic sites, but of interest are the presence (insertion, I allele) or absence (deletion, D allele) of a 287-base pair (bp) Alu element fragment at intron 16. Fragment absence, the D allele, has been most associated with strength-power related phenotype (13), particularly in sprinters (20). This may be due to the increased localized ACE activity within the muscle observed in the presence of the D allele, ultimately leading to a greater conversion of angiotensin I to angiotensin II. A greater amount of angiotensin II has been associated with cell growth in endothelial, cardiac, and vascular smooth muscle cells. Due to the recently increasing evidence of localized renin-angiotensin systems within the muscle, it is possible that the D allele is associated with increased muscle growth, which would be advantageous for strength-power athletes (5).

The observed outcomes of certain *ACTN3* and *ACE* polymorphisms within the context of sport performance primarily address prevalence within certain athletic populations and the implications for talent identification. Few studies address the specific effects of polymorphisms on mechanistic strength related characteristics (9, 10). Though valuable, these investigations often focused on the untrained (3, 9, 10) or elderly (19). Therefore, there is a gap in the current literature exploring the potential effect of various polymorphisms of these 2 candidate genes have on mechanistic physical outputs – especially considering trained, strong subjects. Furthermore, to the authors' knowledge, no study has simultaneously examined the influence that *ACTN3* and *ACE* polymorphisms have on muscle characteristics. Therefore, the purpose of this investigation was to explore the phenotypic physiological and performance outcomes associated with the respective *ACTN3* and *ACE* polymorphisms in trained subjects. Specifically, the authors aimed to provide a rationale for further investigation of (a) the potential effect that *ACTN3* and *ACE* polymorphisms have on whole muscle and fiber-specific characteristics and (b) the effect that *ACTN3* and *ACE* polymorphisms have on isometric and dynamic performance capabilities.

Methods

Experimental Approach to the Problem

To explore the phenotypic physiological and performance outcomes associated with *ACTN3* and *ACE* polymorphisms, subjects were asked to complete a testing series beginning with a whole blood draw which would eventually be used for genotyping. Immediately thereafter, subjects completed standing ultrasonography measurements and a one-time subcutaneous muscle biopsy – both of the vastus lateralis (VL). After 48 hours of rest, subjects returned to complete isometric squat testing performed on dual force platforms to assess isometric strength and rate of force development capabilities. Finally, subjects completed a 1 repetition maximum (1RM) back squat after another 48-hour rest period.

Subjects

Ten well-trained males (mean ± *SD*; age = 25.8 ± 3.0 years, height = 183.3 ± 4.1 cm, body mass = 92.3 ± 9.3 kg, back squat to body mass ratio = 1.8 ± 0.3) volunteered for the current investigation. Subjects, most of whom were former athletes including Division I and professional status, were required to have spent at least the past year engaging in a strength training program that included back squats. Each subject's hydration status (urinary specific gravity) was determined using a refractometer (Atago, Tokyo, Japan) prior to any data collection to ensure hydration status would not influence the results. All subjects read and signed a written informed consent and the procedures were approved by East Tennessee State University's Institutional Review Board.

Procedures

Genotyping

A 10-mL blood sample was drawn into 2 separate 4-mL EDTA tubes (BD Vacutainer K2 EDTA; Franklin Labs, NJ, USA) by venupuncture from certified personnel. The whole blood samples were stored at -80ºC until subsequent analysis. Automated DNA extraction was performed using the manual processing protocol of the QIAamp DNA Blood Mini Kit (Qiagen, Crawley, United Kingdom). Real-time polymerase chain reaction (PCR) was performed to determine the genotype of the *ACTN3* and *ACE* polymorphisms in each subject, with reactions carried out on 96-well microtiter plates. Each 50 µL reaction volume contained 25 µL Platinum Superfi PCR Master Mix (ThermoFisher, Waltham, MA, USA), 10 µL 5X Superfi™ GC Enhancer (ThermoFisher, Waltham , MA, USA), 2.5 µL of both the respective forward and reverse primers for *ACTN3* and *ACE*, and 12.5 µL subject DNA combined with nuclease-free water at a concentration of approximately 250 ng•μL^{-1}.

For *ACTN3*, the 290-bp fragment of exon 15 was amplified using the forward primer CTGTTGCCTGTGGTAAGTGGG and the reverse primer TGGTCACAGTATGCAGGAGGG. Polymerase chain reaction was performed for 35 cycles (30 seconds of denaturation at 94ºC, 30 seconds of annealing at 65ºC, and 60 seconds of extension at 72ºC), final extension at 72 ºC for 5 minutes, and held at 4ºC. Amplified products were then electrophoresed on 0.5% agarose gel stained with ethidium bromide to confirm primer adherence. Samples were then purified using QIAquick PCR Purification Kit (Qiagen, Calgary, UK). Following purification, *ACTN3* polymorphisms were determined using an automated DNA sequencer (CEQ 8000 Genetic Analysis System; Beckman Coulter, Indianapolis, IN).

The *ACE* PCR amplification followed identical procedures of those used for *ACTN3* except for the substitution of specific primers for *ACE* – the forward primer CTGGAGACCACTCCCATCCTTTCT and reverse primer GATGTGGCCATCACATTCGTCAGA. To determine polymorphism, amplified products were electrophoresed and visualized by using agarose gels stained with ethidium bromide. The products were assessed for the presence of a 490 bp fragment (I allele), a 190 bp fragment (D allele), or both (I/D heterozygote) (Figure 1). Genotyping was performed in accordance with published genotyping and quality control recommendations including external control samples and internal controls of genotyping samples in duplicates (23, 29).

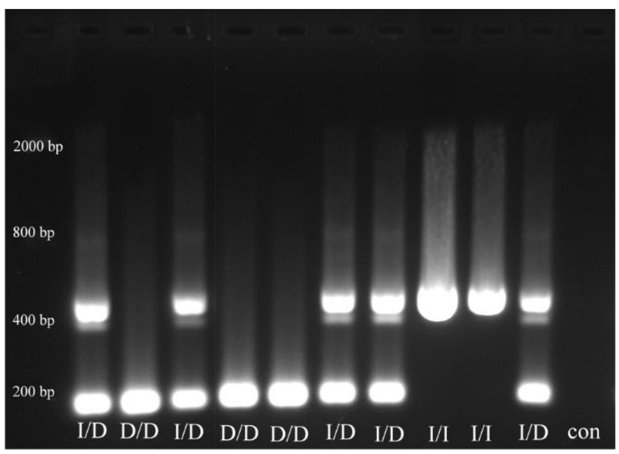

Figure 1. ACE polymorphism results by subject.

Standing Ultrasonography Measurement

Standing ultrasonography measures began with the application of a water-soluble transmission gel to the measurement site and a 16-Hz probe oriented in the short-axis, perpendicular to the VL muscle, while not depressing the skin. Subjects were upright and bearing weight on the opposite leg, which was positioned on a 5-cm tall platform, unweighting the measured leg and creating an internal knee angle of 160 ± 10° (30). Cross-sectional area (CSA-M) was obtained using a panoramic image sweep in the transverse plane perpendicular to the muscle (31). A straight-edge was placed along the skin to ensure that the probe remained along the previously established midline. Three images were obtained and saved for subsequent analysis using the software provided within the ultrasonography device.

Muscle Biopsy Sampling and Processing

Immediately after ultrasonography and blood draw procedures, all subjects received a one-time percutaneous biopsy. Biopsies of the superficial region of right vastus lateralis at a depth of approximately 3 cm were obtained using the Bergström (2) technique and a 5-mm biopsy needle with suction with 1% lidocaine as a local anesthetic. A portion of the muscle tissue was immediately mounted on cork under a microscope to orient the specimen for transverse sectioning, frozen in a slurry of isopentate cooled by liquid nitrogen, and stored at -80 °C until subsequent processing. The samples were sectioned on a cryostat (Leica, Wetzlet, Germany) at a thickness of 14 μm and affixed to a microscope slide in preparation for immunohistochemical analysis.

Following sectioning and mounting, tissues were fixed with acetone at -20°C for 2 sets of 5 minutes each. All samples were then blocked for 2 hours in a 10% normal goat serum. Sections were incubated overnight in monoclonal antibodies specific to myosin heavy chain (MYH) isoforms: MYH2 for type IIA fibers (IgG1, 1:100 dilution) and MYH7 for type I fibers (IgG2b, 1:200 dilution) (Developmental Studies Hybridoma Bank, University of Iowa, Iowa, USA). Finally, samples were then incubated for 2 hours using goat antimouse AlexaFluor 350 (IgG1) and AlexaFluor 555 (IgG2b), each at 1:200 dilution (Invitrogen, Carlsbad, California).

A series of photographs were taken of the slides at x 10 magnification using an Olympus BX41 microscope and imaged using an Olympus Q-Color3 camera. Fibers were classified, counted, and sized using the ImageJ software (National Institute of Health, USA). Using the color composite feature within the software, fiber types were identified and sized objectively based on the color-specific staining intensity within each. Type I-specific CSA (CSA-T1), type II-specific CSA (CSA-T2), and type II to type I CSA cross-sectional area ratio (CSA-R) were calculated from the collected data.

Isometric Strength Assessment

Subjects completed a standardized general warm-up sequence before beginning the isometric strength assessment. Isometric strength was assessed using the ISQ using an adapted protocol from McBride et al. (18). Subject bar heights were set such that an internal knee angle of 100° existed, which was assessed via goniometer (18). Data were collected using a dual force platform design (2 × 91 cm × 45.5 cm force platforms, RoughDeck HP, Rice Lake, WI, USA) inside a custom-built apparatus with data sampled at 1000 Hz.

Participants completed warm-up trials at 50% and 75% of their perceived maximal effort prior to performing a minimum of 2 maximal effort trials. If a countermovement of greater than 200 N was observed, or trials differed by more than 250 N, subjects were required to complete an additional trial (15). Participants were also instructed to push ‘as fast and hard as possible’ and strongly verbally encouraged during trials (18). A 3-minute seated rest interval was prescribed between each of the ISQ trials. LabVIEW (Version 7.1, National Instruments, Austin, TX, USA) was used for collecting and ForceDecks (Version 1.2.6464, NMP Technologies Ltd., London, UK) for processing kinetic data (4). Peak force (IPF), allometrically scaled peak force (IPFa), rate of force development over 50 ms (RFD-50), 100 ms (RFD-100), and 200 ms (RFD-200) were calculated from the collected data.

Dynamic Strength Assessment

Dynamic strength was measured using a one-repetition maximal (1RM) back squat. Dynamic strength testing was completed after ISQ and after 48 hours of rest to ensure subjects were adequately recovered. Before testing, each subject performed a general dynamic warm-up.

After the general warm-up, bar and safety bar heights in the squat rack were adjusted as needed to best accommodate each subject. Subjects warmed up with progressively heavier loads of 30, 50, 70, 80, and 90% of their self-reported 1RM for 5, 3, 2, 1, and 1 repetitions respectively before maximal attempts. Each subject attained their back squat 1RM by attempting progressively heavier loads until they could not complete a successful repetition. For a repetition to be considered successful, the subject's hip crease must have been below the patella at the bottom of the descent during the back squat and was verified by multiple certified strength and conditioning coaches. One repetition maximum back squat and allometrically scaled dynamic strength (DSa) were calculated from the collected data.

Statistical Analyses

Subjects were grouped by polymorphism for both *ACTN3* and *ACE* for analysis. Descriptive statistics including mean and *SD* were calculated. Within-subject reliability for each variable was assessed using intra-class correlation coefficients (ICC) (12). Between-group Cohen's *d* effect sizes were calculated for each dependent variable to determine the magnitude and meaningfulness of performance differences across polymorphisms. Effect sizes were interpreted with magnitude thresholds of 0-0.2, 0.2-0.6, 0.6-1.2, 1.2-2.0, and 2.0 and above as trivial, small, moderate, large, and very large (11). Statistical analyses were performed using Microsoft Excel (Redmond, WA, USA).

Results

All performance-dependent variables in the current investigation returned acceptable ICC values (11). The frequency of RR, RX, and XX *ACTN3* genotypes was 70% (n=7), 30% (n=3), and 0% (n=0), respectively. The frequency of DD, ID, and II *ACE* genotypes was 30% (n=3), 50% (n=5), and 20% (n=2) respectively (Figure 1).

A moderate between-group effect (d = 0.61) favored *ACTN3* RR compared to *ACTN3* RX for CSA-M. Additionally, a small between-group effect favored *ACTN3* RR for CSA-T1 (d = 0.21), CSA-T2 (d = 0.42), and CSA-R (d = 0.58). Isometric and dynamic performance outcomes also favored *ACTN3* RR over *ACTN3* RX, yielding moderate between-group effect magnitudes for IPF (d = 0.73), IPFa (d = 0.94), RFD-200 (d = 0.64), and 1RM (d = 0.99), along with a large effect for DSa (d = 1.51) (Table 1).

A moderate between-group effect for CSA-M favored *ACE* DD compared to *ACE* ID (d = 0.67) and *ACE* ID over *ACE* II (d = 0.65), along with a large positive effect in *ACE* DD over *ACE* II (d = 1.37). A moderate unfavorable effect for CSA-T1 was observed in *ACE* ID compared to *ACE* DD (d = -0.83) and *ACE* II compared to *ACE* DD (d = -0.80) – meaning that CSA-T1 was smallest in *ACE* DD. Conversely, small effects were present favoring *ACE* ID over *ACE* II (d = 0.35) in CSA-T1. *ACE* DD had a moderate effect difference over *ACE* II in CSA-R (d = 0.88). Further, large favorable effects were present comparing *ACE* DD to *ACE* ID in CSA-R. (d = 1.42). Trivial effects were observed comparing all *ACE* polymorphisms for CSA-T2 (Table 1). Considering *ACE* DD with respect to *ACE* ID, a moderate favorable effect was observed for IPF (d = 0.70), 1RM (d = 1.14), and DSa (d = 1.06). *ACE* ID had a moderate favorable effect for RFD-100 (d = 0.69) relative to *ACE* II. Lastly, moderate effects favored *ACE* DD over *ACE* II in RFD-100 (d = 0.66), 1RM (d = 0.93), and DSa (d = 0.62).

Table 1. Between-group Cohen's *d* effect size and the corresponding practical interpretation.

		Muscle Characteristics				Performance Characteristics						
		CSA-M	CSA-T1	CSA-T2	CSA-R	IPF	IPFa	RFD-50	RFD-100	RFD-200	1RM	DSa
ACTN3	RR TO RX	0.61	0.21	0.42	0.15	0.73	0.94	0.43	0.46	0.64	0.99	1.51
		Moderate	Small	Small	Trivial	Moderate	Moderate	Small	Small	Moderate	Moderate	Large
ACE	DD TO ID	0.67	-0.83	-0.14	0.48	0.70	0.58	0.33	0.33	0.50	1.14	1.06
		Moderate	Large	Trivial	Small	Moderate	Small	Small	Small	Small	Moderate	Moderate
	ID TO II	0.65	0.35	0.11	0.33	-0.25	-0.37	0.60	0.69	0.23	0.01	-0.19
		Moderate	Small	Trivial	Small	Small	Small	Moderate	Moderate	Small	Trivial	Trivial
	DD TO II	1.37	-0.80	0.00	0.79	0.38	0.15	0.54	0.66	0.57	0.93	0.62
		Large	Moderate	Trivial	Moderate	Small	Trivial	Small	Moderate	Small	Moderate	Moderate

CSA-M = whole muscle cross-sectional area; CSA-T1= type I fiber cross-sectional area; CSA-T2 = type II fiber cross-sectional area; CSA-R = type II to type I cross-sectional area ratio; IPF = peak force; IPFa = allometrically scaled peak force; RFD-50 = rate of force development at 50 ms; RFD-100 = rate of force development at 100 ms; RFD-200 = rate of force development at 200 ms; 1RM = one-repetition maximum back squat; DSa = allometrically scaled dynamic strength

Discussion

The purpose of this investigation was to explore the potential physiological and performance outcomes associated with *ACTN3* and *ACE* polymorphisms. Specifically, the authors aimed to examine (a) the potential effect that *ACTN3* and *ACE* polymorphisms have on muscle characteristics including whole muscle, fiber-specific morphology and fiber-specific CSA distribution and (b) the effect that *ACTN3* and *ACE* polymorphisms have on isometric and dynamic performance capabilities. The main results of this investigation have shown that subjects possessing the *ACTN3* RR polymorphism had larger whole muscle and fiber-specific CSA as well as a greater CSA-R compared to *ACTN3* RX. Furthermore, our results indicate that individuals with the *ACTN3* RR variant were stronger under both isometric and dynamic conditions and may possess greater RFD capabilities. Although *ACE* DD had the largest whole muscle CSA, a moderate between-group effect favored *ACE* ID and *ACE* II variants for CSA-T1. However, no meaningful effects were observed for CSA-T2.

Whole muscle CSA, often used as an indicator of force production capabilities (26), is affected by both inherited (i.e. candidate gene polymorphism) and environmental factors (i.e. training and nutrition). Because of the α-actinin-3 protein's role as an actin anchor within the Z-line of fast muscle and ACE's role in the synthesis of angiotensin II and cell growth, both provide mechanistic rationale for a larger muscle phenotype. The *ACTN3* R allele has been associated with larger whole muscle size in previous literature (32), which agrees with the findings of the current investigation. However, Zempo et al. (32) compared the presence of the R allele (i.e. *ACTN3* RR and RX) to *ACTN3* XX. In the current investigation, no X allele homozygotes were present, but the findings do reveal the potential that R allele homozygotes (*ACTN3* RR) possess a greater whole muscle size in comparison to heterozygotes (*ACTN3* RX).

The *ACE* DD polymorphism presents a less clear mechanistic rationale as it relates to muscle size (10), although previous literature has indicated that the D allele is associated with greater changes in muscle CSA after resistance training (23). It has been postulated that, because there is a high prevalence of ACE within the muscle, that the generation of angiotensin II (a potent growth regulator in cardiac and smooth muscle) provides a link to larger muscle sizes. The presence of the *ACE* II genotype has been associated with high-level endurance performance (20), which typically favors athletes with lesser muscle mass than strength-power athletes (1). In addition, previous longitudinal research has suggested a preference for *ACE* DD and *ACE* ID variants for the gaining of muscle mass over *ACE* II (5). Indeed, the results of the current cross-sectional investigation indicated that muscle mass was, from greatest-to-least: *ACE* DD > *ACE* ID > *ACE* II. Although training, nutrition, and other factors may ultimately determine the muscle size as an adult, the presence of one or both polymorphisms may provide for a greater potential for muscle hypertrophy, and therefore a greater force production capability.

Strength potential is also closely related to the composition of the muscle. This includes fiber-type specific CSA as well as the CSA-R. The current investigation provided interesting considerations in this regard, demonstrating the potential that *ACTN3* RR may have a small effect on both CSA-T1 and CSA-T2 compared to *ACTN3* RX. The *ACTN3* RR genotype has been linked to elite strength-power performance in track and field (22, 25). Therefore, the findings of the current investigation lend support for previous findings, especially considering ACTN3's function within fast, glycolytic fibers. Interestingly, the *ACE* DD genotype was associated with a moderate decrease in CSA-T1 compared to the other genotypes and no effect in CSA-T2. However, there was a small between-group effect favoring *ACE* DD over *ACE* ID and a moderate effect supporting *ACE* DD over *ACE* II, which creates a potentially favorable scenario for force production abilities. Considering the potential combination of *ACTN3* RR (i.e. larger CSA-T2) and *ACE* DD (i.e. smaller CSA-T1), there may be a situation where the CSA-R may be maximized. Greater CSA-R may minimize the drag effect that T1 fibers have on T2 fibers during whole muscle contraction, potentially increasing the maximum contraction velocity (14, 28). A higher contraction velocity would be beneficial to performances in strength-power events, particularly in sprinting and jumping, which involve high RFDs and dynamic strength.

The *ACTN3* RR and *ACE* DD genotypes were simultaneously present in 2 subjects in the current investigation. Although there are technical limitations of only having two subjects with these genotypes simultaneously, it is interesting to note that these subjects yielded among the greatest scores on isometric and dynamic strength as well as RFD. More specifically, one of the subjects had the highest CSA-M, greatest CSA-R, and ranked first in each performance measure collected including absolute and relative measures of strength performance and RFD at all considered timepoints. The other subject possessing both genotypes had the second highest CSA-M, was second in 1RM, third in IPF and DSa, and fourth in IPFa. The RFD capabilities of the second subject increased in rank as the timepoint expanded, moving from seventh in RFD-50 up to fourth in RFD-200 amongst all subjects. The lower ranking in the early RFD timepoints may be partly due to this subject's seventh-ranked CSA-R, which has been previously connected to RFD capabilities (28). This variability in RFD may indicate the importance of training, as the subjects had different athletic backgrounds. It may also suggest that there are other genes and their respective polymorphisms that must be taken into consideration that more drastically influence RFD capabilities than *ACTN3* and *ACE*. This list may contain more than 40 candidate genes (27) including, but not limited to *MCT1* (monocarboxylate transport 1), *MYLK* (myosin light chain kinase), *COL1-A1* (collagen α-1 chain type I), insulin-like growth factor related genes, or myostatin-related genes (27). As demonstrated, the factors influencing strength performance are robust and comprise bioenergetic, structural, and regulatory aspects.

Although the findings of the current investigation are limited by the sample size, it is the first of the authors' knowledge to investigate the potential influence of *ACTN3* and *ACE* polymorphisms on isometric and dynamic strength testing. This research has the potential to act as a framework for the generation of future hypotheses within strength and conditioning research as it relates to the influence of genetics. The current investigation suggests that the *ACTN3* RR and *ACE* DD tend to result in greater whole muscle size but differ in how they contribute to performance capacities. While *ACTN3* RR's influence appears to be in the T2 fibers and therefore alters gross isometric and strength performance, *ACE* DD appears to influence RFD capabilities through creating a favorable CSA-R. Future investigations should continue to explore the individual and combined effects of these two genotypes as well as the inclusion of other heritable characteristics and their relative contributions to performance potential and outcomes.

Practical Applications

The findings of the current investigation provide unique considerations for talent identification of strength-power athletes. Although previous investigations have explored the general physical qualities associated with these 2 candidate genes and their respective polymorphisms, the current investigation is the first to provide specific effect magnitudes on mechanistic strength qualities, albeit with a limited sample size. This may be valuable for organizations and governing bodies with long-term athlete development models that guide younger athletes toward certain sports in which they have a higher likelihood for success.

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CHAPTER 7

SUMMARY AND DIRECTIONS OF FUTURE RESEARCH

The findings of the current investigation provided extensive insight into the kinetic and kinematic characteristics of accentuated eccentric loading and the different interrepetition strategies typical of its application. Additionally, refining the measurement techniques used in the evaluation of resistance training effects becomes a logical consideration following an examination of programming tactics. The findings of the present investment demonstrate the efficacy of standing ultrasonography measurements of muscle size and architecture in relation to isometric and dynamic strength performance. Furthermore, the current investigation may serve to strengthen the existing literature regarding genetic predisposition for certain muscle phenotype and performance outcomes related to strength performance – all of which may be valuable in programming considerations.

Accentuated eccentric loading, whether applied to a single repetition using straight sets or applied to each repetition within cluster sets, increased eccentric work (W_{ECC}) and eccentric rate of force development (RFD_{ECC}). However, using AEL to elicit concentric potentiation was not supported by the findings of the current investigation. Although potentiation was not observed using AEL, future investigations should explore using different concentric and eccentric load prescriptions. This may be most readily elucidated by manipulating the concentric load against a fixed eccentric overload. Interrepetition rest does appear to have a positive effect on concentric peak power (PP), rate of force development (RFD_{CON}), and average velocity (MV). Once the nuances of AEL and its different applications has been further elucidated, future studies should explore the influence that the chronic exposure to the increased eccentric work and RFD have on muscle size, architecture, and strength outcomes.

In assessing muscle size and architecture, the findings of the current invfavestigation support the use of collecting measurements with the athlete in a standing posture when working with strength-power populations. Not only were standing measures of VL MT, PA, and CSA statistically larger compared with lying measures, but standing measures related more closely and abundantly to measures of maximal strength and RFD. The results suggest that if practitioners intend to gain insight into the strength potential of an athlete or monitor the responses to programing strategies aimed at increasing strength, standing measures may be more efficacious. Future investigations should continue to explore this novel technique, as the present investigation was the first. The findings could allow for a more appropriate athlete monitoring strategy or a valid and non-invasive means of estimating strength potential, especially considering the relationship with training-induced changes in muscle size and architecture with strength performance (Aagaard et al., 2001; Balshaw et al., 2017; Erskine, Fletcher, & Folland, 2014; Seynnes, de Boer, & Narici, 2007).

Strength potential may also be assessed by the presence of certain genotypes. *ACTN3* RR and *ACE* DD polymorphisms appeared to influence strength and RFD performance in the current investigation, but in potentially different manners. *ACTN3* RR tended to result in larger type II fibers and have a greater influence on maximal strength, whereas *ACE* DD tended to drive RFD characteristics through the presence of more advantageous type II-to-type I CSA ratios. Future investigations should continue to explore the separate and interdependent effects of these two genes. Further, the inclusion of other genes and their respective polymorphisms would give a more robust picture of the genes related to strength phenotypes.

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